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Lateral density distributions of muons and electrons in EAS from the KASCADE-Grande data for different zenith angle intervals.

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KASCADE-Grande was a cosmic ray experiment located at the Karlsruhe Institute of technology (110 m a.s.l., 49°N, 8°E), Germany, and it was designed to study extended air showers (EAS) initiated by primary nuclei in the energy range between 10 PeV and 1 EeV. KASCADE-Grande was capable of measuring the local density of charged particles, muons and electrons of the EAS at ground level using different types of particle detectors. Using such data, we have estimated the mean radial density distributions of muon and electrons in EAS. The study was done in the radial range from 150 m to 650 m and zenith angles from 0 to 40 degrees. The zenith angle interval was divided in three bins with the same acceptance: [0°, 21.78°], [21.78°, 31.66°] and [31.66°, 40°]. Moreover, the data was further subdivided into distinct intervals in the total number of charged particles. The measurements were confronted against expectations of Monte Carlo shower simulations with iron nuclei and protons as primaries. The simulations were performed using the hadronic interaction models SIBYLL 2.3, QGSJET-II-04, SIBYLL 2.3 c and EPOS-LHC.

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1. Introduction

The discovery and measurement of Extended Air Shower (EAS) by P. Auger in 1938 [1] gave the possibility to detect cosmic rays with energies greater than 1 PeV by indirect means. One of the most relevant quantities in EAS measurements is the lateral or radial density distribution, ($\rho(r)$), which has information about the size of the shower, primary energy and mass composition of the incident cosmic ray, that is why it is important the research on this topic.

In this work we present a comparison of the muon and electron lateral density distribution with the corresponding predictions for primary protons and iron nuclei of four different high energy hadronic models: QGSJET-II-04, EPOS-LHC, SIBYLL 2.3 and SIBYLL 2.3 c, which are used nowadays in cosmic rays research [2, 3].

2. Analysis procedure

KASCADE-Grande was an EAS detector dedicated to investigate cosmic rays with energies in the range from 10^{15} to 10^{18} eV [4], and it was located at the Karlsruhe Institute of Technology, Germany at 110 m a.s.l. The experiment consisted of several detector systems, but here, we will use information from the main electromagnetic and muon surface detector arrays from KASCADE and the array of charged particle detectors from Grande. The electromagnetic array was composed by 252 liquid scintillators detectors and the muon array, by 192 shielded plastic scintillator detectors (E_μ > 230 MeV for vertical incidence), both arrays are distributed over an area of 200×200 m^2. The Grande array is composed by 37 plastic scintillators detectors separated 137 meters from each other (E_{ch} > 3 MeV for vertical incidence). This array was distributed over an area of 700×700 m^2 [4].

We applied several quality cuts to diminish the systematic uncertainties, in particular, we only considered events obtained during stable data acquisition periods with no hardware problems [5]. We also kept events with shower cores located within the limits of a central area of 2.25×10^5 m^2 for radial distances in a range of R = [150 m, 650 m] from the center of KASCADE array (see figure 1). In addition We considered events with zenith angles $\theta \leq 40^o$ and a muon content of $N_\mu \geq 3\times10^4$ and a total number of charged particles $N_{ch} \geq 1.1\times10^4$. Finally, we used events that activated more than 11 Grande stations. After all the selection cuts, we got 1.13×10^7 events from the total observation time between December 2003 to November 2012.

The air showers simulations were performed using CORSIKA 7.5 [6]. The interaction between the secondary particles and the detector were performed with GEANT 3.21 [7]. The low energies interactions (E_h < 200 GeV) of the EAS were simulated with FLUKA [8]. High energy interactions were treated with the post-LHC models mentioned before: EPOS-LHC, SIBYLL 2.3, QGSJET-II-04 and SIBYLL 2.3c. The simulations are in an energy range from 10^{14} eV to 10^{18} eV with zenith angles in the interval 0^o-42^o with a spectral index γ = 2, but for the analysis it is converted to γ = 3. The simulations were produced for five primary nuclei (H, He, C, Si and Fe) with roughly the same number of events [9]. For the analysis we applied the same quality cuts for simulations and measured data.

