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A report by the WHISP working group on the combined analysis of muon data at cosmic-ray energies above 1 PeV

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Different measurements of the muon content in extensive air showers at energies between 1 PeV and a few EeV have revealed discrepancies with the predictions of high-energy hadronic interaction models. Measurements cover several zenith angles, distances from the core, and muon energy thresholds from some hundreds of MeV to approximately tens of GeV. One of the most puzzling anomalies is the muon excess in air showers, which is observed particularly at very-high primary energies in some experiments. An updated combined analysis of several air-shower experiments has been carried out to investigate the presence of this discrepancy in the shower data. For this purpose, the energy scales of the experiments were cross-calibrated using a reference cosmic-ray energy spectrum. Comparisons with the predictions of several post-LHC hadronic interaction models are performed. Below 100 PeV, we observed that the data is found between the predictions of the hadronic interaction models for protons and iron nuclei. At higher energies, some experiments shows an overall increment of the shower muon content with respect to the model predictions, which grows with the primary energy. Other experiments, however, seems to be in agreement with the simulations, while one experiment, seems to show a deficit in the measured data at ultra-high energies.

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1. Introduction

The collisions of high-energy cosmic rays with the Earth's atmosphere produce cascade of secondary particles, which are know as *Extensive Air Showers* (EAS). They dissipate the energy of cosmic rays in the atmosphere and posses several properties which are sensitive to the characteristics of incident particles. Part of the goal of the physics of cosmic rays is to study EAS with ground-based detectors and analyze them to find out the energy, composition and arrival direction of the primary radiation at energies above 10^{14} eV. The estimation of the energy and composition of cosmic rays with EAS techniques needs the comparison of shower data with Monte Carlo (MC) simulations, which incorporate our current knowledge of particle physics interactions. Difficulties appear due to the limited description of the hadronic interactions in simulations at energies and physics conditions that have not been fully explored at modern particle-physics laboratories. These limitations introduce systematic uncertainties in the prediction of EAS observables and therefore in the estimation of the cosmic-ray properties. This is the case, for example, of the muon content of EAS, which is sensitive to the composition of cosmic rays.

Measurements of muons in cosmic-ray EAS carried out by different experiments at energies above 10^{16} eV have shown several anomalies in the data [1]. Perhaps, one of the most puzzling discrepancies in this regard is the problem of the excess in the number of shower muons with respect to the p/Fe predictions of MC simulations, which has been reported by several EAS experiments [2–8]. The most intriguing aspect of this discrepancy is that it has not been observed by other experiments, see, for example, [9–11]. That could be due to different experimental conditions of the detectors which may lead to probe different regions of the phase space of shower muons and due to different systematic uncertainties.

As a part of the current efforts to understand this muon puzzle, as it is called [12], on the number of shower muons a meta-analyses of measurements from different EAS observatories on the lateral muon density of EAS at primary energies between 10^{15} eV and $\sim 10^{18}$ eV has been carried out in [1, 13, 14] by the Working group on Hadronic Interactions and Shower Physics (WHISP), which is composed by the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array (TA) and Yakutsk EAS Array Collaborations. The data comes from the Cherenkov stations of IceTop [15, 16], the shielded scintillating detectors of KASCADE-Grande [11], the underground scintillation detectors of Yakutsk [10] arrays, the underground Geiger-Mueller counters of EAS-MSU [9], the tracking detector and water-Cherenkov calorimeter NEVOD-DECOR [3, 4], the underground liquid-scintillator tanks of SUGAR [8], the buried scintillator counters of HiRes-MIA [2], the surface detector of TA [7], which is made of plastic scintillators, the surface water-Cherenkov array [5, 6, 17] and the underground scintillator modules [18] of Auger and the shielded scintillator array of AGASA [19]. The novelties of the meta-analyses of these data were that it included measurements from different EAS detectors, besides they employed a common parameter for the comparisons with the models, and furthermore they also took into account the differences in the primary energy scales among the instruments. These studies showed that the muon density measurements are in agreement with the predictions of the post-LHC hadronic interaction models QGSJET-II.04 [20] and EPOS-LHC [21] up to energies of around 10^{17} eV, and that the excess of muons with respect to the p/Fe MC simulations appears in the data at higher energies, in particular, for NEVOD-DECOR, TA, SUGAR and the surface (SD) and underground muon detectors (UMD) of Auger. At energies > 10^{17} eV, only the data from Yakutsk did not exhibit this anomaly.

