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Muon Density Measurements with KASCADE-Grande

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KASCADE-Grande is a multi detector setup for the investigation of extensive air showers in the primary energy range of the knee including energies around the so-called second knee. Besides total number of electrons and muons the experiment measures local muon densities of air showers for different muon energy thresholds between 230 MeV and 2.4 GeV. These densities are reconstructed for showers in the primary energy range up to 1 EeV and in radial distances up to 700 m. Expectations of detailed Monte Carlo shower simulations based on various hadronic interaction models in the frame of the CORSIKA code are compared to the data and their validity is discussed. This allows a comprehensive test of the simulation procedures of the muon energy spectrum in the Monte Carlo codes.

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 the cosmic ray investigations is aspired for tests, but also by means of cosmic ray measurements there appear possibilities to probe the validity of the models [1]. In the present contribution we endeavor to analyze local muon densities in air showers in the primary energy range $10^{14} - 10^{18}$ eV for three 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 [2] data, local muon densities were used to reconstruct the primary energy spectrum of cosmic rays in the energy range of 1 to 10 PeV [3]. A systematic inconsistency was found by using two different muon thresholds for transforming the measured local muon density spectrum to the primary energy spectrum

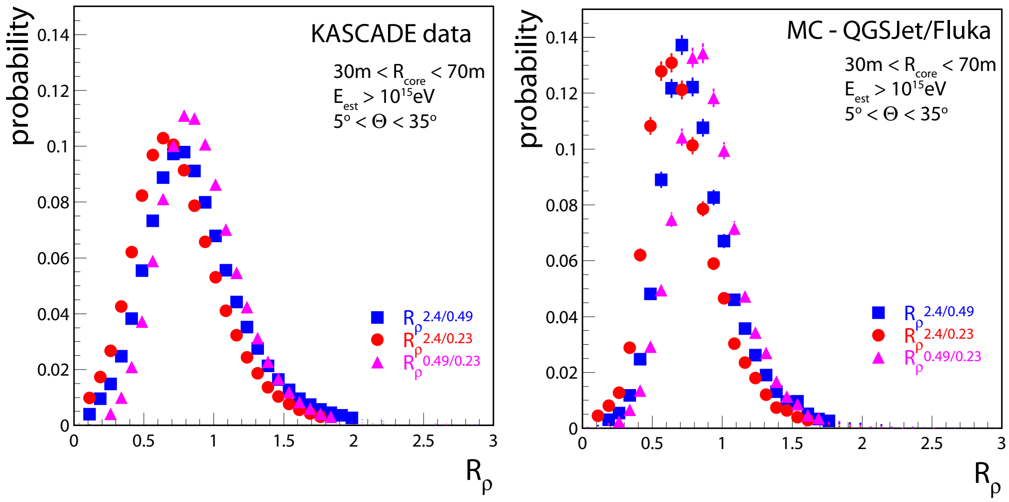

Figure 1. Examples of distributions of the ratio parameters R_ρ of local muon densities measured by KASCADE (left) and predictions by QGSJet/Fluka simulations.

with help of Monte Carlo simulation procedures. To proceed a more direct comparison between measured and simulated data in respect to the muon energy spectrum, the ratio R_ρ of these local muon densities estimated on an event-by-event basis was used [4]. It was found, that there is a general disagreement between the predicted muon density ratio by different hadronic interaction models and the measurements.

With the extension of KASCADE to KASCADE-Grande [5] this kind of analysis can be continued and applied on data of higher primary energies and for larger core distances. This seems to be very important as simulations have shown, that at large distances from the shower core the muon generation is dominated by the low-energy hadronic interactions, whereas at small distances high-energy interactions are responsible [6]. This gives a handle to check the validity of high-energy and low-energy interaction models embedded in the CORSIKA [7] simulation program separately. Additionally, at KASCADE-Grande energies, 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. Reconstruction of local muon density ratios

The local muon density of the EAS is measured for three muon energy thresholds by separate detector set-ups of KASCADE. Two of them are installed at the 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 $\rho_\mu^{2.40GeV}$ for each single EAS. The total absorber corresponds to a threshold for muons of 2.4 GeV kinetic energy. The second muon detection system is a layer of 456 plastic scintillation detectors in the third gap of the central detector, called trigger plane. Here the muon density $\rho_\mu^{0.49GeV}$ is estimated for muons with a threshold of 490 MeV for vertical incidence. The third local muon density is reconstructed with help of the KASCADE array data. 196 detector stations contain shielded plastic scintillators which are used to reconstruct the total muon number of the EAS by fitting the lateral distributions. For the present analyses this LDF is used to estimate the densities of muons at the place of the central detector ($\rho_\mu^{0.23GeV}$). Global shower parameters like core position, arrival direction, and