Finally, we present and compare the results of simulations made by four different high energy hadronic models (SIBYLL2.3, SIBYLL 2.3c, EPOS-LHC, QGSJET-II-04) with the KASCADE-

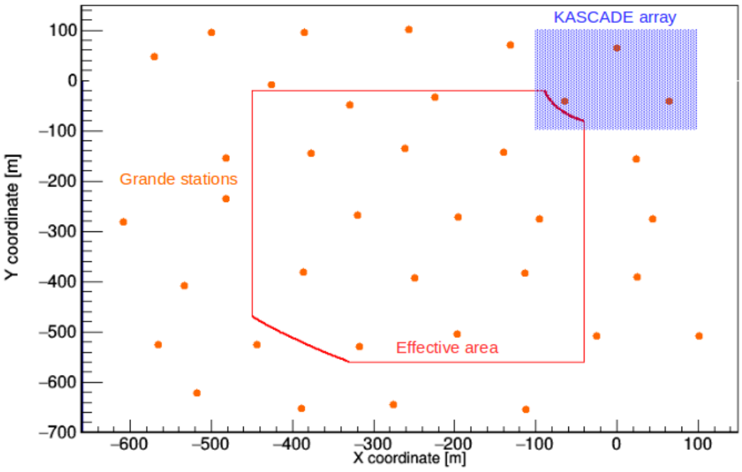

Figure 1: Sketch of the KASCADE-Grande experiment. Small orange circles represent the Grande stations. The KASCADE array area is located at the upper right hand of the figure in blue color and the red lines show the effective area selected for the present analysis.

Grande measurements for the mean muon or electron (ρ_μ, ρ_e) lateral distribution at the shower plane for $r < 600$ m. As mentioned before, this work was made using three zenith angles with the same acceptance: [0°, 21.78°], [21.78°, 31.66°] and [31.66°, 40°], and three different energy intervals by means of the number of charged particles using different intervals according to the energy of the primary in order to have energy bins with an adequate statistics and reproduce the following energies for the primary 10 PeV, 100 PeV and 1 EeV, those energies were used to calculate the mean electron and muon densities.

3. Results and discussions

The results of the electron and muon mean densities calculations can be seen in the figs 2, 3 and 4, starting with the electron densities:

The plots 2, 3 and 4 show that the mean electron density is well described by the four high-energy hadronic interaction models, that means that all the values obtained for the experimental data are inside the band that covers the predictions for H and Fe primary nuclei even for those events with high energies (1 EeV) and large values of the zenith angles.

The results for the mean muon lateral distribution of EAS are presented in figures: 5 to 7.

The results show that the experimental data is within the predictions of the high-energy hadronic interaction models considered in this work. There seems to be, however, an exception for EPOS-LHC in case of vertical EAS at ultra high energies. Here, real data do not seem to lie within the predictions of the hadronic interaction model at all radial distances, for $r > 500$ m. In this case, EPOS-LHC predictions are above the measured data.

We also observe that at high energies, the slope of the LDF of the muon data is steeper than the expectations of the model. Such discrepancies may bring also differences between the mean total muon number of data and simulations.

