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Energy dependence of the number of muons for hadronic air showers with KASCADE-Grande

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The muon number of cosmic-ray air showers detected by the KASCADE-Grande experiment is presented as a function of the primary energy between 10^{16} eV and 10^{18} eV for three zenith angle intervals. For this work, data with zenith angles smaller than 40 degrees and radial distances between 150 m and 650 m from the core are used. The measurements correspond to 5 years of effective time of observation. For energy calibration a method based on the comparison of the measured muon-number distributions with the respective Monte Carlo (MC) predictions from the GSF model and the Pierre Auger energy scale is employed. For this procedure, we used the hadronic-interaction models QGSJET-II-04, EPOS-LHC and SIBYLL 2.3d. The results are compared with the corresponding MC estimations for the GSF model and for pure protons and iron nuclei. We found that while for larger shower inclinations, one observes a reasonable agreement between the simulation results and the data of KASCADE-Grande, current interaction models tend to overestimate the muon number in vertical air showers.

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1. Introduction

The analyses of the shower muon content in extensive air showers (EAS) induced by cosmic rays of ultra high energies, which have been carried out by experiments like the Pierre Auger [1, 2] and the Telescope array [3] observatories have reveal a discrepancy in the muon sector between the measurements and the predictions of the post-LHC hadronic interaction models of high energies. The anomaly is an excess of muons in the measured EAS with regard to the MC expectations for protons and iron primaries. A recent analysis performed by the Working group in Hadronic Interactions and Shower Physics have shown that the muon anomaly in EAS appears already at energies around 10^{17} eV [4]. The origin of such anomaly is unknown. New shower muon data with high precision and statistics is needed and more analyses are required in order to have further insights into the cause of the discrepancy. Although KASCADE-Grande [5] was decommissioned several years ago, it has a large set of precise data on the muon densities of EAS from 10^{15} to 10^{18} eV, which has not completely analyzed. Motivated by the problem of the muon excess and the opportunity that the KASCADE-Grande data offer for the study of this puzzle, in this work, we have updated our analysis of [6] on the muon content of EAS. In particular, we have estimated the number of muons in air showers, N_μ, against the primary energy in the energy range from 10^{16} to 10^{18} eV and we have compared the results with the predictions of the post-LHC hadronic interaction models QGSJET-II-04 [7], SIBYLL 2.3d [9] and EPOS-LHC [8].

To establish an energy scale in our analysis, we have employed as a reference the all-particle energy spectrum of the Pierre Auger Observatory (PAO) published in [10] and we have adapted the calibration procedure proposed by the NEVOD-DECOR [11, 12] and the SUGAR [13] collaborations. The method consists in the comparison of the measured N_μ flux, that is $d\Phi_{exp}/dN_{\mu,exp}$, with the flux, $d\Phi_{sim}/dN_{\mu,sim}$, predicted by a given high-energy hadronic interaction model using the total energy spectrum and cosmic-ray composition of the GSF model [14], but shifted to match the PAO energy spectrum of [10]. From the comparison between the measured and MC fluxes, the ratio R that relates the muon number in MC simulations with the actual one at a given energy is estimated. The ratio R is defined by the following expression [15]:

$$\begin{aligned} d\Phi_{exp}(N_{\mu,exp})/dN_{\mu,exp} &= d\Phi_{sim}(N_{\mu,sim})/dN_{\mu,sim} \times dN_{\mu,sim}/dN_{\mu,exp} \\ &= d\Phi_{sim}(N_{\mu,exp}/R)/dN_{\mu,sim} \times 1/R. \end{aligned} \tag{1}$$

Then, we applied this factor R event-by-event to the MC simulations in order to obtain an estimation of the experimental shower muon number at a given primary energy, E. We will present the details of the analysis and the results of the study in the following sections.

