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Study of the muon content of high-energy air showers with KASCADE-Grande


1Institut of Physics and Mathematics, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Mexico
2Institut für Kernphysik, KIT - Karlsruher Institut für Technologie, Germany
3Department of Physics, University of Bucharest, Bucharest, Romania
4Osservatorio Astrofisico di Torino, INAF Torino, Italy
5Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
6Universidade de São Paulo, Instituto de Física de São Carlos, Brasil
7 Fachbereich Physik, Universität Wuppertal, Germany
8Institut für Physik, Siegen University, Germany
9Department of Physics, Radboud University Nijmegen, The Netherlands
10National Centre for Nuclear Research, Department of Astrophysics, Lodz, Poland
11Frankfurt Institute for Advanced Studies (FIAS), Frankfurt am Main, Germany
12Department of Physics, University of Bucharest, Bucharest, Romania
13National Centre for Nuclear Research, Department of Astrophysics, Lodz, Poland
14Now at: Institute Nazionale di Ricerca Metrologica, INRIM, Torino, Italy
15Now at: DLR Oberpfaffenhofen, Germany
16Now at: University of Duisburg-Essen, Duisburg, Germany
17Spokesperson KASCADE-Grande

Abstract. In this work, we report measurements on the muon content (\(E_{\text{th}} > 230\,\text{MeV}\)) of extensive air showers (EAS) induced by cosmic rays with primary energy from 10 PeV up to 1 EeV performed with the KASCADE-Grande experiment. The measurements are compared with data from air shower observatories. In this regard, the study of the shower muons becomes extremely useful, since they are sensitive to the hadronic interactions that occur in the early phases of the EAS development [5]. Hence, a failure of the models to describe the shower muon data may imply a problem in our phenomenological description of the hadronic physics of EAS. In this paper, we present preliminary results obtained from three tests of the above post-LHC hadronic interaction models SIBYLL 2.3, QGSJET-II-04 and EPOS-LHC.

1 Introduction

At very high-energies, collisions of cosmic rays with the Earth’s upper atmosphere produce an extensive air shower (EAS) of particles (\(\gamma's, e^+e^-, m_0, h_0\), etc.) in the forward direction, whose study can provide valuable information over the main properties of the primary particle. Unfortunately, the interpretation of the EAS data relies on the employment of hadronic interaction models, which are subject to theoretical and experimental uncertainties that may hamper composition studies of cosmic-rays. Recently, a lot of progress has been done towards the reduction of such uncertainties motivated, in part, by the results of measurements at the LHC [1]. In this regard, several models were updated, for instance, SIBYLL 2.3 [2], QGSJET-II-04 [3] and EPOS-LHC[4]. To check the reliability of such models at the energies relevant for EAS studies, the predictions of the models can be compared with data from air shower observatories. In this regard, the study of the shower muons becomes extremely useful, since they are sensitive to the hadronic interactions that occur in the early phases of the EAS development [5]. Hence, a failure of the models to describe the shower muon data may imply a problem in our phenomenological description of the hadronic physics of EAS. In this paper, we present preliminary results obtained from three tests of the above post-LHC models using shower muons measured with the KASCADE-Grande observatory.

KASCADE-Grande was a ground-based air-shower observatory dedicated to investigate the energy spectrum, the composition and the arrival direction of cosmic rays in the energy range from \(10^{15}\) to \(10^{18}\) eV [6]. The instrument...
was located at the Karlsruhe Institute of Technology, Campus North (110 m a.s.l., 1022 g/cm² atmospheric depth) in Karlsruhe, Germany and took data from December 2003 up to November 2012. It consisted of several detector systems aimed to measure with high precision different components and properties of the EAS. One of the main systems of the observatory was the Grande array (0.5 km² of area), which was composed of 37 scintillator detectors separated by a mean distance of 137 m. The data collected with Grande was employed to estimate the shower core position at ground, the angle of incidence and the shower size or total number of charged particles (i.e. $e^+$’s plus $\mu$’s with $E_{\mu} > 3$ MeV for vertical incidence) of the event. Another important detector system of the observatory was the set of 192 shielded scintillator detectors from the KASCADE array (200 x 200 m²), which provided local muon density measurements ($E_{\mu} > 230$ MeV) of the EAS and, hence, information about the total number of muons, $N_{\mu}$, in the shower.