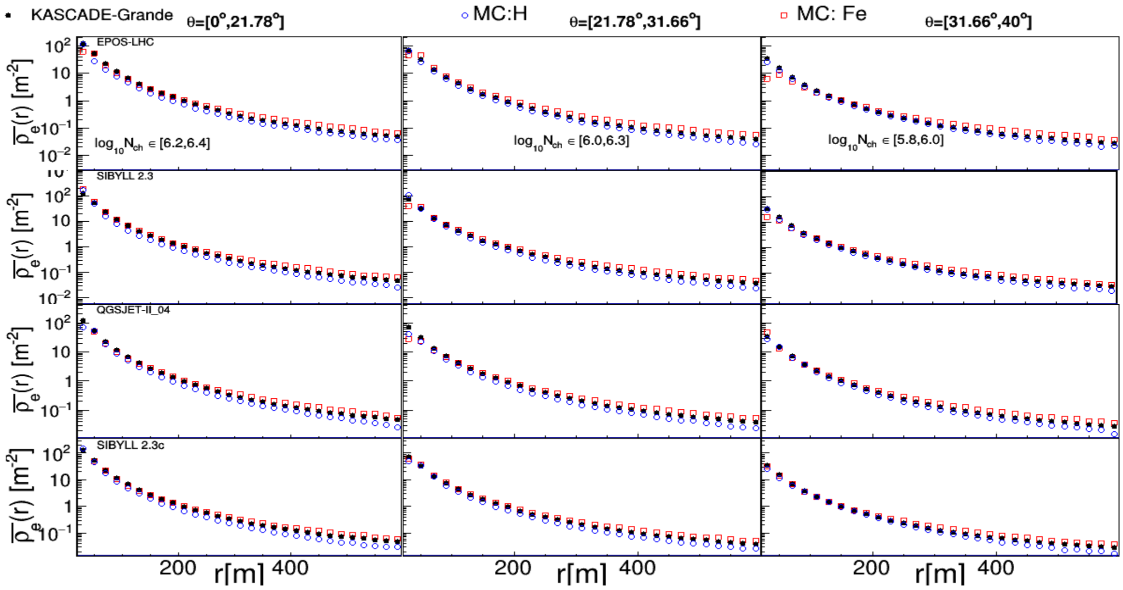

Figure 2: Mean electron lateral distributions of EAS from KASCADE-Grande data and four different hadronic interaction models. The data is shown for three $log_{10}N_{ch}$ intervals, from left to right: $log_{10}N_{ch} \in [6.2, 6.4]$, $log_{10}N_{ch} \in [6.0, 6.3]$ and $log_{10}N_{ch} \in [5.8, 6.0]$. The black points represent the KASCADE-Grande data, the red squares are for iron nuclei, the blue circles for protons. The columns correspond to three different zenith angle interval while each row is for a different hadronic interaction model, from top to bottom: EPOS-LHC, SIBYLL 2.3, QGSJET-II-04 and SIBYLL 2.3c.

