Muon Density Measurements as Probe of the Muon Component of Air-Shower Simulations

A. Haungs[2], T. Antoni[1], W.D. Apel[2], F. Badea[1,a], K. Bekk[2], A. Bercuci[2,a], M. Bertaina[3], H. Blümer[1,2], H. Bozdog[2], I.M. Brancus[4], M. Brüggemann[5], P. Buchholz[5], C. Büttner[1], A. Chiavassa[3], P. Doll[2], R. Engel[2], J. Engler[2], F. Feßler[2], P.L. Ghia[6], H.J. Gils[2], R. Glasstetter[7], D. Heck[2], J.R. Hörandel[1], A. Iwan[8], K-H. Kampert[7], H.O. Klages[2], Y. Kolotaev[5], G. Maier[2], H.J. Mathes[2], H.J. Mayer[2], J. Milke[2], C. Morello[6], M. Müller[2], G. Navarra[3], R. Obenland[2], J. Oehlschläger[2], S. Ostapchenko[1,c], M. Petcu[4], S. Plewnia[2], H. Rebel[2], M. Roth[1], H. Schieler[2], J. Scholz[2], T. Thouw[2], G.C. Trinchero[6], H. Ulrich[2], S. Valchierotti[3], J. van Buren[2], W. Walkowiak[5], A. Weindl[2], J. Wochele[2], J. Zabierowski[8], S. Zagromski[2]

(1) Institut für Exp. Kernphysik, Universität Karlsruhe, 76021 Karlsruhe, Germany
(2) Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany
(3) Dipartimento di Fisica Generale dell'Università, 10125 Torino, Italy
(4) National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania
(5) Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany
(6) Instituto di Fisica dello Spazio Interplanetario, CNR, 10133 Torino, Italy
(7) Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany
(8) Soltan Institute for Nuclear Studies, 90950 Lodz, Poland
[a] *on leave of absence from (4)*
[b] *on leave of absence from Moscow State University, 119899 Moscow, Russia*

Abstract

The KASCADE experiment measures local muon densities of EAS in the knee region at various core distances for different muon energy thresholds. Expectations of detailed Monte Carlo simulations including various combinations of high-energy and low-energy hadronic interaction models in the frame of the CORSIKA code are compared with the data. This allows a comprehensive test of the simulated muon energy spectra for various Monte Carlo codes in the primary energy range of $10^{14} - 10^{16}\,$eV for KASCADE and of $10^{16} - 10^{18}\,$eV for KASCADE-Grande.

1. Introduction

The validity of hadronic interaction models used as generators of Monte Carlo simulations is an important subject in context of EAS analyses. A co-operation between present and future accelerator experiments and cosmic-ray investigations is aspired for tests, but also by cosmic-ray measurements there appear possibilities to probe the validity of the models [11]. In the present paper we endeavor to analyze local muon densities in high energy air-showers for two

---

pp. 37–40

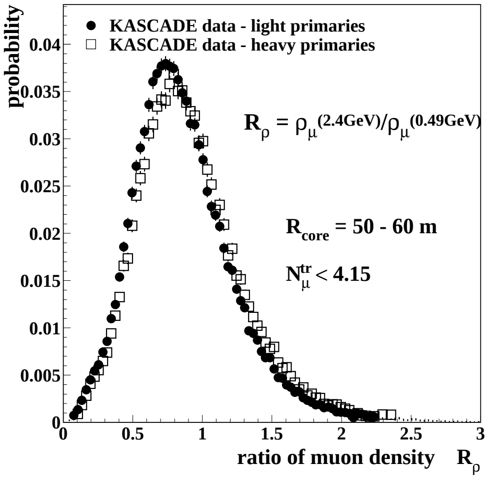

Fig. 1. Examples of the distribution of the ratio of local muon densities measured by KASCADE.