2 Experimental and simulated data
The present studies were carried out using events collected from zenith angles $\theta < 40^\circ$ and during the full data acquisition period of the experiment. In addition to reducing the effect of systematic uncertainties in the results, several selection cuts were applied to the data (see [7] for a detailed description). For example, to avoid border and punch-through effects, only events with cores located within the limits of a central area of $2.2 \times 10^5$ m² inside the KASCADE-Grande array and within radial distances in the interval $R = [100$ m, 600 m] were selected. After applying selection cuts, systematic uncertainties for $N_{\mu}$ and $N_{\nu}$ were found to to be $\leq 15\%$ and $\leq 20\%$, respectively, in the region of maximum efficiency, i.e. $\log_{10}(E$/GeV) $\geq 7.2 \pm 0.3$.

On the other hand, MC data sets were built for different combinations of the abovementioned post-LHC models and Fluka 2011.2 [8]. The former were used to describe the high-energy ($E_{\mu} \geq 200$ GeV) hadronic interactions in the EAS, while the latter, the corresponding low-energy regime. The production and development of the EAS were simulated with CORSIKA 7.5 [9] and the response of the detector to the passage of the shower, with a GEANT 3.21 [10] based program. MC events were generated for zenith angles $\theta < 42^\circ$ and the energy interval from $E = 10^{14}$ eV to $3 \times 10^{18}$ eV using an $E^\gamma$ primary spectrum with spectral index $\gamma = -2$. For the analysis, the MC events were weighted in order to simulate an $E^{-3}$ power-law spectrum. MC data samples were produced for five primary nuclei: H, He, C, Si and Fe, each of them with roughly the same number of events. Finally, all of them were processed with the same reconstruction algorithm employed with the experimental events [6] and were subject to the same cuts that were applied to the measured data.

3 Results of the model tests
3.1 Muon radial density distributions
The purpose of this analysis is to compare the predictions of SIBYLL 2.3 and the KASCADE-Grande measurements on the mean muon lateral distributions at the shower plane, $\rho_{\mu}(r)$, at different zenith angles and $\log_{10}(N_{\mu})$ intervals. In fig. 1, upper panel, the results for vertical EAS ($\theta = [0^\circ, 16.71^\circ]$) and three distinct shower size ranges are presented. The mean $\rho_{\mu}(r)$ distributions were obtained at shower disk coordinates and were built neglecting corrections due to atmospheric absorption when projecting on the shower disk plane. From fig. 1, it is seen that the measured distributions are in general within the MC predictions for pure protons and iron nuclei. However, the shape of the predicted lateral density distributions seems to be flatter than the measured one. The results for inclined events will be analyzed elsewhere [7].

3.2 The total muon number
The aim of this study is to confront the measurements on $N_{\mu}$ as a function of the shower size (as a proxy of the primary energy) versus the expectations from SIBYLL 2.3 for hydrogen and iron nuclei and different $\theta$ ranges. As a first step, for this analysis, the accuracy of $N_{\mu}$ was improved by correcting both the MC and measured $N_{\mu}$ data for systematic biases. This was achieved using a correction function calibrated with SIBYLL 2.3 predictions (see, e.g., [12] for a description of this function). This way, the final bias on $N_{\mu}$ became smaller than $8\%$. The experimental results and the SIBYLL 2.3 predictions for the dependence of $N_{\mu}$ on $E_{\mu}$ are presented in the lower panel of fig. 1 for three zenith angle intervals: $[0^\circ, 16.71^\circ]$, $[23.99^\circ, 29.86^\circ]$ and $[35.09^\circ, 40^\circ]$. From this figure, in general, it is observed that the measured $N_{\mu}$ is in agreement with the predictions of the SIBYLL 2.3 model. However, there are a few exceptions at high zenith angles and high shower sizes for two data points. The reason could be the poor statistics for the respective $\log_{10}(N_{\mu})$ bins or misreconstructed events that passed the selection cuts. The cause is under study.

