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

J.C. Arteaga-Velázquez[1], W.D. Apel[2], K. Bekk[2], M. Bertaina[3], J. Blümer[2,4], H. Bozdog[2], I.M. Brancus[5], P. Buchholz[6], E. Cantoni[3,7], A. Chiavassa[3], F. Cossavella[4,13], K. Daumiller[2], V. de Souza[8], F. Di Pierro[3], P. Doll[2], R. Engel[2], J. Engler[2], M. Finger[4], D. Fuhrmann[9], P.L. Ghia[7], H.J. Gils[2], R. Glasstetter[9], C. Grupen[6], A. Haungs[2], D. Heck[2], J.R. Hörandel[10], D. Huber[4], T. Huege[2], P.G. Isar[2,14], K.-H. Kampert[9], D. Kang[4], H.O. Klages[2], K. Link[4], P. Łuczak[11], M. Ludwig[4], H.J. Mathes[2], H.J. Mayer[2], M. Melissas[4], J. Milke[2], B. Mitrica[5], C. Morello[7], G. Navarra[3,15], J. Oehlschläger[2], S. Ostapchenko[2,16], S. Over[6], N. Palmieri[4], M. Petcu[5], T. Pierog[2], H. Rebel[2], M. Roth[2], H. Schieler[2], F.G. Schröder[2], O. Sima[12], G. Toma[5], G.C. Trinchero[7], H. Ulrich[2], A. Weindl[2], J. Wochele[2], M. Wommer[2], J. Zabierowski[11]

[1] *Universidad Michoacana, Instituto de Física y Matemáticas, Morelia, Mexico*
[2] *Institut für Kernphysik, KIT - Karlsruher Institut für Technologie, Germany*
[3] *Dipartimento di Fisica Generale dell' Università Torino, Italy*
[4] *Institut für Experimentelle Kernphysik, KIT - Karlsruher Institut für Technologie, Germany*
[5] *National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[6] *Fachbereich Physik, Universität Siegen, Germany*
[7] *Istituto di Fisica dello Spazio Interplanetario, INAF Torino, Italy*
[8] *Universidade São Paulo, Instituto de Física de São Carlos, Brasil*
[9] *Fachbereich Physik, Universität Wuppertal, Germany*
[10] *Dept. of Astrophysics, Radboud University Nijmegen, The Netherlands*
[11] *Soltan Institute for Nuclear Studies, Lodz, Poland*
[12] *Department of Physics, University of Bucharest, Bucharest, Romania*
[13] *now at: Max-Planck-Institut Physik, München, Germany;* [14] *now at: Institute Space Sciences, Bucharest, Romania;* [15] *deceased;* [16] *now at: Univ Trondheim, Norway*
arteaga@ifm.umich.mx

Abstract: The KASCADE-Grande experiment is an air-shower ground-based observatory designed to study in detail the energy spectrum and composition of primary cosmic rays in the region of $10^{16} - 10^{18}$ eV. These analyses are based on precise measurements of the charged, electron and muon numbers of the cosmic ray air-showers performed through different detector systems which come into play simultaneously in KASCADE-Grande during the data acquisition. Due to the quality of the data and the number of air-shower observables at disposal through the experiment the collected data proves to be also useful to test hadronic interaction models used for air-shower simulations. In this contribution, predictions of the QGSJET II-2, SIBYLL 2.1 and EPOS 1.99 hadronic models are confronted with the KASCADE-Grande muon data. Besides, the influence of these models on the all-particle energy spectrum derived from the muon size is also investigated.

Keywords: KASCADE-Grande, hadronic models, muons, simulations, energy spectrum

1 Introduction

The interpretation of high-energy cosmic ray data relies on the extensive air shower (EAS) simulations in which an important source of uncertainty is the description of hadronic interactions. The main problem is that for the physics of air showers the relevant processes lie in the kinematical region of small transverse momenta where QCD cannot be applied perturbatively and, in most of the cases, where no data is available. In this way, phenomenological models and parametrizations of accelerator data at low energies must be invoked. These models are later extrapolated to high energies where they are used as valuable tools to understand the EAS observations at cosmic ray observatories [1]. Actually, air shower experiments can also help as laboratories to test and improve the modern hadronic interaction models in energy regions which at the moment are not reachable in particle accelerators. This task requires the measurement of as many EAS properties as possible with enough precision, such as the ones performed with the KASCADE experiment [2]. In the energy interval of $10^{14} - 10^{16}$, tests of early versions of the hadronic interaction models QGSJET,

