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INDIRECT MEASUREMENTS AROUND THE KNEE — RECENT RESULTS FROM KASCADE

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(for the KASCADE COLLABORATION)

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In the presented analysis of air shower data measured with the KASCADE experiment energy spectra for five mass groups are reconstructed. The results show a change of composition towards heavier elements across the knee but also demonstrate an insufficient description of the data by the used hadronic interaction models QGSJet and SIBYLL.

Keywords: Cosmic rays; air shower; energy spectra.

1. Introduction

A major component of the KASCADE experiment[1] is the field array whose main reconstructed observables are the electron number N_e and the truncated muon number $N_\mu^{\mathrm{tr.}}$ which are used in this analysis. The latter one is the number of muons with distances to the shower core between 40 m and 200 m. Information about the reconstruction and the measurement

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procedures are given in Ref. 1. The accessible energy range covers the knee, the effective measurement time added up to 900 days.

2. Outline of the analysis

Starting point of the analysis is the correlated frequency distribution of $\lg N_e$ and $\lg N_\mu^{\mathrm{tr.}}$ displayed in Fig. 1 (left panel). The lower boundaries in $\lg N_e$ and $\lg N_\mu^{\mathrm{tr.}}$ were chosen in a

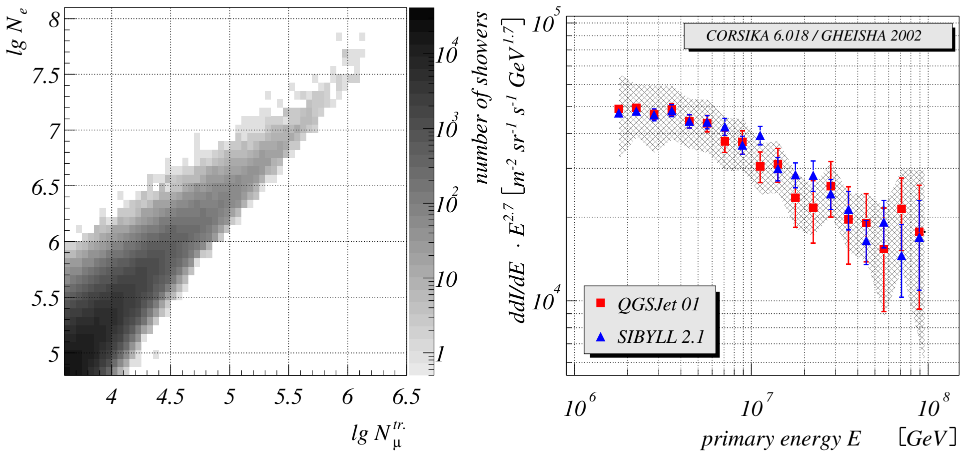

Fig. 1. Left: Correlated shower size distribution. Right: All particle energy spectrum for QGSJet and SIBYLL analysis (shaded band indicates methodical uncertainties).

way to minimize influences from efficiencies. Considered zenith angles range from 0° to 18°. The content N_j of each cell can be written as

$$N_j = C \sum_{A=1}^{N_A} \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \, p_A \left(\lg N_{e,j}, \lg N_{\mu,j}^{\mathrm{tr.}} \,|\, \lg E \right) d\lg E. \quad (1)$$

Here, C is a normalizing constant (time, aperture), the sum is carried out over all primary types with mass A, and p_A describes the probability for an EAS with primary energy $\lg E$ to be measured and reconstructed with shower sizes $\lg N_e$ and $\lg N_\mu^{\mathrm{tr.}}$. This probability consists of the shower fluctuations s_A, efficiencies ε_A and reconstruction properties r_A. For sake of simplicity the integration over cell area and solid angle is omitted in Eq. (1) but of course accounted for in the analysis. The data of Fig. 1 left are therefore regarded as a system of coupled integral equations. For the analysis the primary particles H, He, C, Si and Fe were chosen as representatives for five mass groups.

The probability distributions s_A, ε_A and r_A were determined by Monte Carlo simulations using CORSIKA[2] (version 6.018) and the two interaction models QGSJet[3] (2001 version) and SIBYLL[4] (version 2.1). In order to solve the equation system unfolding methods were applied. Three different algorithms were used to cross-check systematic uncertainties. Details of the analysis and the used unfolding methods can be found in Ref. 5.

3. Results and conclusion

In the upper part of Fig. 2 the results for the spectra of light elements (left) and heavy elements (right) of QGSJet based analysis are shown, in the lower part the corresponding spectra using SIBYLL simulations. The resulting all particle spectra for both cases are shown in the right panel of Fig. 1. The shaded bands in the figures represent an estimate of the methodical uncertainties.