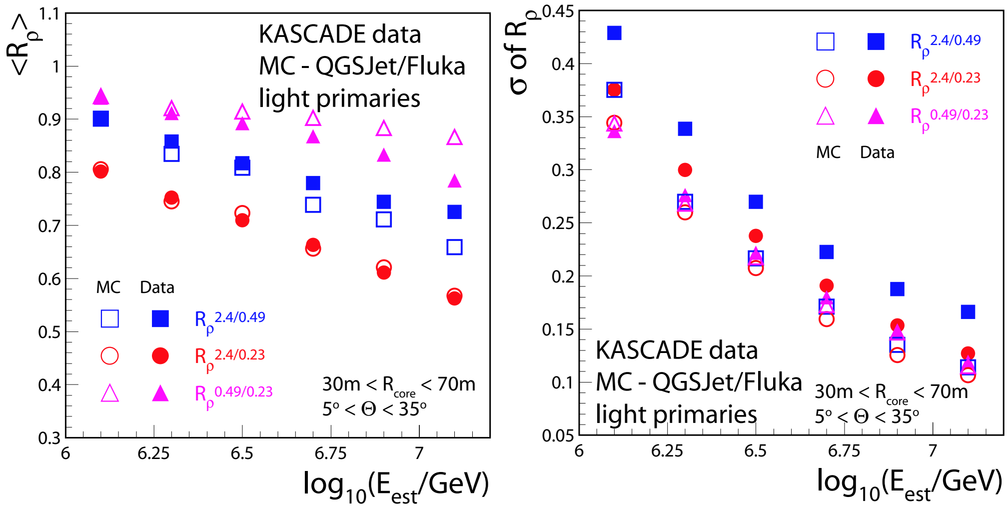

Figure 2. Mean and width of the muon density ratio distributions R_ρ vs. primary energy for measurements and simulations using QGSJet/Fluka.

primary energy are reconstructed with help of the KASCADE-Grande detector arrays. The primary energy is roughly estimated by a combination of reconstructed shower size determined by data of the KASCADE or the Grande array and the shower muon number determined by the KASCADE array muon detectors optimized by detailed shower simulations. 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 arrays data only.

The ratios $R_\rho^{2.4/0.49} = \rho_\mu^{2.40GeV}/\rho_\mu^{0.49Gev}$, $R_\rho^{2.4/0.23} = \rho_\mu^{2.40GeV}/\rho_\mu^{0.23Gev}$, and $R_\rho^{0.49/0.23} = \rho_\mu^{0.49GeV}/\rho_\mu^{0.23Gev}$ are the relevant parameters for the present analyses. Due to the already available large data set measured by the original KASCADE experiment first the analyses will be concentrated to showers in the core distance of $30 - 70$ m (inside KASCADE, but not disturbed by punch-through or trigger effects at the central detector), requiring primary energy above 10^{15} eV. But, the same analyses will be performed also for showers where the global parameters are estimated with help of the Grande array. Grande measures in coincidence with KASCADE since end of the year 2003. Fig. 1, left shows as example the measured distributions of the R_ρ parameters for the whole selected data set from KASCADE events.

3. Comparisons with simulations

A large set of CORSIKA simulations [7] have been performed using different interaction models, e.g. QGSJET (vers. of 1998 [8]) or SIBYLL (vers.2.1 [9]), for the high-energy interactions and GHEISHA [10] and Fluka [11] for low-energy interactions. Observation level, Earth's magnetic field, and the particle thresholds are chosen in accordance with the experimental situation of KASCADE-Grande as well as the simulation of the detector responses. The simulations are performed for the zenith angular range $0° - 42°$ and for five primary masses: protons, helium, oxygen, silicon, and iron nuclei. The right part of Fig. 1 shows the predictions in the muon density ratios in the case of QGSJet/Fluka simulations, again with cuts applied for the case of the KASCADE selection for a direct comparison with the measurements. 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. Beside the influence of the unknown composition of the primary cosmic rays, further possible uncertainties in the R_ρ parameters, like the unknown slope of the primary energy spectrum or effects of detector inefficiencies were investigated. Whereas varying the slopes of the simulations from -2.3 to -3.3 show no influence on the final distributions of the muon density ratios, efficiency effects of the detectors do so. The efficiencies are calculated for the individual detector components for each run using the shower data. Despite the fact, that the data are corrected for these effects, a remaining uncertainty of 5% in the R_ρ parameters have to be assumed regarding the following considerations.

Fig. 2 shows the dependence of the mean and fluctuations (width of distributions) of the three considered density ratios on the primary energy for data and predictions by the model combination QGSJET/Fluka analyzed by same procedures. The general behavior of decreasing mean and fluctuation with increasing energy is reproduced by the simulations, but a clear deviation on the mean values and on the amount of fluctuations is visible. QGSJET/Fluka are in agreement with the data for low energies and for the full energy range in the ratio $R_\rho^{2.4/0.23}$, which is not the case for other model combinations. For the other two ratio parameters $R_\rho^{2.4/0.49}$, $R_\rho^{0.49/0.23}$ and, especially for the amount on predicted fluctuations there is a general deviation from the data. Other interaction model combinations (e.g. Sibyll/GHEISHA) show a similar behavior, but the disagreement is smallest for the Fluka model.

At KASCADE-Grande [5] 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. This test of the validity of the muon component will be of high relevance for the shower simulation procedures at ultra-high energies.

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