In order to continue the investigation of the muon excess in cosmic-ray induced EAS, in this paper we have updated the meta-analyses of [1, 13, 14] by incorporating updated results from Yakutsk [10] and SUGAR [22], and data from Haverah Park not considered previously by WHISP [23], as well as estimations obtained from an analysis of KASCADE-Grande data that employs, as an external input for the energy calibration, the energy scale of the Pierre Auger Observatory [24]. In addition, we have collected information about the characteristics of the detectors and its experimental conditions, as a first step to identify possible differences or coincidences among the experiments, which can help us to get some clues about the energy dependence of the muon content in air showers. To start with, we will present a brief summary about the main properties of the collected data. Next, we will give a brief description of the meta-analysis. Then, we will present the results and, finally, the discussions and some conclusions. This is a progress report, as the analysis is still ongoing.

2. The muon density data

The measurements analyzed in this study were recorded at ground level under different experimental conditions. They cover different values of primary energy, E, zenith angle of observation, θ, slant depths, energy thresholds at detection level and lateral distances, r to the axis of the EAS. Plots for the muon energy threshold at observation level, the zenith angle of the shower axis and the radial distances of the measurements considered in this work are presented in Fig. 1. The detection techniques are also different, as discussed in the previous section, and the analyses methods are not the same. Even more, the reported observables are not always the muon lateral densities, but related quantities, for example, NEVOD-DECOR provides mean values of the muon densities measured at different radial distances at a given energy and KASCADE-Grande presents results for the total muon number. For the meta-analysis, the data can not be directly compared among them due to the above differences. To avoid this difficulty, we have compared the data with their corresponding MC simulations. The latter takes into account the details of the EAS development, the response of the detector and the details of the analysis chain in each experiment to avoid any possible bias due

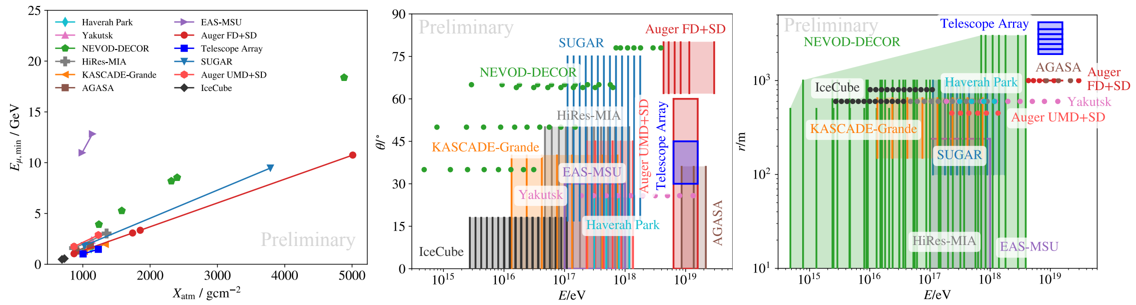

Figure 1: The muon phase space of cosmic-ray induced EAS covered by the experiments included in the meta-analysis. On figure of the left, the muon energy threshold but at the production site in the EAS (estimated according to [13]), $E_{\mu,\mathrm{min}}$, versus the effective atmospheric depth is presented (left). Points connected by a line indicate variations due to the zenith angle of observation. At the central and right figures, the zenith angle of observation θ and the lateral distances, r, respectively, are plotted against the primary energy, E, of the EAS. The points and the lines represent measurements in a limited region of the phase space, while the shaded areas indicate the regions over which the measurements were integrated.

