Test of hadronic interaction models with the KASCADE-Grande muon data


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Abstract. KASCADE-Grande is an air-shower observatory devoted for the detection of cosmic rays with energies in the interval of $10^{14} - 10^{18}$ eV, where the Grande array is responsible for the higher energy range. The experiment comprises different detection systems which allow precise measurements of the charged, electron and muon numbers of extensive air-shower (EAS). These data is employed not only to reconstruct the properties of the primary cosmic-ray particle but also to test hadronic interaction models at high energies. In this contribution, predictions of the muon content of EAS from QGSJET II-2, SIBYLL 2.1 and EPOS 1.99 are confronted with the experimental measurements performed with the KASCADE-Grande experiment in order to test the validity of these hadronic models commonly used in EAS simulations.

1 Introduction

Cosmic-ray simulations are a useful tool to reconstruct the properties of primary cosmic rays at high energies, when studying the extensive air showers that the primary radiation induce in the Earth’s atmosphere. Hadronic interaction models are an important part of these simulations. They are also the main source of uncertainties in cosmic ray studies, which arises due to the lack of an accurate description of the physical phenomena occurring in the kinematical region of small transverse momenta, the most important one for EAS development. The difficulty comes from the fact that in the very forward region (small $\rho$), QCD can not be applied perturbatively and, even worse, almost no data is available. This situation demands the employment of phenomenological models tuned up with accelerator data at low energies to describe hadronic interactions. At the high-energy regime models are extrapolated to be used in EAS simulations [1]. The distinct phenomenological approaches and parameterizations used in the models result in very important differences in relevant EAS quantities at high-energies, such as the inelastic cross section, the inelasticity of hadron-hadron interactions and the total number of charged particles, which can be measured with dedicated air-shower observatories. Combining precise measurements of several EAS parameters, air-shower data can be used to test and improve hadronic interaction models. In this way, EAS facilities can serve also as particle physics laboratories to explore kinematic and energy regions not available for present collider experiments.

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In general, EAS studies show that predictions of hadronic models employed in EAS simulations present discrepancies from the observed data. For example, analyses performed with the multi-detector set-up KASCADE have shown that models such as QGSJET 98 and 01, EPOS 1.66, SIBYLL 1.6 and 2.1, VENUS, NEXUS and DPMJET are not able to describe simultaneously all the data on the hadron, electron and muon contents of air-showers (see [2] and references therein) in the primary cosmic ray energy interval 10^{14} − 10^{16} eV. These studies in KASCADE have been extended up to 10^{18} eV with its extension, the KASCADE-Grande observatory [3]. Some of these analyses are focused on the muon content. Muons, as a penetrating component of air-showers, are an important tool to get insight into the hadronic interactions happening during the development of the EAS. With KASCADE-Grande, in [4] it has been shown that predictions with QGSJET II about the muon production height (H_µ) distributions for EAS with zenith angles below θ < 18° show a discrepancy compared to the measured data (specifically, a disagreement at large muon production heights, H_µ > 3.5 km). Investigations of muon pseudorapidities with the Muon Tracking Detector of KASCADE-Grande [5] have also shown the deficiencies of QGSJET II. In addition, in [6] the lateral distribution function (LDF) of muons was studied with KASCADE-Grande. In general, it was observed that the slope of the muon LDF is not in agreement with results of the Monte Carlo simulations (QGSJET II and EPOS 1.99). In this work, predictions on the muon content of EAS from several current hadronic interaction models are confronted with measurements from KASCADE-Grande in the energy interval 10^{16} − 10^{18} eV. In particular, the muon attenuation length is extracted and studied as a tool to investigate the dependence of the muon content on the zenith angle in the atmosphere. The study is performed in an energy-independent way by using the so-called constant intensity cut method.