2. Experimental set-up and the measured data set

The KASCADE-Grande experiment was an air-shower detector dedicated to the study of cosmic rays with energies between 10^{15} up to 10^{18} eV [16, 17]. The instrument was installed at 110 m a.s.l. in the Karlsruhe Institute of Technology (49.1° N, 8.4° E), campus north, Germany, and it was composed by different systems of particle detectors dedicated to measure various EAS observables, such as the number of electrons, muons (at different energy thresholds) and hadrons. The number of electrons, N_e, (with energies > 5 MeV for vertical incidence) was measured with

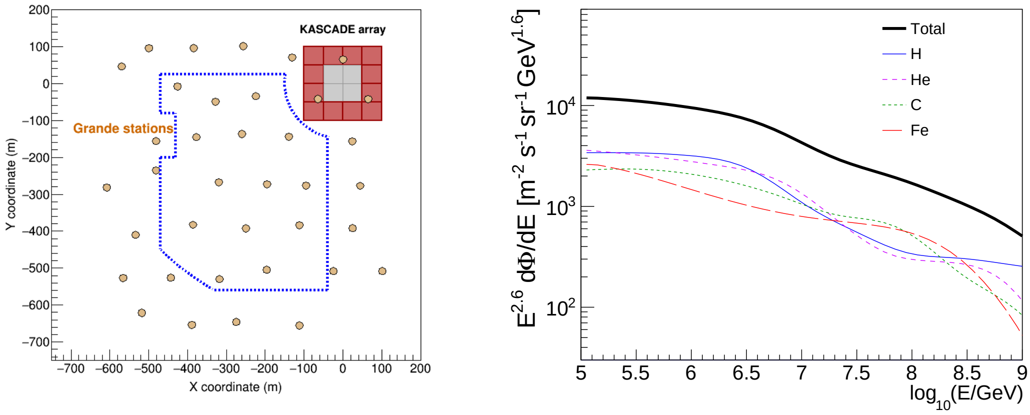

Figure 1: Left panel: Layout of the KASCADE-Grande experiment. The KASCADE array is shown on the upper right part of the figure. Each small square in the KASCADE area represents a cluster of electromagnetic detectors. The outer clusters in red contains also shielded scintillator detectors. The Grande array is shown with the grid composed by small circles. The fiducial area employed for this study is enclosed by the dotted lines. Right panel: The energy spectra for the H, He, C and Fe mass groups of cosmic-rays according to our composition model. The model takes the energy spectra of the GSF model [14] but the energy scale is shifted in such a way that its all-particle spectrum matches the reported one by the Pierre Auger Observatory in [10].

the electromagnetic array of KASCADE, which was composed of 252 liquid scintillator detectors distributed over an area of $200 \times 200\,\mathrm{m}^2$. The detectors were separated by a distance of 13 m from each other and were grouped in 16 clusters. On the other hand, the number of muons, N_μ, (with energy threshold of 230 MeV for vertical incidence) was obtained from the measurements of the shielded plastic scintillator detectors of KASCADE. There were 192 muon detectors, which were installed in the 12 outer clusters of the KASCADE array. Meanwhile, the number of charged particles, N_{ch}, ($e+\mu$ with more than 3 MeV for vertical incidence) was estimated using the data from the 37 plastic scintillator detectors of the Grande array, which were arranged in an hexagonal grid of $700\times700\,\mathrm{m}^2$. The average distance between such detectors was 137 m. The Grande detector was designed to extend the measurements of KASCADE from 10^{17} eV up to 10^{18} eV and also provided measurements of the EAS core position and the arrival direction of cosmic rays at high energies.

For our analysis, we have employed EAS measurements collected from December 2003 to November 2012. The experimental data sample consisted of 1.276×10^7 events, which were selected using different cuts in order to reduce the effect of the systematic uncertainties in our results. First, we discarded events that were not successfully reconstructed, were measured during unstable runs with hardware problems or have anomalous energy deposits at the Grande stations. From the remaining events, we kept those showers arriving with zenith angles $\theta < 40°$, with shower cores landing on a central area of Grande with radial distances between $r = 150$ and 650 m from the center of KASCADE as shown in Fig. 1, left, that activated at least 12 Grande detectors, with lateral shower ages in the range from -0.385 to 1.485, $N_e > 1 \times 10^4$ and $N_\mu > 3 \times 10^4$.

Using MC simulations, we found that our selected data has a trigger and reconstruction energy threshold for cosmic-ray induced EAS of $\log_{10}(E/\mathrm{GeV}) = 7.1 \pm 0.2$ and an N_μ threshold of $\log_{10}(N_\mu) = 5.15 \pm 0.15$.

3. MC simulations

For our analysis, we produced MC simulations based on the CORSIKA v7.5 package [18] and the QGSJET-II-04, EPOS-LHC and SIBYLL 2.3d hadronic interaction models for hadronic energies $E_h > 200$ GeV. At lower energies, we used Fluka 2011.2 [19]. We did not use thinning for the EAS simulations. For each high-energy hadronic model, we generated simulations for H, He, C, Si and Fe cosmic-ray nuclei, with zenith angles $\theta < 42°$ and primary energies between 10^{15} eV and 3.16×10^{18} eV following an E^{-2} spectrum.