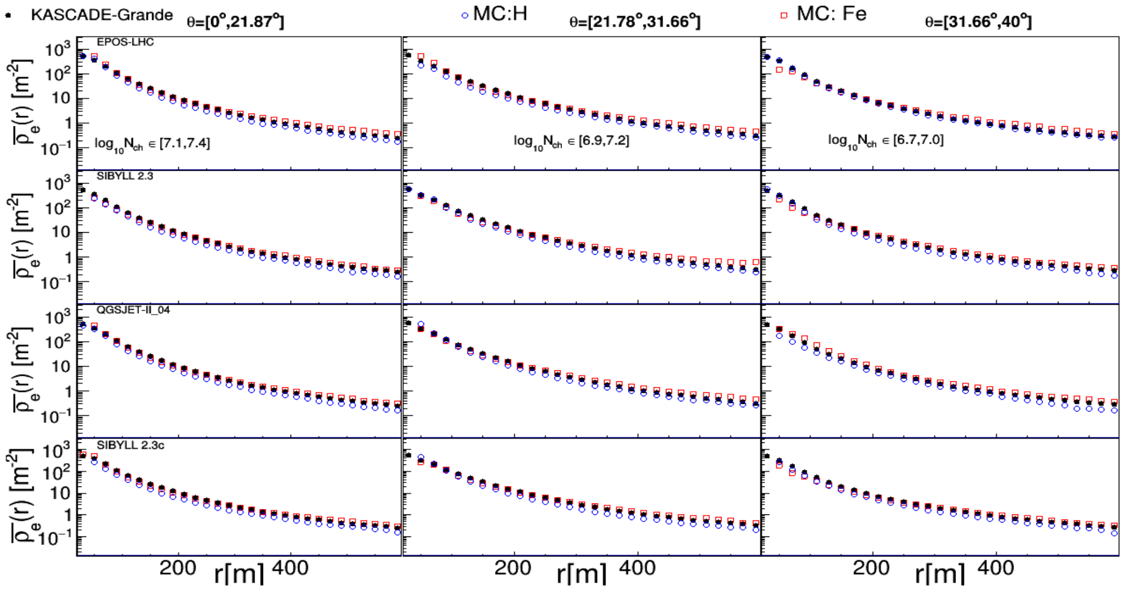

Figure 3: Mean electron lateral distributions of EAS from KASCADE-Grande data and four different hadronic interaction models. The data is shown for three $log_{10}N_{ch}$ intervals, from left to right: $log_{10}N_{ch} \in [7.1, 7.4]$, $log_{10}N_{ch} \in [6.9, 7.2]$ and $log_{10}N_{ch} \in [6.7, 7.0]$. The description of the plots is the same for 2.

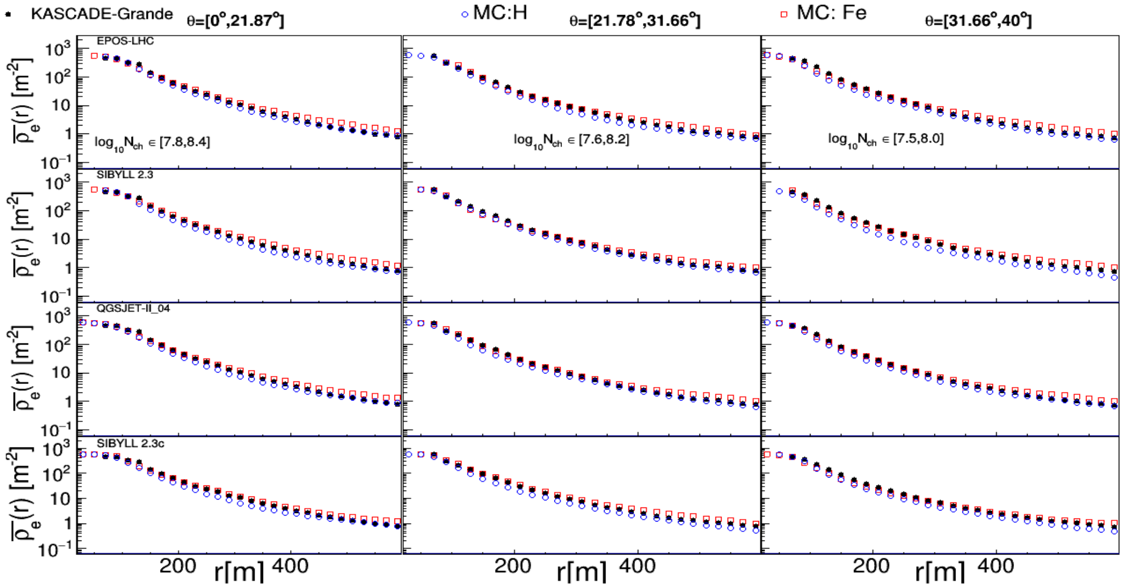

Figure 4: Mean electron lateral distributions of EAS from KASCADE-Grande data and four different hadronic interaction models. The data is shown for three $log_{10}N_{ch}$ intervals, from left to right: $log_{10}N_{ch} \in [7.8, 8.4]$, $log_{10}N_{ch} \in [7.6, 8.2]$ and $log_{10}N_{ch} \in [7.5, 8.0]$. The description of the plots is the same for 2.. The description of the plots is the same for 2