2 The KASCADE-Grande observatory

In KASCADE-Grande, measurements of the total muon number in EAS (N_µ, number of muons with energy greater than 230 MeV) are performed with an array of 192×3.2 m² shielded scintillator detectors belonging to the KASCADE part of the experiment. The procedure implies the calculation of the number of penetrating particles traversing each KASCADE muon station from the energy deposits obtained by sampling the shower front at distances larger than 40 m from the core [3]. The estimation is done by using a lateral energy correction function (LECF),

\[ E_{dep}(r)_{\mu on} = \left[ 7.461 + e^{1.762 - 0.0166 \cdot r} + 0.0002886 \cdot r \right] \text{MeV}, \]  

(1)
derived from simulations based on CORSIKA. The number of muons in the EAS is estimated from a maximum likelihood estimation, assuming that locally the detected muons fluctuate according to a Poisson distribution[3]:

\[ N_\mu = \sum_{i=1}^{k} n_i f(r_i) A_i \cdot \cos(\theta), \]  

(2)

where n_i is the number of muons measured at a core distance r_i in the i-th KASCADE muon station with sensitive area A_i. Here, θ is the zenith angle of incidence of the EAS and f(r) is a lateral distribution function for muons, which has a Lagutin-Raikin form [7],

\[ f(r) = \frac{0.28}{r_0^2} \cdot \left( \frac{r}{r_0} \right)^{p_1} \left( 1 + \frac{r}{r_0} \right)^{p_2} \left[ 1 + \left( \frac{r}{10 \cdot r_0} \right)^2 \right]^{p_3}. \]  

(3)
The coefficients \( p_1 = -0.69 \), \( p_2 = -2.39 \), \( p_3 = -1.0 \), and \( r_0 = 320 \) m were obtained from fits to CORSIKA/QGSJET01 simulations (protons and iron nuclei with energies of 10^{16} and 10^{17} eV). As it can be seen, the shape of the lateral distribution function is fixed and is not fitted event by event [3]. That comes from the fact that the number of muon data points is too low to produce a stable fit. On the other hand, arrival times and charged particle densities, employed for estimations of the EAS arrival direction, charged particle content and core position, are measured with an extension called the Grande array [3], which is composed by 37 × 10 m² plastic scintillator detectors distributed on a surface of 0.5 km².
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treated with FLUKA [12]. MC simulations for single pri-
maries in the zenith angle interval

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< 40.00
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< 23.99
< 16.71

KASCADE-Grande. In these plots,

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has been corrected for systematic ef-
ects according to QGSJET II.

3 MC simulations

Three high-energy hadronic interaction models were
tested in this study: QGSJET II-02 [8], EPOS 1.99 [9] and
SIBYLL 2.11 [10]. EAS development in the atmosphere
was simulated with CORSIKA [11] and the response of
the KASCADE-Grande detectors, with a GEANT 3.21
based code. The low-energy hadronic interactions were
treated with FLUKA [12]. MC simulations for single pri-
aries: H, He, C, Si and Fe were performed. Additionally,
a set with mixed composition was created (five primaries
of equal abundance). Data was generated following a

E −2
distribution. Proper weights were added to produce data
sets with spectral indexes: γ = −2.8, −3.0 and −3.2.

Selection cuts were applied to both experimental and
MC data. They were chosen according to MC studies to
avoid as much as possible the influence of systematic un-
certainties in the measurements of the EAS parameters.
Data sets were composed of events with more than 11
triggered stations in Grande, shower cores inside a central
area of 1.52 \times 10^5 m^2 and arrival directions confined to the
zenith angle interval of \Delta \theta = 0^\circ \text{–} 40^\circ . These events were
registered during stable periods of data acquisition and
passed successfully the standard reconstruction procedure
of KASCADE-Grande. Additionally, only showers with
log_{10} N_{\mu} > 5.1 were considered for this work. Both the
experimental and simulated data were analyzed and re-
constructed with the same algorithms. With the above quality
cuts, the effective time of observation with KASCADE-
Grande was equivalent to 1424 days. The threshold for
full efficiency was found at log_{10} N_{\mu} \approx 5.4.

The models tested predict different muon contents for
EAS at a fixed energy. In general, EPOS 1.99 gives more
muons than QGSJET II-2 and SIBYLL 2.1, while the latter
produces less muons for the same energy than QGSJET
II-2. For example, comparing simulated data for air show-
ers in the zenith angle interval \theta = 20^\circ \text{–} 26^\circ , at different
energies (see Fig 1) it is found that the mean number of
muons from EPOS 1.99 is higher by 14\% than QGSJET
II-2, and 21\% higher than SIBYLL 2.1. The evolution of

N_{\mu} \text{ in the atmosphere is also different in each case. This}
point will be analysed later in section 5.