In order to correct the measured N_μ for systematic effects, we applied a muon correction function on both MC and measured data. The correction depends on the zenith angle, EAS core position and the the shower size. It was build according to [20, 21] using our QGSJET-II-04 MC simulations and assuming a mixed composition with all elemental nuclei having equal abundances and individual power-law intensities with spectral index $\gamma = -3$.

As we mentioned in previous paragraphs, we need a reference energy spectrum and composition model of cosmic rays for our analysis. For this purpose, we have used the spectrum and relative abundances predicted by the GSF model [14] but with the energy scale modified to match the spectrum reported by the Pierre Auger Collaboration in [10]. By using appropriate weights for the H, He, C and Fe primaries in our MC simulations, we reproduced the elemental spectra predicted by the above composition model for the H, He, O and Si+Fe elemental mass groups. This procedure was performed for each set of MC simulations generated with QGSJET-II-04, EPOS-LHC and SIBYLL 2.3d. The cosmic-ray composition model employed for the present analysis is shown in Fig. 1, right.

4. Method of analysis

To start the analysis, we divided the data into three intervals of zenith angle: $\Delta\theta_0 = [0°, 21.78°]$, $\Delta\theta_1 = [21.78°, 31.66°]$ and $\Delta\theta_2 = [31.66°, 40°]$, each of them with the same aperture in order to have similar statistics in the region of maximum efficiency. Then, we built the distribution of N_μ for the experimental data, $n^{(k)}_{exp}$, in each interval $\Delta\theta_k$, where $k = 0, 1, 2$. Next, for a given post-LHC hadronic interaction model, we applied a shift $\delta_{\mu,k}(E)$ in logarithmic scale to the estimated muon number of each simulated event in $\Delta\theta_k$ and we constructed the corresponding N_μ distribution, $n^{(k)}_{MC}(\delta_{\mu,k})$, using our cosmic-ray composition model. We introduced this shift to find the difference between the measured muon number and the expected one at a given primary energy E, for a specific zenith angle interval and a particular high-energy hadronic model. Finally, we estimated $\delta_{\mu,k}(E)$ by minimizing the corresponding χ^2, which is defined as follows

$$\chi^2 = \sum_{i=1}^{m} \left[\frac{n^{(k)}_{exp} - n^{(k)}_{MC}(\delta_{\mu,k})}{\sigma^{(k)}_{i,exp}} \right]^2, \tag{2}$$

where $i = 1, ..., m$ labels each bin of $n^{(k)}_{exp}$ and $\sigma^{(k)}_{i,exp}$ is the statistical error for the i-th bin of the measured muon number histogram, which was estimated assuming a Poisson distribution inside the corresponding N_μ interval.

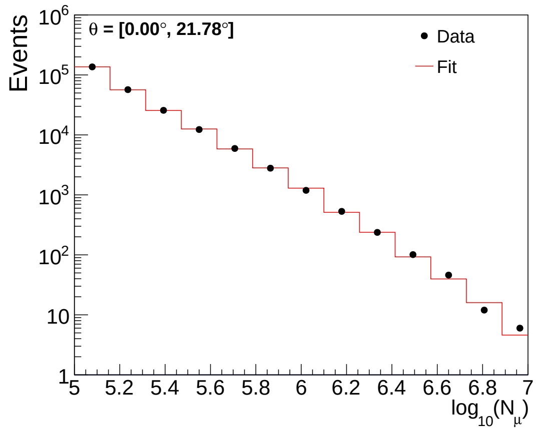

Figure 2: Result of the fit to the muon number distribution of the experimental data (black circles) for the zenith angle interval $\theta < 21.78°$ using the fitting procedure described in the text and the QGSJET-II-04 MC simulations.