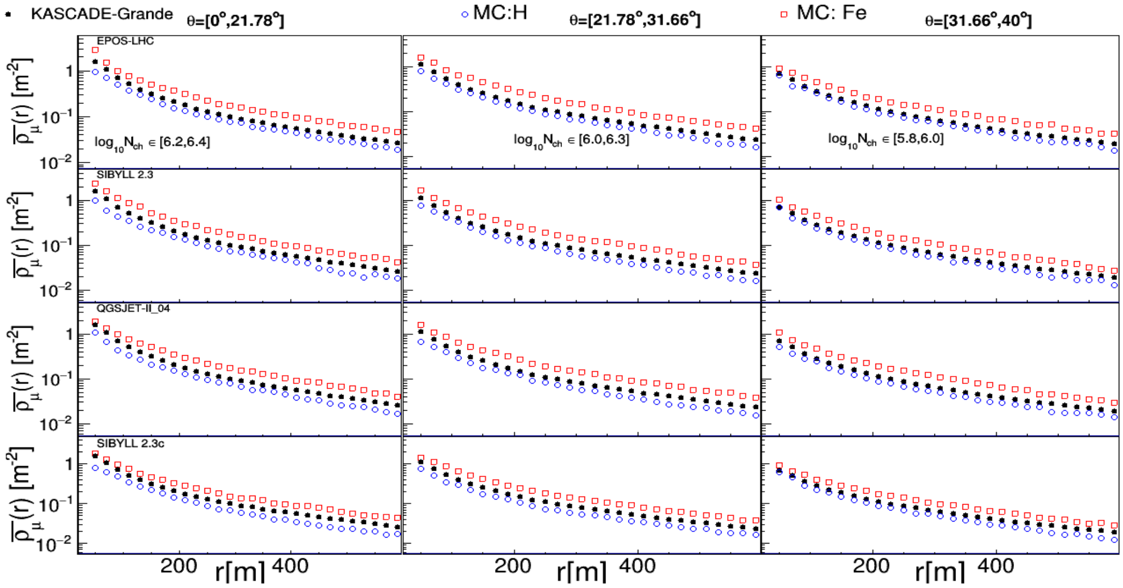

Figure 5: Mean muon lateral distributions of EAS from KASCADE-Grande data and four different hadronic interaction models. The data is shown for three $log_{10}N_{ch}$ intervals, from left to right $log_{10}N_{ch} \in [6.2, 6.4]$, $log_{10}N_{ch} \in [6.0, 6.3]$ and $log_{10}N_{ch} \in [5.8, 6.0]$. The black points represent the KASCADE-Grande data, the red squares are for iron nuclei, the blue circles for protons. The columns correspond to different zenith angle intervals, while each row is for a different hadronic interaction model: From top to bottom EPOS-LHC, SIBYLL 2.3, QGSJET-II-04 and SIBYLL 2.3c.