Finally, it is noticed that fig. 1 also shows an increment towards heavier nuclei of the measured data for inclined EAS. This effect could be attributed to a mismatch between the predicted and the measured $\theta$-evolution of $N_{\mu}$ for EAS, which has been observed before when testing other hadronic interaction models [12]. This point is investigated in the analysis of the next subsection.

3.3 The muon attenuation length
In order to investigate the behaviour of the corrected $N_{\mu}$ with $\theta$ for air showers, the attenuation length of muons in the Earth’s atmosphere, $\lambda_{\mu}$, was investigated using the method described in [12]. This parameter is especially useful for cross-checking hadronic interaction models and is sensible to shower properties such as the inelasticity, spectrum and production of pions, among others. Recent analyses performed in [12] have shown that $\lambda_{\mu}$, as predicted by QGSJET-II-2, QGSJET-II-04, EPOS-LHC and SIBYLL 2.1 [13], deviates from the measured value at KASCADE-Grande for the primary energy interval $E \sim [10^{16.3}, 10^{17}]$ eV and zenith angles $< 40^\circ$. From the results of the last subsection it is suspected that also the prediction of SIBYLL 2.3 could deviate from the experimental
result. To test this hypothesis an analysis like the one described in [12] was applied here. Also, the full data set of KASCADE-Grande was used to reduce the statistical error of the measurement in comparison with that presented in [12]. This also allowed to update the tests of $\Lambda_\mu$ presented in [12] for QGSJET-II-04 and EPOS-LHC.

Now, in order to reduce the systematic uncertainties of the expected $\Lambda_\mu$ due to the unknown cosmic ray composition a composition model derived from the data itself was applied to the MC data. The model was obtained by comparing, for each hadronic interaction model, a linear combination of templates for five mass groups (H, He, C, Si and Fe) with the measured $\log_{10}(N_\mu) / \log_{10}(N_{ch})$ distribution. The MC templates for each mass group were weighted using double power-law formulas to model features of the individual spectra. The best parameters of these expressions were obtained by applying a loglikelihood fit using data with $\log_{10}(N_\mu) \geq 4.8$. Before weighting, the MC energy spectra resemble an $E^{-3}$ power-law function. It is worth mentioning that the measured and simulated $N_\mu$ data were corrected using the same correction function calibrated with the post-LHC model under consideration. An example of the result of the fit for SIBYLL 2.3 is presented in figure 2. We applied the re-
and within an area of \(8 \times 10^4 \text{ m}^2\) located at the center of the KASCADE-Grande array, as they further reduce the systematic bias on \(N_\mu\). Then, to obtain \(\Lambda_\mu\), we applied the constant intensity cut (CIC) method [14] to the data as described in [12]. The same procedure was applied to the measured data sets and the MC models derived above. Results are presented in fig. 3. We observe that the predictions of the post-LHC hadronic interaction models for \(\Lambda_\mu\) are in general below the measured value.

### 4 Conclusions

In this work, the SIBYLL 2.3 predictions on the muon content of EAS with primary energies around \(E = 10^{17} \text{ eV}\) have been tested using data from the KASCADE-Grande observatory. The results show that the measured data is in agreement with the predictions of the model. However, the actual muon lateral density distributions seems to be steeper than the model expectations. In addition the attenuation length of shower muons in the atmosphere was measured using the CIC method. It was found that the result is above the predictions of the post-LHC models SIBYLL 2.3, QGSJET-II-04 and EPOS-LHC.

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