We parameterized the shift of the muon number in the following way

$$\delta_{\mu,k}(E) = \begin{cases} a_{0,k} + a_{1,k}\log_{10}(E/E_0) + a_{2,k}\log^2_{10}(E/E_0), & \log_{10}(E) < E_0, \\ \\ a_{0,k} + a_{1,k}\log_{10}(E/E_0) + a_{3,k}\log^2_{10}(E/E_0), & \log_{10}(E) \geq E_0, \end{cases} \tag{3}$$

where the quantities $a_{j,k}$ (with $j = 0, 1, 2, 3$) are free parameters and $E_0 = 10^8$ GeV. Once, the shift is estimated, it is applied event-by-event to the true muon number, according to its primary energy E, that is predicted by the corresponding MC simulations used for the fit. This modified muon number is our estimation for the measured one as a function of the primary energy for a given zenith angle interval. In Fig. 2, we illustrate the fitting procedure presented above, using vertical EAS and the QGSJET-II-04 hadronic intercation model.

5. Results and discussions

Using our modified MC simulations, we provided an estimation of $\log_{10}[N_\mu/E]$ in measured EAS a function of the primary energy $\log_{10}(E)$. The results are compared in Fig. 3 against the predictions of the corresponding MC simulations used for the fit (i.e. with no muon shifts applied) for pure H and Fe primaries and our cosmic-ray composition model. Our results are shown with their corresponding statistical and systematic uncertainties. The statistical error is due to the limited statistics of the MC simulations, while the systematic errors include the uncertainties of the errors in the fit, the energy scale, the relative abundances of cosmic rays and the shape of the lateral distribution function (LDF) of muons. The errors were added in quadrature to obtain the systematic uncertainty. The uncertainty due to the errors of the fit was estimated from the maximum and minimum variations observed when varying the fitted parameters of the muon shift inside their corresponding 68 % C.L. intervals. The error from the uncertainties in the energy scale, were evaluated by repeating the calculations with our cosmic-ray composition model but shifted in energy by ±14 %, which is the estimated error in the energy scale of the total cosmic-ray spectrum reported by the Pierre Auger Observatory [10], and then by recording the variations introduced in the results. On the other hand, the errors due to the composition model were obtained by computing the maximum/minimum differences with respect to the original result that are obtained when modifying the relative abundance of the heavy (C+Fe) to the light (H+He) mass groups, first by 2.9 and, then by 0.99 at 100 PeV. In our composition model, this value is ~ 1.61. The selected values correspond to the ones observed in the composition analyses of [22]. Finally, to find the error due to the LDF of the muons, we divided the data in two subsets by using a cut at $r = 410$ m. The analysis procedure was repeated for each data subset and the measured variations with respect to the reference result was used to estimate the corresponding systematic error.

Returning to the main results, we found that in general the data for the muon number in hadronic EAS has a diferent evolution with the zenith angle that the MC predictions. In particular, the MC simulations seems to decrease faster with the zenith angle than the data, which confirms the KASCADE-Grande results of [21] about the effective muon attenuation length in air showers. We also see from Fig. 3 that KASCADE-Grande data calibrated with the Pierre Auger energy scale [10] is in better agreement with the MC expectations for inclined EAS than for vertical events. If we look at the results for events from the vertical direction, the disagreement is worst for the EPOS-LHC and SIBYLL 2.3d models above 10^{17} eV. Specifically, we observed that the shower muon data calibrated with the PAO energy scale tend to be below the predictions of the MC models for vertical EAS. QGSJET-II-04, on the other hand, is still bracketed by the MC expectations for H and Fe primaries, however, the composition seems to be lighter than the expectations from our cosmic-ray composition model. The previous results imply that the post-LHC hadronic interaction models QGSJET-II-04, EPOS-LHC and SIBYLL 2.3d tend to overestimate the measurements for small zenith angles. The fact that the composition of cosmic rays seems to be lighter than protons at high energies in the results of Fig. 3 implies that the KASCADE-Grande muon data calibrated with the PAO energy scale can not be used for this kind of studies due to the observed differences between the data, using the energy scale of PAO, and simulations. The analysis of composition in the N_μ vs $N_{ch}(N_e)$ phase space seems to be more robust as there exists a better agreement with MC simulations in this case [23, 24].

It is important to point out that more evidence in favor of an overestimation of the number of particles in measured EAS could be found in the results for the total energy spectrum reconstructed by KASCADE-Grande in comparison with the Pierre Auger spectrum, which provides the energy scale for our analysis. We have observed that if we calibrate our data with hadronic interaction models that produce more shower particles, the reconstructed spectrum is shifted to lower energies [25]. It happens that the all-particle energy spectrum obtained with $N_\mu - N_{ch}$ data of KASCADE-Grande and the hadronic intercation models EPOS-LHC or QGSJET-II-04 for energy calibration is below the spectrum measured by the Pierre Auger collaboration [26] at around 10^{17} eV, which may imply that the EPOS-LHC and QGSJET-II-04 are providing more shower particles than the actual ones at high energies.

