Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 291–293 (2017) 152–157

www.elsevier.com/locate/nppp

Muon density measurements for the light and heavy mass groups of cosmic rays at the KASCADE-Grande observatory

J.C. Arteaga-Velázquez[a,*], W.D. Apel[b], K. Bekk[b], M. Bertaina[c], J. Blümer[b,d], H. Bozdog[b], I.M. Brancus[e], E. Cantoni[c,f,1], A. Chiavassa[c], F. Cossavella[d,2], K. Daumiller[b], V. de Souza[g], F. Di Pierro[c], P. Doll[b], R. Engel[b], D. Fuhrmann[h,3], A. Gherghel-Lascu[e], H.J. Gils[b], R. Glasstetter[h], C. Grupen[i], A. Haungs[b,**], D. Heck[b], J.R. Hörandel[j], T. Huege[b], K.-H. Kampert[h], D. Kang[d], H.O. Klages[b], K. Link[d], P. Łuczak[k], H.J. Mathes[b], H.J. Mayer[b], J. Milke[b], B. Mitrica[e], C. Morello[f], J. Oehlschläger[b], S. Ostapchenko[l], T. Pierog[b], H. Rebel[b], M. Roth[b], H. Schieler[b], S. Schoo[b], F.G. Schröder[b], O. Sima[m], G. Toma[e], G.C. Trinchero[f], H. Ulrich[b], A. Weindl[b], J. Wochele[b], J. Zabierowski[k]

[a] *Inst. of Physics and Mathematics, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Mexico*
[b] *Institut für Kernphysik, KIT - Karlsruher Institut für Technologie, Germany*
[c] *Departimento di Fisica, Università degli Studi di Torino, Italy*
[d] *Institut für Experimentelle Kernphysik, KIT - Karlsruher Institut für Technologie, Germany*
[e] *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[f] *Osservatorio Astrofisico di Torino, INAF Torino, Italy*
[g] *Universidade de São Paulo, Instituto de Física de São Carlos, Brasil*
[h] *Fachbereich Physik, Universität Wuppertal, Germany*
[i] *Department of Physics, Siegen University, Germany*
[j] *Department of Astrophysics, Radboud University Nijmegen, The Netherlands*
[k] *National Centre for Nuclear Research, Department of Astrophysics, Lodz, Poland*
[l] *Frankfurt Institute for Advanced Studies (FIAS), Frankfurt am Main, Germany*
[m] *Department of Physics, University of Bucharest, Bucharest, Romania*

Abstract

KASCADE-Grande was an air-shower experiment aimed to investigate cosmic rays between 10^{16} and 10^{18} eV. The instrument was located at the site of the Karlsruhe Institute of Technology, Germany at an altitude of 110 m a.s.l. and covered an area of 0.5 km^2. KASCADE-Grande consisted of several detector systems dedicated to measure different components of the cosmic ray induced air showers, e.g. the muon content ($E_{th} > 230$ MeV) and the number of charged particles ($E_{th} > 3$ MeV) at ground, which are the basis for several energy and composition studies of cosmic rays. In this contribution, using these observables, the KASCADE-Grande data is divided into light and heavy mass groups and their respective muon densities are reconstructed at different zenith angle intervals. The results are compared with the expectations of the post-LHC hadronic-interaction models, EPOS-LHC and QGSJET-II-04, in order to test the validity of the model predictions.

Keywords: Cosmic rays, KASCADE-Grande, extensive air showers, muon radial densities, hadronic interaction models

1. Introduction

Above ~ 1 PeV, cosmic rays are studied by means of indirect techniques as a consequence of their low flux at the high-energy regime. These techniques are based on the detection of the extensive air showers (EAS) that

*Corresponding author: arteaga@ifm.umich.mx
**Spokesperson KASCADE-Grande: haungs@kit.edu
[1] Now at: Istituto Nazionale di Ricerca Metrologica, INRIM, Torino, Italy
[2] Now at: DLR Oberpfaffenhofen, Germany
[3] Now at: University of Duisburg-Essen, Duisburg, Germany

https://doi.org/10.1016/j.nuclphysbps.2017.06.030

cosmic rays induce in the Earth's atmosphere. For this goal, air-shower observatories are equipped with several kinds of detectors that are used to study the various components of the EAS at different stages of their development. However, the interpretation of the data is not an easy task as it is hampered by the uncertainties of the high-energy hadronic interaction models.