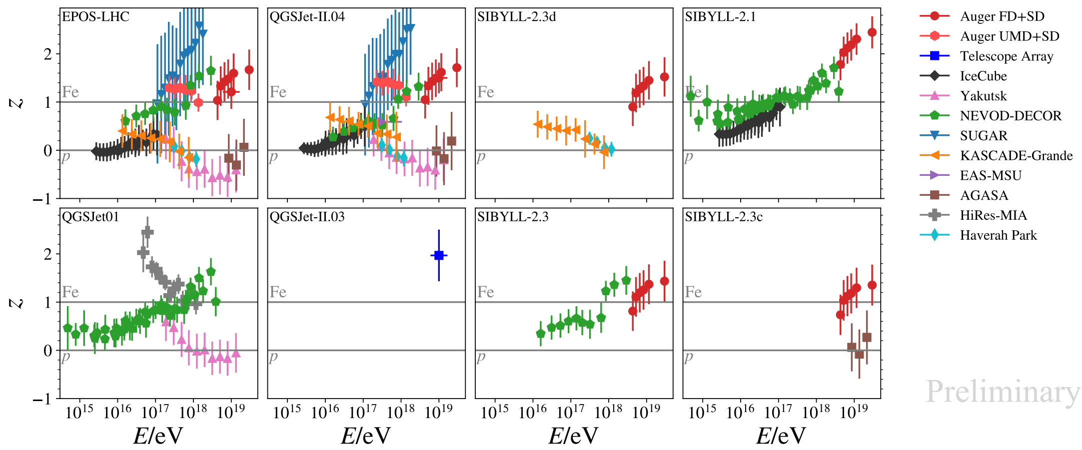

Figure 2: The z-scale derived from the muon density measurements using Eq. (1) and predictions of different pre- and post-LHC hadronic interaction models. If no points of an experiment are shown for a given panel, it means that the corresponding MC simulations were missing. The error bars represent total uncertainties (statistical and systematic errors added in quadrature), but for Haverah Park, where only statistical uncertainties are shown.

to experimental differences between the simulations and the data. The MC simulations are usually provided by the different experimental collaborations. The Haverah Park data used for our analysis do not include the detector simulations yet, since the corresponding working group is in process of updating the Haverah Park analysis in the light of the new high-energy hadronic interaction models.

The comparison of the measured data and the MC simulations is done through the calculation of the so called z-scale, which is defined as

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

where $\langle N_{\mu}^{\mathrm{det}}\rangle$ is the mean value of the measured muon density and $\langle N_{\mu,\mathrm{p}}^{\mathrm{det}}\rangle$ ($\langle N_{\mu,\mathrm{Fe}}^{\mathrm{det}}\rangle$) is the respective prediction for the average muon density for proton (iron) cosmic-ray nuclei. The z-scale is defined in such a way that $z = 1$ and when the measurements are in agreement with the predictions for iron primaries and $z = 0$, when they are consistent with the expectations for protons-induced EAS. The definition has the advantages that it eliminates the energy dependence that is observed in the muon density data and cancel possible linear biases in these quantities. More details about the z-scale can be found at [1, 19].

In Fig. 2, we present the values of the z-scale for the data from eleven experiments [2–7, 9, 10, 17–19, 22–25]. The comparisons are performed in the framework of different post- and pre-LHC high-energy hadronic interaction models, when MC simulations are available. For the former, we considered the QGSJET-II.04 [20], EPOS-LHC [21], SIBYLL 2.3 [26], SIBYLL 2.3c [27] and SIBYLL 2.3d [28] models, and for the latter, QGSJET01 [29], QGSJet-II.03 [30], and SIBYLL 2.1 [31]. From a first analysis of the results of Fig. 2, we observe that the measurements are found between the predictions of the hadronic interaction models only up to $\sim 10^{17}$ eV. At higher energies, we distinguish two possible behaviors of the data: a muon excess over the MC predictions for p and Fe primaries and a tendency of the data to lie close to, or even below, the

Experiment	E estimation	Muon contribution in E estimator	Full detection simulation	Vertical atm. depth (g/cm^2)	$E_{\text{data}}/E_{\text{ref}}$
EAS-MSU	SD	(10%, 50%)	✓	990	−−
HiRes-MIA	FD	(−10%, 0%)	✓	870	−−
Pierre Auger					
FD+SD	FD	(−10%, 0%)	✓	880	0.948
UMD+SD	FD/SD	(−10%, 0%)/< 10%	✓	880	0.948
SUGAR	Flux	−−	✗	1015	0.948
KASCADE-Grande	Flux	−−	✓	1022	0.948
Telescope Array	FD	(−10%, 0%)	✓	880	1.052
NEVOD-DECOR	Flux	−−	✗	1014	1.08
Haverah Park	SD	> 50%	✗	1016	1.16
IceCube/IceTop	SD	< 10%	✓	690	1.19
Yakutsk EAS array	SD	(10%, 50%)	✓	1020	1.24
AGASA	SD	(10%, 50%)	✗	920	1.47

Table 1: Characteristics of the shower muon analyses performed by each of the experiments considered in this work. The second column indicates whether the primary energy E of the EAS was determined in an independent way, using the fluorescence detector technique (FD), a method based on the data of the surface detector (SD) or an internal calibration between both methods (FD/SD). The label *Flux* is displayed, when the all-particle intensity is used, in comparison with the total spectrum from an external cosmic-ray model of composition, for energy calibration. The third column shows the contribution of the muon content to the energy estimator. The muon contribution in the case of a fully independent energy measurement, i.e. FD, was taken from [32]. The fourth column indicates whether an EAS reconstruction method and a full detection simulations were employed. The fifth column shows the vertical atmospheric depth of the sites. The last column displays the energy-scale factors applied to the data for cross-calibration in this analysis.

predictions for protons. The first effect is reported by Auger, TA, NEVOD-DECOR, SUGAR and AGASA and HiRes-MIA, while the second one is observed by Yakutsk, Haverah Park and the KASCADE-Grande related analysis. The observed difference between the experiments is prone to different systematic uncertainties, some of which are investigated in the next section. However, the correlation between the systematic uncertainties and the meta-analysis will be the subject of a further work.