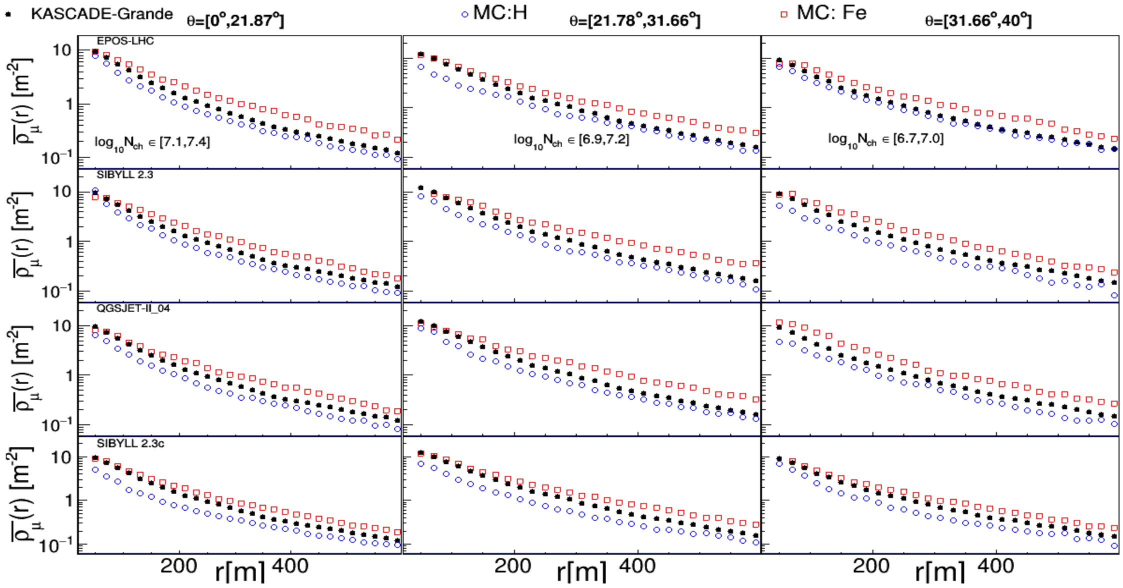

Figure 6: Mean muon lateral distributions of EAS from KASCADE-Grande data and four different hadronic interaction models. The data is shown for three $log_{10}N_{ch}$ intervals, from left to right: $log_{10}N_{ch} \in [7.1, 7.4]$, $log_{10}N_{ch} \in [6.9, 7.2]$ and $log_{10}N_{ch} \in [6.7, 7.0]$. The description of the plots is the same for 5.

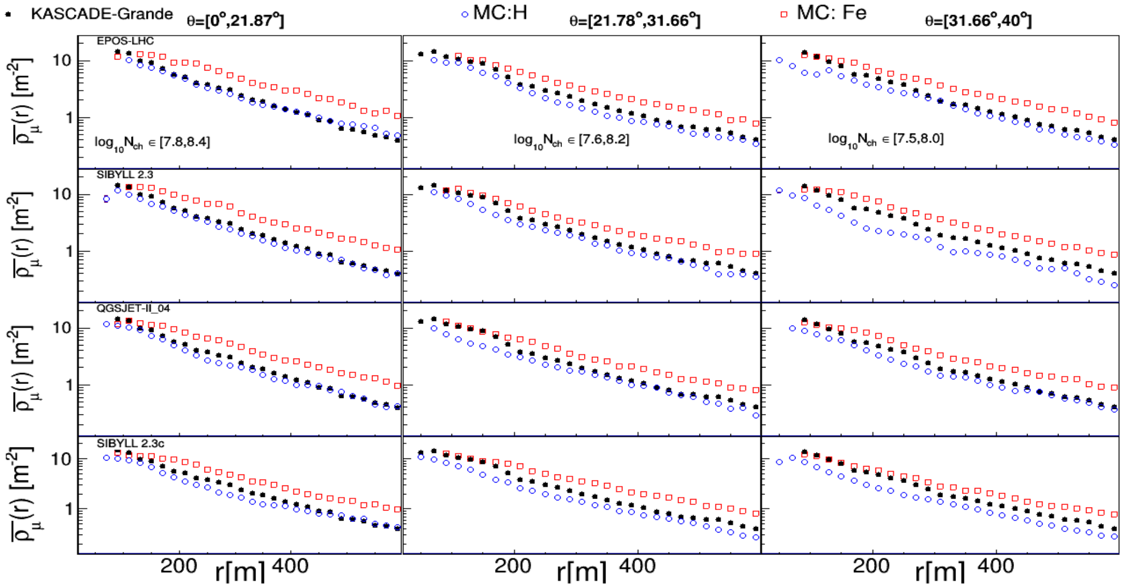

Figure 7: Mean electron lateral distributions of EAS from KASCADE-Grande data and four different hadronic interaction models. The data is shown for three $log_{10}N_{ch}$ intervals, from left to right: $log_{10}N_{ch} \in [7.8, 8.4]$, $log_{10}N_{ch} \in [7.6, 8.2]$ and $log_{10}N_{ch} \in [7.5, 8.0]$. The description of the plots is the same for 5.

4. Conclusions

The post LHC high energy hadronic models SIBYLL 2.3, SIBYLL 2.3c, EPOS-LHC and QGSJET-II-04 were tested by comparing the predicted mean electron and muon densities for iron nuclei and protons with energies of 10 PeV, 100 PeV and 1 EeV with the data measured with KASCADE-Grande. It was found that the number of electrons in the shower is well described by the models, but when the different muon densities are compared there is an exception for the EPOS-LHC model which seems to have a difference in the phase space of N_μ vs N_{ch} at ultra high energies.

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