4 Muon systematics

Systematic errors on the muon number were studied in
detail with MC simulations. From these analyses muon
correction functions were built as functions of the arrival
direction, core position and muon content of the EAS for
each hadronic interaction model, assuming a mixed com-
position and \gamma = −3. Experimental data was corrected
with the aforementioned functions to study also the effect
of the hadronic interaction model in the interpretation of
the muon data. Each MC muon data set was treated with
the correction function of the respective hadronic interac-
tion model.

In Fig. 2 the mean value of the muon correction func-
tion for different hadronic interaction models is plotted as
a function of the uncorrected \N_{\mu}. In general, after cor-
rection the systematic error on the muon number above
threshold is found to be almost independent of the cor-
rected muon size, \N_{\mu}, and smaller than 6\%.

5 Analysis and results

To test the hadronic interaction models with the
KASCADE-Grande muon data, predictions on the evolu-
tion of the muon content with the arrival zenith angle of
the EAS were confronted with observations. As a first
step, the muon fluxes were reconstructed for five dif-
ferent zenith angle intervals, each with the same acceptance
(c.f. Fig 3). Then, the integral muon fluxes, J(\N_{\mu}), are

\text{calculated for each } \Delta \theta \text{ range. If MC fluxes are normalized in such a way that vertical showers agree with the experi-
mental values around log \N_{\mu} = 5.1 \text{–} 5.6, one observes that MC values for more inclined showers deviate from
the measured fluxes. The differences increase for higher
zenith angles, as can be seen from Fig. 4. In general, it
is observed that the values of the experimental number of
muons in EAS are larger than the predictions by MC simulations and that the difference between the measured and predicted \( N_\mu \) increases for more inclined showers.

A more detailed comparison between the expected and observed muon measurements can be done by calculating the muon attenuation length, \( \Lambda_\mu \). This quantity is extracted by applying the Constant Intensity Cut (CIC) method to the \( J(N_\mu) \) data as described in reference [13] but using a global fit to the attenuation curves, \( \log_{10} N_\mu(\theta) \), with the known formula

\[
N_\mu = N_\mu^0 \exp(-X_0 \sec(\theta)/\Lambda_\mu)
\]

where \( X_0 = 1023 \text{ g/cm}^2 \) is the average atmospheric depth for vertical showers and \( N_\mu \) is a normalization parameter to be determined for each attenuation curve. The results for \( \Lambda_\mu \) are presented in Table 1 for simulated data and Table 2 for experimental measurements (corrected with appropriate correction functions). Comparison of the data and simulations is shown in Fig. 5. Discrepancies between the experimental values and the simulation results can be observed for the studied models. The differences do not disappear when modifying the primary composition or spectral index. As a consequence, the predicted evolution of the muon component with the zenith angle, \( N_\mu(\theta) \) (see equation 2) shows also a disagreement with the observations as shown in Fig. 6, where the evolution of the mean muon number from MC data (\( \gamma = -3 \)) is compared with that from experimental data (corrected for systematic effects) in the framework of the QGSJET II hadronic interaction model. Data has been normalized at \( \theta = 22^\circ \), where the maximum of the experimental zenith angular distribution is found. Similar results are found when the EPOS and SIBYLL hadronic interaction models are employed.

The percentage of deviation for \( N_\mu(\theta) \) between experiments and simulations depends on the zenith angle of normalization. The maximum deviation for inclined showers is found when normalizing at \( \theta = 0^\circ \). Such a differences are plotted in Fig. 7 assuming a mixed composition scenario with \( \gamma = -3 \) for MC data, for the models QGSJET II-2, EPOS 1.99 and SIBYLL 2.1. Formula 2 was employed to calculate the curves of Fig. 7 using the values for \( \Lambda_\mu \) from Tables 1 and 2.