3. Energy-scale adjustments and cross-calibration

In order to investigate the presence of anomalies in the data of Fig. 2, first we must correct the measurements for differences in the energy scale between the data and MC simulations, since this effect introduces offsets in the observed z parameter. This offset can be understood by taking into account that the muon number N_μ is sensitive to the primary energy E and the mass A of cosmic rays. The Matthews-Heitler model of hadronic EAS [33] predicts that $N_\mu = A^{1-\beta} \cdot (E/\xi_C)^\beta$, where $\beta \simeq 0.9$ and ξ_C is the critical energy of pions decaying into muons in the atmosphere. From this formula and Eq. (1), it can be shown that an offset in the energy-scale of 20% in the measured data produces a variation in the z-scale of 18% [1]. Since each experiment has its own energy scale, the offset for the z parameter can change according to the data set. This introduces a further complication in the analysis, which can be avoided by using a common energy scale for the measurements. Such energy scale is determined by establishing a reference energy spectrum for the cross-calibration and by shifting the energy scale of each experiment in such a way that its energy spectrum matches the reference one.

The procedure requires the calculation of a scaling factor $E_{\text{data}}/E_{\text{ref}}$ that allows to adjust the energy scale of a given experiment. As a reference scale, we have chosen the value that

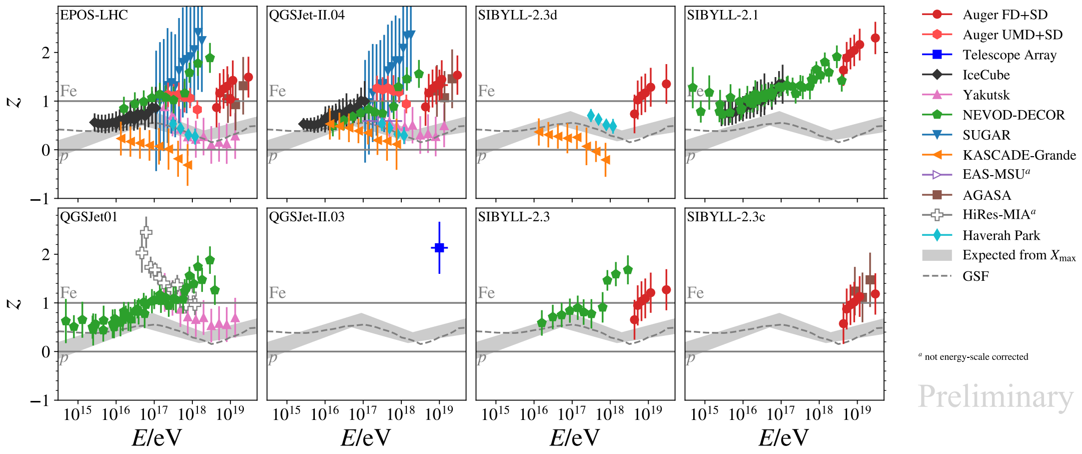

Figure 3: The z-scale values of Fig. 2 after applying the energy-scale adjustments described in the text for cross calibration. The data for EAS-MSU and HiRes-MIA are shown for comparison but were not cross-calibrated. The data is compared with predictions of the GSF model (dashed line) and with expectations from optical measurements of $X_{\max}$ [35] assuming a mixed composition scenario.

allows to shift the measured spectra to the position between the results for Auger and TA. The relative difference between the energy scales of these two experiments is $\sim 10.4\%$ according to the Spectrum Working Group of Auger and TA [34]. KASCADE-Grande and SUGAR reported their measurements based on the energy scale of Auger [24], hence, the same energy adjustment was applied for these experiments. In table 1, we present the values of the energy-scale factor applied to the data of each experiment. Notice that in case of the EAS-MSU and HiRes-MIA experiments no energy-scale shift is available, as we need more information about the internal energy calibration in their data.