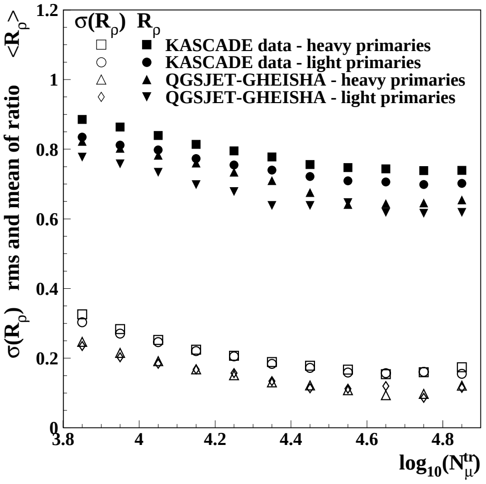

Fig. 2. Mean and width of the muon density ratio distributions vs. N_μ^{tr} for measurements and simulations.

different muon energy thresholds. Therewith the consistency of the simulations with respect to the muon energy spectrum and systematic features of different Monte Carlo models can be revealed. Analyzing KASCADE data, the local muon densities were used to reconstruct the primary energy spectrum of cosmic rays in the energy range of 1 to 10 PeV [1]. A systematic inconsistency were found by using the two different muon thresholds for transforming the measured local muon density spectrum in the primary energy spectrum with help of Monte Carlo simulation procedures. To proceed a more direct comparison between measured and simulated data with respect to the muon energy spectrum, in the present paper the ratio R_ρ of the local muon densities estimated on an event-by-event basis is used. With the extension of KASCADE to KASCADE-Grande [6] this kind of analysis can be continued and applied on data of higher primary energies, where systematic validity checks of the models are even more important, as no accelerator data will exist in next decades at energies above 100 PeV, but the models will be used for interpretations of the data of giant air-shower experiments.

2. Measurements at KASCADE

The local muon density of the EAS is measured with two separate detector set-ups of the KASCADE central detector which is placed in the geometrical center of the KASCADE detector array. A setup of 32 large multiwire proportional chambers (MWPC) is installed in the basement of the building and enables the estimation of the muon density $\rho_\mu^\star$ for each single EAS. The total absorber corresponds to a threshold for muons of 2.4 GeV. The second muon detection system is a layer of 456 plastic scintillation detectors in the third gap of the central

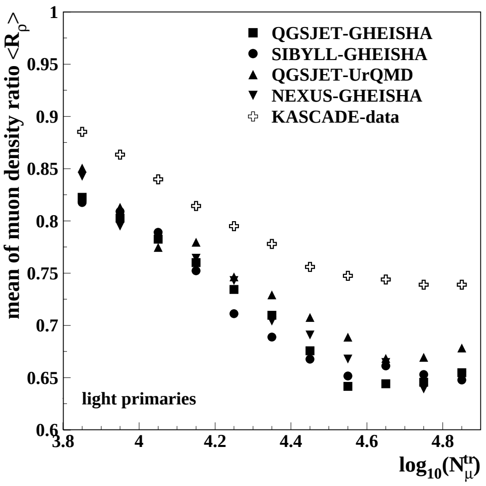

Fig. 3. Comparison of $\langle R_\rho \rangle$ for different model combinations with KASCADE data.

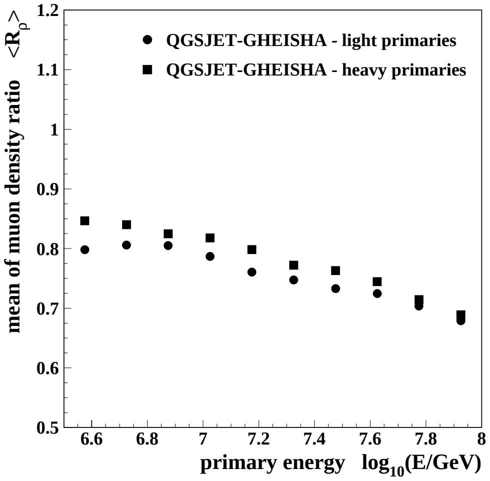

Fig. 4. Expectations of R_ρ for the case of KASCADE-Grande measurements in dependence of the primary energy.