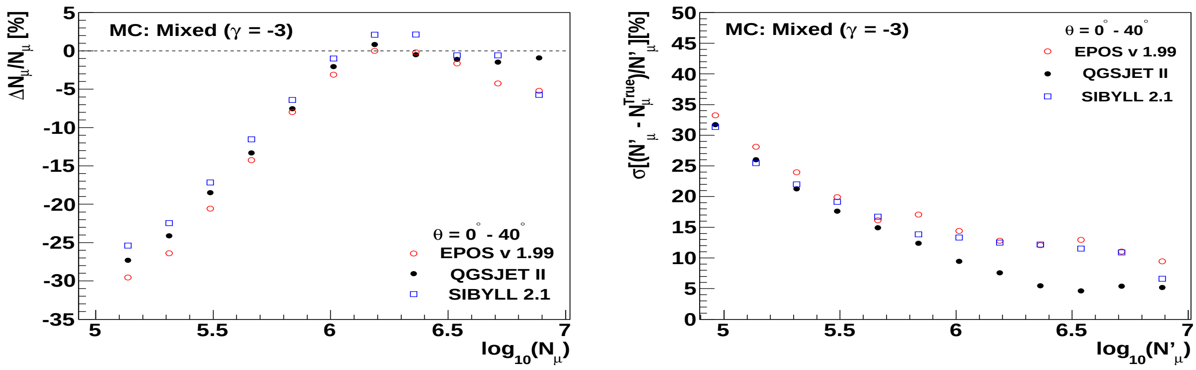

Figure 1: Left: Mean values of the muon correction function shown against the reconstructed muon number N_μ. Right: Fluctuations for the muon number after using the correction function versus the corrected muon number (N'_μ) assuming a mixed primary composition. MC results for different hadronic interaction models are presented.

EPOS, DPMJET and SIBYLL have been carried out with the KASCADE observatory (see [3] and references therein) through detailed studies involving the hadron, electron and muon contents of air showers. None of the above models was able to describe simultaneously all the KASCADE EAS data in the energy region around 1 PeV. Now, with the enhanced detector KASCADE-Grande [4], the possibility to extend these tests to the $10^{16} - 10^{18}$ eV interval is opened.

First investigations on this subject have been already performed with KASCADE-Grande. For example, in [5] it has been shown that predictions with QGSJET 01 about the muon production height (H_μ) distributions for EAS with zenith angles below $\theta < 18°$ have a discrepancy with the measured data. On the other hand, in [6] measurements on the muon lateral distributions (ρ_μ) of EAS performed with KASCADE-Grande were confronted with the expected results of QGSJET II-2 and EPOS 1.99 finding an agreement between experiment and model predictions [6]. Some tests regarding the sensitivity of the KASCADE-Grande results to the QGSJET II-2 and EPOS 1.99 hadronic models have also been done, in particular, associated with the composition and the all-particle energy spectrum of cosmic rays derived from the ρ_μ and the charged particle number (N_{ch}) analyses, respectively [6]. EPOS 1.99 favors an abundance of light primary particles in the data and predicts a higher flux ($\sim 33\%$) in comparison with QGSJET II-2 [6].

In this work, the hadronic interaction models QGSJET II-2 [7], SIBYLL 2.1 [8] and EPOS v1.99 [9] are tested with the KASCADE-Grande muon data. The advantage of using muons is that in an air shower these particles undergo less atmospheric interactions than the electromagnetic component and, in consequence, they reflect directly the physics of the first hadronic interactions in EAS. Other tests and comparisons employing the ρ_μ distributions and the all-particle energy spectrum, derived by combining the information from the $N_{ch} - N_\mu$ observables, are done in [10, 11].