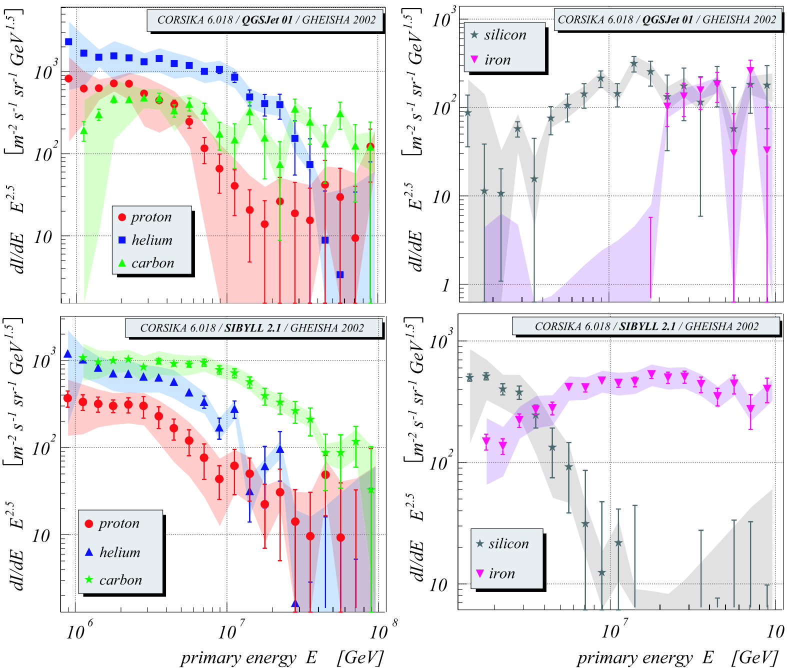

Fig. 2. Results for the energy spectra, H, He, C in left column, Si, Fe in right column. Upper row: QGSJet hypothesis; lower row: SIBYLL hypothesis. Bands indicate methodical uncertainties.

The all particle energy spectrum shows a knee at ≈ 4 PeV for both results and inside the statistical uncertainties the results coincide. The decrease of light elements across the knee, i.e. the occurence of knee-like features in the light element spectra is also revealed independent of the used simulation code. In contrast the spectra of Si and Fe differ significantly and look quite unexpected. This can be understood by judging the ability of the simulations to describe the data.

Figure 3 (upper row) shows the distribution of residuals of a χ^2-comparison between data and forward folded (according to Eq. 1) solutions. For both interaction models the overall value of χ^2 p.d.f. is about 2.4 and strong systematic effects are found in the distribution of the residuals. These systematics reflect properties of the used interaction models and are not caused by improper understanding of reconstruction or detector simulation.

To demonstrate the kind of these deviations a comparison between the measured and the $\lg N_e$-distribution resulting from forward folding for two fixed $\lg N_\mu^{\mathrm{tr.}}$ bins are displayed

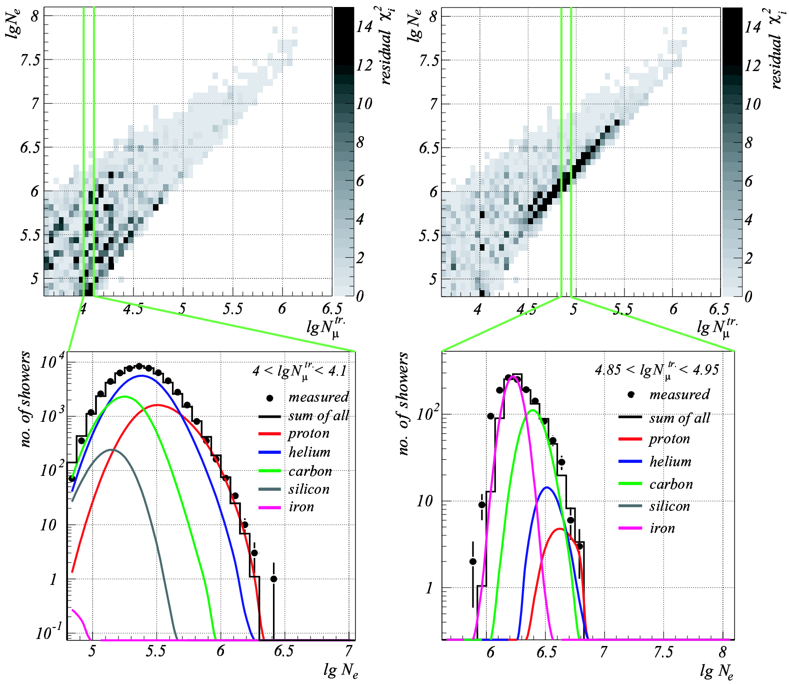

Fig. 3. Upper row: Distribution of deviations between data and forward folded solution for QGSJet (left) and SIBYLL (right). Lower row: Example of insufficient description of measured data for fixed $\lg N_\mu^{\mathrm{tr.}}$ bins; left panel for QGSJet, right panel for SIBYLL.

in the lower row of Fig. 3. It turns out that both interaction models fail to reproduce the overall correlation between $\lg N_e$ and $\lg N_\mu^{\mathrm{tr.}}$ as observed in the data. In the case of QGSJet simulations the predictions are incompatible with the data in the low energy regime (simulations look too heavy), for SIBYLL incompatibility occurs at higher energies (simulations look too light).

Summarizing the results of this analysis the knee in the all particle spectrum is due to kinks in the light element spectra resulting in a heavier composition above the knee. A more specific statement seems inappropriate since neither QGSJet nor SIBYLL describe the measured data consistently over the whole measurement range. The analysis is ongoing in close cooperation with model developing groups.

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