6. Conclusions

The estimation of the total number of muons in EAS vs the primary energy at ground level with KASCADE-Grande using the energy scale of the Pierre Auger Observatory [10] has shown

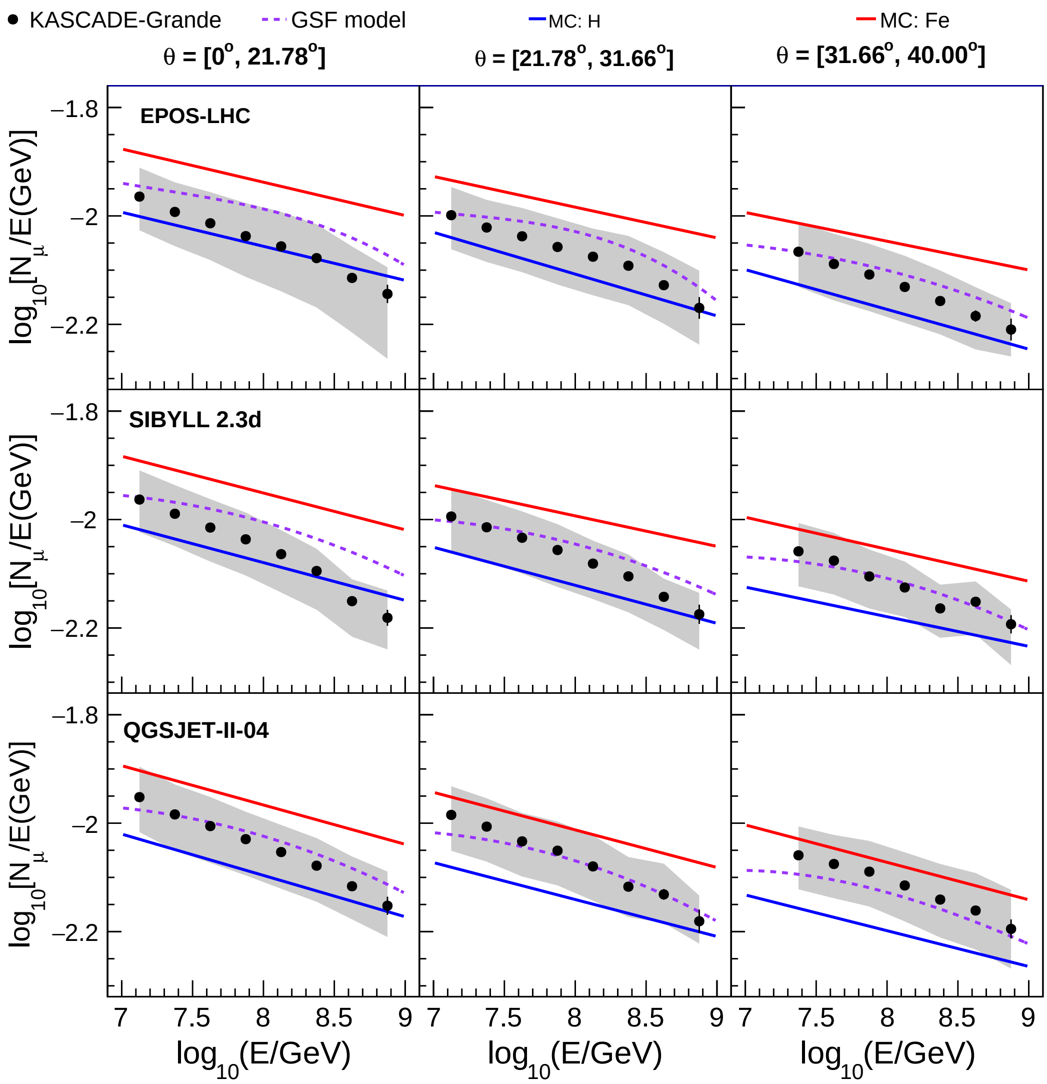

Figure 3: Experimental (data points, calibrated with the energy scale of the Pierre Auger Observatory [10]) and expected (lines) mean values of $\log_{10}[N_\mu/E(\mathrm{GeV})]$ versus $\log_{10}(E/\mathrm{GeV})$ in the framework of several post-LHC hadronic interaction models, from top to bottom: EPOS-LHC, SIBYLL 2.3d and QGSJET-II-04. Each column correspond to a different zenith angle bin. Inside each panel, the upper red lines represent the expectations for iron nuclei, the middle dashed lines in violet, for the GSF model and the lower blue lines, for H. The vertical error bars on the experimental plot represent statistical errors, while the gray band, the total systematic error.