In KASCADE-Grande, measurements of the total muon number in EAS (N_μ, number of muons greater than $100\,\mathrm{MeV}$) are performed with an array of $192 \times 3.2\,\mathrm{m}^2$ shielded scintillator detectors belonging to the former KASCADE experiment [2]. On the other hand, arrival times and charged particle densities, employed for estimations of the EAS arrival direction, N_{ch} content and core position, are measured with an enhancement, called the Grande array, which is composed by $37 \times 10\,\mathrm{m}^2$ plastic scintillator detectors scattered on a surface of $0.5\,\mathrm{km}^2$ [4].

2 Description of data sets

For the present analysis, all air shower simulations were performed with CORSIKA [12] using Fluka [13] to treat hadronic interactions in the low energy regime. At high energies, the hadronic interaction models QGSJET II-2, SIBYLL 2.1 and EPOS v1.99, subjects of this investigation, were employed. The response of the detector was simulated with a GEANT 3.21 based code. Sets with spectral indexes $\gamma = -2.8, -3, -3.2$ were produced for several primary particle assumptions: H, He, C, Si, Fe and a mixed composition scenario (all single primaries in equal abundances).

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 uncertainties in the measurements of the EAS parameters. The selected data were composed of events with more than 11 triggered stations in Grande, shower cores inside a central area of $1.52 \times 10^5\,\mathrm{m}^2$ and with arrival directions confined to the zenith angle interval of $\Delta\theta = 0° - 40°$. These events were registered during stable periods of data acquisition and passed successfully the standard reconstruction procedure of KASCADE-Grande [4]. Additionally, only showers with $\log N_\mu > 5.1$ were considered for this work. Both the experimental and simulated data were analyzed and reconstructed 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 $\log_{10} N_\mu \approx 5.4$.

Model	Λ_μ (g/cm^2) $\gamma=-2.8$ H	Mixed	Fe	$\gamma=-3.0$ H	Mixed	Fe	$\gamma=-3.2$ H	Mixed	Fe
EPOS 1.99	445 ± 26	624 ± 31	636 ± 37	459 ± 23	607 ± 30	624 ± 31	476 ± 25	614 ± 30	604 ± 30
QGSJET II	824 ± 33	832 ± 31	690 ± 43	900 ± 40	833 ± 31	693 ± 42	897 ± 100	825 ± 50	750 ± 62
SIBYLL 2.1	546 ± 44	657 ± 29	681 ± 46	637 ± 39	672 ± 29	688 ± 38	725 ± 44	681 ± 29	699 ± 40

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, γ, of the MC sample under study are specified in the upper lines of the table.

3 Description of the analysis and results

To start with, all muon data was corrected for systematic uncertainties using muon correction functions derived from MC simulations for each hadronic interaction model assuming mixed composition and $\gamma = -3$. The functions were parametrized with respect to core position, azimuthal and zenithal angles, and muon size. In Fig. 1 the mean value of the muon correction function for different hadronic interaction models is plotted against the uncorrected N_μ. In general, after correction the systematic error on the muon number above threshold is found to be almost independent of the corrected muon size, N'_μ, and smaller than 6%. Fluctuations on N'_μ were also investigated. They are shown in Fig. 1 for a scenario with mixed composition and $\gamma = -3$. Note that although fluctuations exhibit the same tendency independently of the hadronic model under consideration, they present slight differences in magnitude, as it is the case for the correction functions. Therefore, some differences are expected when interpreting the same muon experimental data with the hadronic interaction models under consideration.

In a second step, to test the hadronic interaction models with the KASCADE-Grande muon data, predictions on the evolution of the muon content with the arrival zenith angle of the EAS were confronted with observations. The task was done comparing the expected and observed values of the muon attenuation length, Λ_μ. This quantity was extracted by applying the Constant Intensity Cut (CIC) method to the data as described in reference [14] but using a global fit to the attenuation curves, $\log_{10} N'_\mu(\theta)$, with the known formula

$$N'_\mu = N'^{0}_\mu \exp[-X_0 \sec(\theta)/\Lambda_\mu], \tag{1}$$

where $X_0 = 1023\,\mathrm{g/cm^2}$ is the average atmospheric depth for vertical showers and N'^{0}_μ is a normalization parameter to be determined for each attenuation curve. The results for Λ_μ are presented in Tables 1 and 2, showing the discrepancies between the experimental values and the simulation results for the studied models. The differences do not disappear when modifying the primary composition or spectral index. As a consequence, the predicted behavior of the muon component with the zenith angle, $N'_\mu(\theta)$ (see equation 1) shows also a disagreement with the observations. The percentage of deviation for $N'_\mu(\theta)$ between experiment and simulations (mixed composition scenario