Several factors, which are model dependent, may come into play in the observed differences. Beginning from predicted muon correction function (see graphs in Fig. 2), up to the description of the production, evolution and fluctuations of the shower, and systematic errors from the assumed shape of the muon lateral distribution function and the lateral energy correction function for muons in KASCADE-Grande. Therefore, one should be cautious when extracting conclusions from these differences. Systematic studies are underway to investigate these individual possibilities.

### 6 Conclusions

The predictions on the muon content of EAS from three hadronic interaction models: QGSJET II-2, EPOS 1.99 and SIBYLL 2.1 were tested in this work. In particular, the muon attenuation lengths of the penetrating component was calculated from MC simulations and compared with the values extracted from KASCADE-Grande observations. It was found that the above hadronic interaction models do not describe this aspect of the muon component in air-showers. More tests are under way. These tests include a more detailed analyses of the effect of the muon systematics on \( \Lambda_\mu \).

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Table 1. Muon attenuation lengths extracted from Monte Carlo data. The first column represents the hadronic interaction model. The corresponding composition scenario and spectral index, \( \gamma \), of the MC sample under study are specified at the upper lines of the table.

<table>
<thead>
<tr>
<th>Model</th>
<th>( \gamma = -2.8 )</th>
<th>( \Lambda_\mu ) (g/cm(^2))</th>
<th>( \gamma = -3.0 )</th>
<th>( \Lambda_\mu ) (g/cm(^2))</th>
<th>( \gamma = -3.2 )</th>
<th>( \Lambda_\mu ) (g/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>Mixed</td>
<td>Fe</td>
<td>H</td>
<td>Mixed</td>
<td>Fe</td>
</tr>
<tr>
<td>EPOS 1.99</td>
<td>445 ± 26</td>
<td>624 ± 31</td>
<td>636 ± 37</td>
<td>459 ± 23</td>
<td>607 ± 30</td>
<td>624 ± 31</td>
</tr>
<tr>
<td>QGSJET II</td>
<td>824 ± 33</td>
<td>832 ± 31</td>
<td>690 ± 43</td>
<td>900 ± 40</td>
<td>833 ± 31</td>
<td>693 ± 42</td>
</tr>
<tr>
<td>SIBYLL 2.1</td>
<td>546 ± 44</td>
<td>657 ± 29</td>
<td>681 ± 46</td>
<td>637 ± 39</td>
<td>672 ± 29</td>
<td>688 ± 38</td>
</tr>
</tbody>
</table>

Table 2. Muon attenuation lengths extracted from KASCADE-Grande data. Muon data has been corrected with different correction functions derived according to the hadronic interaction models shown on the left column.

<table>
<thead>
<tr>
<th>Muon correction function</th>
<th>( \Lambda_\mu ) (g/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPOS 1.99</td>
<td>1851 ± 142</td>
</tr>
<tr>
<td>QGSJET II</td>
<td>1383 ± 84</td>
</tr>
<tr>
<td>SIBYLL 2.1</td>
<td>1443 ± 86</td>
</tr>
</tbody>
</table>

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Figure 5. Attenuation lengths extracted from measured and simulated data in KASCADE-Grande. Different correction functions are applied to the data (see column on the left).
Figure 6. Predicted and observed evolution of the muon component with the zenith angle for $\log_{10}(N_{\mu,CIC}) = 5.6 - 5.8$. Data is normalized at $\theta = 22^\circ$. For the MC simulations QGSJET II has been used ($\gamma = -3$ and composition between H and Fe nuclei).

Figure 7. Relative deviation of measured data from model predictions for the dependence of the muon content with the zenith angle in the framework of three hadronic interaction models. The normalization angle is chosen at $\theta = 0^\circ$.

Acknowledgements

KASCADE-Grande is supported by the BMBF of Germany, the MIUR and INAF of Italy, the Polish Ministry of Science and Higher Education and the Romanian Authority for Scientific Research. This study was partly supported by Helmholtz Alliance for Astroparticle Physics (HAP) funded by the Initiative and Networking Fund of the Helmholtz Association, the DAAD-Proalmex program (2009-2012) and CONACYT.

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