that the shower muon content for vertical EAS seems to be overestimated by the post-LHC hadronic interaction models QGSJET-II-04, EPOS-LHC and SIBYLL 2.3d, but for more inclined events, at least up to 40°, the data is in better agreement with the MC expectations. We also observe that the rate of attenuation of the number of muons in air showers with the atmospheric depth is larger in MC simulations than in the experimental data, which confirms the KASCADE-Grande results on the effective muon attenuation length [21]. Since we are sampling muons with higher muon energies at production site for events with larger zenith angles, one possible consequence of the KASCADE-Grande observations calibrated with the PAO energy scale is that the differences between N_μ data and MC simulations may be due to a steeper muon energy spectra in the simulated air-shower events than in the actual EAS data. Deficiencies in the description of the experimental lateral density distributions of muons could be also a feasible explanation [27]. The role of the low-energy hadronic interaction models should be also investigated [28] among other possibilities.

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References

[1] A. Aab et al., Pierre Auger Collab., Phys. Rev. D 91, (2015) 032003.
[2] A. Aab et al., Pierre Auger Collab., Phys. Rev. Lett. 117, (2016) 192001.
[3] R. U. Abbasi et al., Telescope Array Collab., Phys. Rev. D 98, (2018) 022002.
[4] J.C. Arteaga-Velázquez for the WHISP Collaboration, PoS(ICRC2023) 466.
[5] W.D. Apel et al. , KASCADE-Grande Collaboration, NIM A 620 (2010) 202.
[6] J.C. Arteaga-Velázquez for the KASCADE-Grande Collaboration, PoS(ICRC2021) 376 (2021).
[7] S. Ostapchenko, Phys. Rev. D 83, (2011) 014018.
[8] T. Pierog et al., Phys. Rev. C 92, (2015) 034906.
[9] F. Riehn et al., Phys. Rev. D 102, (2020) 063002.
[10] V. Verzi et al., Pierre Auger Collab., ICRC 2019, POS(ICRC2019) 450.
[11] A.G. Bogdanov et al., Phys. Atom. Nucl. 73, 1852 (2010), Yad. Fiz.73,1904(2010).
[12] A.G. Bogdanov et al., Astropart. Phys. 98, 13 (2018).
[13] J.A. Bellido et al., Phys. Rev. D98, 023014 (2018).
[14] H.P. Dembinski et al., ICRC 2017, PoS (ICRC2017) 533.
[15] H.P.Dembinski et al., for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, PierreAuger, SUGAR, Telescope Array, and Yakutsk EAS Array collaborations, arXiv:1902.08124v1 [astro-ph.HE].
[16] W.D. Apel et al., NIM A 620, 202 (2010).
[17] T. Antoni et al., NIM A 513, (2003) 490.
[18] D. Heck et al., Report No. FZKA 6019, Forschungszentrum Karlsruhe-Wissenschaft Berichte (1998).
[19] A.Fasso et al., Report CERN-2005-10,INFN/TC-05/11, SLAC-R-773 (2005).
[20] W.D. Apel et al., KASCADE-Grande Collaboration, Astrop. Phys. 36 (2012) 183.
[21] W.D. Apel et al., KASCADE-Grande Collaboration, Astrop. Phys. 95 (2017) 25.
[22] J.C. Arteaga-Velázquez et al., KASCADE-Grande Collaboration, EPJ Web of Conf. 172, (2018) 07003.
[23] T. Antoni et al., KASCADE Collab., Astrop. Phys. 24 (2005) 1.
[24] J.C. Arteaga-Velázquez et al., KASCADE-Grande Collab., EPJ Web of Conf. 172, (2018) 07003.
[25] M. Bertaina et al., KASCADE Collab., ICRC2015, PoS (ICRC2015) 359.
[26] A. Coleman et al., Pierre Auger Collab., ICRC2019, PoS (ICRC2019) 225.
[27] S. Ostapchenko, Adv. in Spac. Res. 64, (2019) 2445.
[28] A. Aab et al., Pierre Auger Collab., Phys. Rev. Lett. 117, 192001 (2016).

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