Model	Λ_μ (g/cm^2)
EPOS 1.99	1851 ± 142
QGSJET II	1383 ± 84
SIBYLL 2.1	1443 ± 86

Table 2: Muon attenuation lengths extracted from KASCADE-Grande data under the framework of different hadronic interaction models. When comparing MC and experimental data it should be understood that the same correction function was employed.

with $\gamma = -3$) inside the frameworks of QGSJET II-2, EPOS 1.99 and SIBYLL 2.1 is presented in Fig. 2. Formula 1 was employed to calculate the curves of Fig. 2 using the values for Λ_μ of Tables 1 and 2 and normalizing data in such a way that the predicted N'_μ at $\theta = 0^\circ$ agrees with the measured value. Several factors, which are model dependent, may come into play in the observed differences: from the predicted muon correction function (see graphs in Fig. 1), up to the description of the production, evolution and fluctuations of the shower.

To finalize this analysis, the KASCADE-Grande energy spectra were reconstructed using QGSJET II-2, EPOS 1.99 and SIBYLL 2.1, under the assumption of a mixed composition scenario and a spectral index $\gamma = -3$, and were compared with each other to test the influence of the hadronic interaction model on the KASCADE-Grande muon data.

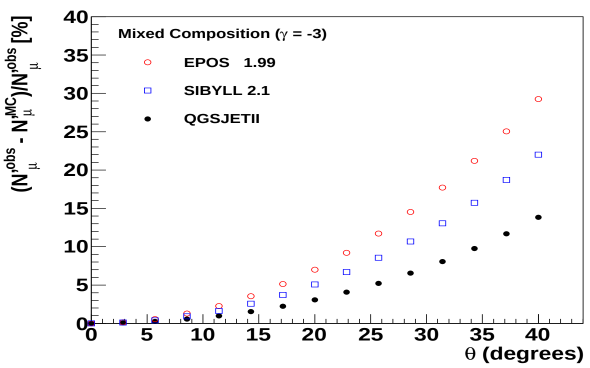

Figure 2: Relative deviation of measurements from model predictions for the dependence of the muon content with the zenith angle at fixed primary energy in the framework of three hadronic interaction models.

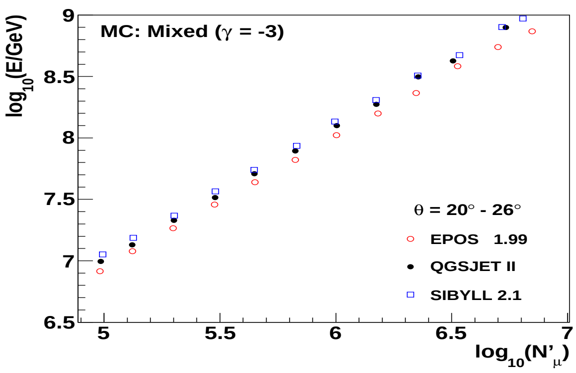

Figure 3: Primary energy as a function of the corrected muon number estimated from MC simulations for a mixed composition scenario with $\gamma = -3$ using QGSJET II-2, EPOS 1.99 and SIBYLL 2.1.

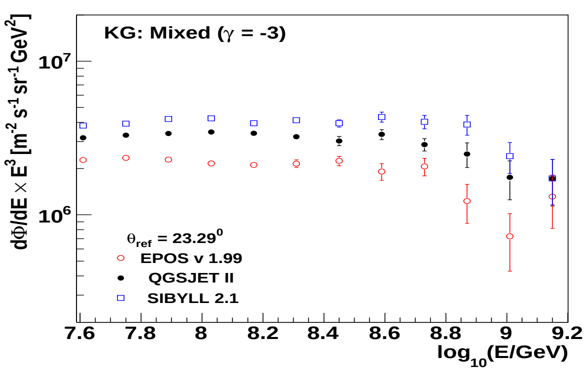

Figure 4: Energy spectra derived from KASCADE-Grande muon data using several hadronic models and assuming a mixed composition scenario with $\gamma = -3$.