detector, called trigger plane. Here the muon density ρ_μ^{tp} is estimated for muons with a threshold of 490 MeV for vertical incidence. Global shower parameters like core position, arrival direction, shower size and truncated muon number are reconstructed with help of the KASCADE detector array. The truncated muon number describes the muon content ($>$ 300 MeV) of the shower between 40 m and 200 m core distance and was found to be a valuable coarse primary energy estimator in case of the experimental conditions of KASCADE. The total sample of measured EAS is further divided in "electron-rich" and "electron-poor" showers performed by a cut along the ratio $lg(N_\mu)/lg(N_e)$, i.e. observables estimated by the array data only. The ratio $R_\rho = \rho_\mu^\star/\rho_\mu^{\mathrm{tp}}$ is the relevant parameter for the present analyses. As example Fig. 1 shows measured distributions of R_ρ for a certain core distance and primary energy range. Differences for various primaries (electron-rich EAS as predominantly induced by light ions and electron-poor EAS as predominantly induced by heavy ions) are found to be small compared to the width of the distributions.

3. Comparisons with Simulations

A large set of CORSIKA [8] simulations including a full simulation of the detector have been performed using the interaction models QGSJET (vers. of 1998 [10]), SIBYLL (vers.2.1 [4]), and NEXUS (vers.2 [3]) for the high-energy interactions and GHEISHA [5] and UrQMD [2] for interactions below $E_{\mathrm{lab}} = 80$ GeV. Observation level, Earth's magnetic field, and the particle thresholds are chosen in accordance with the experimental situation of KASCADE. The simulations cover the energy range of $10^{14} - 3 \cdot 10^{16}$ eV. The calculations are performed for

the zenith angular range $0^\circ - 42^\circ$ and for three primary particle types: protons, oxygen, and iron nuclei.
Fig. 2 shows the dependence of the mean and fluctuations (width of distributions) of the density ratio on the truncated muon number ($\propto E_0$, $E_0 \approx 1 - 10\,\mathrm{PeV}$) for data and predictions by the model combination QGSJET/GHEISHA analyzed by same procedures. The general behavior of decreasing mean and fluctuation with increasing energy is reproduced by the simulations, but in contrast a clear deviation on the mean values and on the amount of fluctuations is visible. To perform a test of the interaction models by comparing the calculated predictions with air shower data the sensitivity to differences in the simulations should be of significance (see also [7]). Fig. 3 compares the mean values for different model combinations, where differences of up to 10% in R_ρ are revealed. None of the models can reproduce the measurements, but the behavior of the models neXus and UrQMD comply better then QGSJET, SIBYLL, or GHEISHA. Next generation of CORSIKA will include FLUKA and NEXUS 3 as new models, which show in first tests a significant different behavior of the muon component (see [9]).

4. Expectations for KASCADE-Grande

At KASCADE-Grande [6] similar measurements can be performed for EAS of primary energies at least up to 10^{17} eV. The muon detection at the KASCADE central detector will then be possible for core distances of $50 - 550$m with reasonable muon statistics. Fig. 4 shows the expectations of Monte Carlo simulations for KASCADE-Grande measurements on the muon density ratio. The test of the validity of the description of the muon component will be of high relevance for the shower simulation procedures at ultra-high energies.

References

1. Antoni T. et al. - KASCADE Coll. 2002, Astropart.Phys. 16, 373
2. Bleicher M. et al. 1999, J.Phys.G 25, 1859
3. Drescher H.J. et al. 2001, Phys. Rep. 350, 93
4. Engel R. 1999, Proc.26th ICRC, Salt Lake City, 1, 415
5. Fesefeldt H. 1985, PITHA-85/02, RWTH Aachen
6. Haungs A. et al. 2003, Proc.28th ICRC, Tsukuba, these proceedings
7. Haungs A. et al. - KASCADE Coll. 2003, Nucl.Phys.B(Proc.Suppl.), in press
8. Heck D. et al. 1998, FZKA 6019 Forschungszentrum Karlsruhe
9. Heck D. et al. 2003, Proc.28th ICRC, Tsukuba, these proceedings
10. Kalmykov N.N. and Ostapchenko S.S. 1993, Yad. Fiz. 56, 105
11. NEEDS-workshop 2002: http://www-ik.fzk.de/~needs/