Recently, some hadronic interaction models used to interpret the observations of EAS at high energies experienced an improvement by calibrating them with the new data of the Large Hadron Collider (LHC) at TeV energies [1, 2, 3]. Nevertheless, in spite of these updates and the consequent reduction of uncertainties, post-LHC models still show some incompatibilities with the muon data from EAS (see, for example, [4, 5, 6, 7, 8]). Muons are the direct messengers of the hadronic processes occurring in the shower. Therefore, any discrepancy between the models and the measurements in this sector could expose the deficiencies of the former in the description of the hadronic physics relevant for EAS. Even more, the study of the corresponding anomalies could provide complementary information for model builders to improve the hadronic interaction models.

Guided by these objectives, several tests of high-energy hadronic interaction models have been carried out at the KASCADE-Grande observatory with the muon data from EAS [4, 5, 6, 9, 10, 11]. In regard to post-LHC models, one of these tests has revealed that, at energies between $10^{16.3}$ and $10^{17.3}$ eV, the post-LHC models QGSJET-II-04 [1] and EPOS-LHC [2] predict a smaller muon attenuation length, as defined with the constant intensity cut method (CIC) [12], than the experimental one [4, 5]. In [4], it has been shown that systematic and statistical effects can not explain the effect and that the discrepancy seems to be related to a deficiency of the models to describe the zenith-angle dependence of the local muon density distributions, $\rho_\mu(r)$, of the measured data. However, in spite of the observed deviations, the actual $\rho_\mu(r)$ distributions along CIC curves are still bracketed by the predictions of the post-LHC models [4]. The reason behind the anomaly is unknown, but it might be related with a wrong model description of the energy spectra of muons in EAS at production site [13]. The problem is complex. Thus all the information that could be gathered in this regard might result useful to find a way through it. In this sense, in this work we have designed a preliminary analysis to find out whether the abovementioned discrepancy observed between the measurements and the post-LHC models QGSJET-II-04 and EPOS-LHC has a contribution from both the light and heavy mass groups or just one of them. The analysis and results will be presented in the following lines after a brief description of the experiment, the systematic errors, the event selection and the MC data employed for the tests.

2. The KASCADE-Grande observatory

KASCADE-Grande (110 m a.s.l.) was an air-shower detector array designed to study cosmic-ray events with energies in the range from 10^{15} to 10^{18} eV [14]. The detector was composed by several detector systems aimed to measure with high precision distinct components and properties of the EAS, for example, the total number of charged particles (electrons plus muons) for $E_{th} > 3$ MeV and of muons with $E_{th} > 230$ MeV. The former together with other gross shower variables like the EAS core position and the angle of incidence were estimated from data collected by the 0.5 km^2 main array of $37 \times 10\,\mathrm{m}^2$ scintillator detectors, while the latter, from local muon density measurements performed with the shielded detectors from the $200 \times 200\,\mathrm{m}^2$ KASCADE array (more details about the experiment can be found in [14, 15]). At KASCADE-Grande systematic uncertainties for the core and the arrival direction of vertical EAS are of the order of 6 m and 0.8°, respectively [14]. On the other hand, for the total number of charged particles (N_{ch}) the estimated resolution is $\leq 15\,\%$ [14], while for the total number of muons (N_μ), it is $\leq 25\,\%$ [16].

3. The Experimental and MC data

KASCADE-Grande was operated from December 2003 up to November 2012. The events analyzed in this work correspond to a data sample registered during the full operation period of the experiment. This data set is composed by selected events passing several instrumental and reconstruction cuts. The aim is to reduce systematic effects in the final results. For instance, to guarantee a data sample with stable detector performance only events taken during stable data acquisition runs and no hardware problems were accepted. Also events from runs with no technical problems (like high detector noise, inhomogeneous core distributions, low counting rates, low statistics, etc.) were included in the analysis. Furthermore, data from runs without missing KASCADE detector clusters [15], and with more than 36 Grande working stations were considered. In addition, to exclude misreconstructed shower events affecting the quality of the data, just events that have passed successfully the full reconstruction chain [14] were included. On the other hand, EAS which activated more than 11 Grande stations and had sufficiently high muon