Details about the method of reconstruction can be found in [14]. One important difference with respect to reference [14] is that in the present work, the energy spectra were unfolded using the Gold algorithm [15]. As it was the case in [14] the primary energy was calculated using a calibration function of the form $E = \alpha_\mu [N'_\mu(\theta_{ref})]^{\beta_\mu}$, where $N'_\mu(\theta_{ref})$ is the corrected muon number of the EAS that is expected at θ_{ref} according to the CIC method. $\theta_{ref} = 23.3°$ is a zenith angle of reference. On the other hand, α_μ and β_μ are model dependent parameters, which are determined from a fit to the MC data presented in Fig. 3. Note that at a fixed energy, the predictions of EPOS 1.99 for the mean number of muons in the interval $\theta = 20° - 26°$ give values higher by 1.1% comparing to QGSJET II-2, and 1.6% to SIBYLL 2.1. The reconstructed energy spectra are shown in Fig. 4 for the full efficiency region.

As seen in Fig. 4, the all-particle energy spectrum derived with QGSJET II-2 is smaller than the spectra calculated with SIBYLL 2.1 but bigger than the flux estimated with EPOS 1.99. In particular, at $E = 10^8$ GeV, the above differences are of the order of 23% and 36%, respectively. These values are comparable to those derived from reference [6] ($\sim 30\%$) where the charged particle number is used instead to reconstruct the energy spectra within the QGSJET II-2 and the EPOS 1.99 frameworks. In this case, however, the EPOS 1.99 fluxes are shifted to higher energies in comparison with those estimated with QGSJET II-2.

4 Conclusions

Three hadronic interaction models: QGSJET II-2, EPOS 1.99 and SIBYLL 2.1 were tested in this paper by comparing their predictions for the attenuation of the muon content of EAS in the atmosphere with the observations of KASCADE-Grande. It was found that the above hadronic interaction models do not describe this aspect of the measured muon data. The sensitivity of the all-particle energy spectrum derived from the N_μ measurements to the hadronic interaction models was investigated. The spectrum reconstructed using EPOS 1.99 is lower ($\sim 36\%$) in comparison with that from QGSJET II-2. The latter being smaller ($\sim 23\%$) than the spectrum derived with SIBYLL 2.1

Acknowledgment: KASCADE-Grande is supported by the BMBF of Germany, the MIUR and INAF of Italy, the Polish Ministry of Science and Higher Education (in part by grant for 2009-2011) and the Romanian Authority for Scientific Research. This study was partly supported by the DAAD-Proalmex program (2009-2010) and CONACYT.

References

[1] J. Knapp et al., Astrop. Phys. **19** (2003) 77.
[2] T. Antoni et al., NIM A **513** (2003) 429.
[3] W. D. Apel et al., J. Phys. G: Nucl. Part. Phys. 36, 035201 (12pp) (2009).
[4] W.-D. Apel et al., NIM A **620**, 202 (2010).
[5] W.-D. Apel et al., Astrop. Phys. **34**, 476 (2011).
[6] Donghwa Kang *et al.*, KASCADE-Grande Coll., Proc. XVI ISVHECRI, astro-ph/1009.4902 (2010).
[7] S.S. Ostapchenko, Nucl. Phys. B (Proc. Suppl.) **151** (2006) 143&147; S. Ostapchenko, Phys. Rev. D 74, 014026 (2006).
[8] E.J. Ahn et al., Phys. Rev D 80, 094003 (2009).
[9] T. Pierog et al., Report FZKA 7516, Forschungszentrum Karlsruhe 133, (2009).
[10] V. de Souza *et al.*, KASCADE-Grande Coll., these proceedings.
[11] M. bertaina *et al.*, KASCADE-Grande Coll., these proceedings.
[12] D. Heck et al., Report FZKA 6019, Forschungszentrum Karlsruhe (1998).
[13] A. Fassò et al., Report CERN-2005-10, INFN/TC-05/11, SLAC-R-773 (2005).
[14] J.C. Arteaga *et al.*, Proc. 31^{st} ICRC, icrc0805, (2009).
[15] R. Gold, AEC Research and Development Report ANL-6984, Argonne National Laboratory, Argonne, IL, 1964.