The plot for the z-scale after applying procedure of energy cross-calibration to the measurements with an available energy scale is presented in Fig. 3. In this plot, we observe that the measured data lie between the predictions of the high-energy hadronic interaction models only up to energies of 10^{17} eV. As we approach the ultra-high energy regime, the muon excess with respect to the p/Fe MC predictions is revealed by Auger, TA, NEVOD-DECOR and AGASA experiments, however, is not observed by the other experiments. In case of Yakutsk and Haverah Park, the data is in agreement with the MC predictions, while for KASCADE-Grande, the measured values are below the model predictions. To proceed with the meta-analysis, we must remove the mass dependence of the z-scale. This is achieved by subtracting the expected value z_{mass} from the z-parameter. z_{mass} was estimated using the Global Spline Fit (GSF) model. The resulting values for $\Delta z = z - z_{\mathrm{mass}}$ are plotted in Fig. 3 for the EPOS-LHC and the QGSJET-II-04 models. In this plot, we observe a trend in the muon data, which seems to imply that the excess of muons respect to the GSF model predictions and the expectations from $X_{\max}$ data is energy dependent and that it appears at energies close to $\sim 10^{17}$ eV. There is also data, however, that is in agreement with the MC simulations, one experiment, namely, KASCADE-Grande calibrated with the Auger energy scale [24], whose results lie below the MC expectations. The differences between the observed trends of the data may give some keys to understand the muon puzzle. To extract such clues, first, we must understand, among other issues, how the experimental conditions may be related with the regions of the parameter

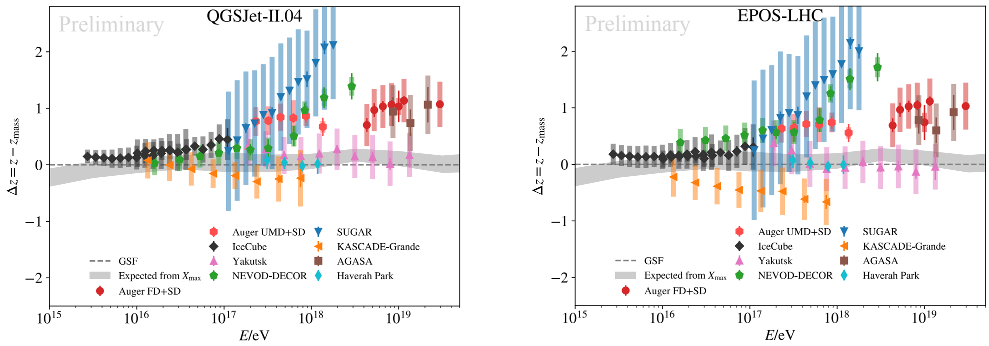

Figure 4: $\Delta z = z - z_{\rm mass}$ as a function of the primary energy for the combined data considered in this analysis and the hadronic interaction models QGSJET-II.04 (left) and EPOS-LHC (right). We did not included measurements from EAS-MSU and HiRes-MIA, as the energy scale of the data was not cross-calibrated. It was estimated by subtracting $z_{\rm mass}$ from the data for the z-scale presented in Fig. 2. $z_{\rm mass}$ is the prediction of the GSF model for the z-parameter.

space of the EAS muon data (see Fig. 1) and investigate the possible influence of systematic errors in the results. Even more, we must also consider what energy-calibration method was employed, the role of the low- and high-energy hadronic interaction models in the MC or whether important details about the simulations of the EAS development and the detector were taken into account (see table 1). These differences must be evaluated in more detail to understand their link with the muon puzzle. Some physical possibilities behind the muon deficit in MC simulations at ultra-high energies can be reviewed in [12].

4. Summary and future work

A meta-analysis of global data on muon densities in EAS induced by cosmic rays at high energies has revealed that in the ultra-high energy regime of primary energies there are several experiments that show a muon excess with regard to the p/Fe MC simulations based on post-LHC and pre-LHC hadronic interaction models. The discrepancy, however, is not observed by other experiments like Yakutsk and Haverah Park. Even more, in case of the KASCADE-Grande data calibrated with the Auger energy scale [24], it seems that the MC simulations are overestimating the measurements, in particular, in the case of EPOS-LHC. To understand these differences a more detailed analysis of the experimental conditions, simulations characteristics, detection methods, energy calibration techniques, etc., must be carried out. This task is still in progress and has started with the compilation of the main characteristics of the experiments as a preparation for the next stage of the study. In addition, further improvements of the meta-analysis are under consideration, as it is still preliminary, for example, to take into account a possible energy dependence of the energy scaling factors.

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