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On the hadronic component of extensive air showers

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The hadronic component of extensive air showers is investigated with the large calorimeter of the KASCADE experiment. The transverse momentum transfer in EAS is explored by investigations of the geometrical structure in the hadronic shower core and the arrival times of hadrons. The flux of unaccompanied hadrons is studied to probe hadronic cross sections. The measured results are compatible with simulations using CORSIKA/QGSJET.

1. Introduction

The hadronic component of extensive air showers (EAS) reveals important information about the mass and energy of the shower inducing primary particle. In EAS, energies and kinematical regions are covered which are not accessible at present-day accelerator experiments. The extreme forward direction, important for the development of EAS, has been only scarcely investigated with particle beams. Due to the energy dependence of the coupling constant α_S of the strong interaction, quantum chromodynamics cannot be applied to describe these soft interactions and phenomenological approaches have to be used instead. The validity of these models has to be checked experimentally.

The KASCADE experiment with its hadron calorimeter is a suitable instrument to test hadronic interaction models using EAS. The results of CORSIKA [1] simulations using different hadronic interaction models are compared to measured data and consistency checks prove, that the model QGSJET describes the data best [2,3].

The transverse momentum transfer in hadronic interactions is explored by investigations of the geometrical structure of the hadronic shower cores at detector level and of hadron arrival times. Inelastic total hadronic cross sections are probed by measurements of the flux of unaccompanied hadrons at ground level.

2. Experimental set–up

To investigate cosmic rays from several 10^{13} eV up to 10^{17} eV the experiment KASCADE consists of three major parts, a scintillator array, an underground muon tracking detector, and a central detector.

The 200×200 m^2 scintillator array is formed by 252 detector stations housing liquid scintillation counters to measure the electromagnetic component and, below an absorber of 10 cm lead and 4 cm iron, plastic scintillators to register muons with an energy threshold of 230 MeV. The position of the shower core, the angle of incidence

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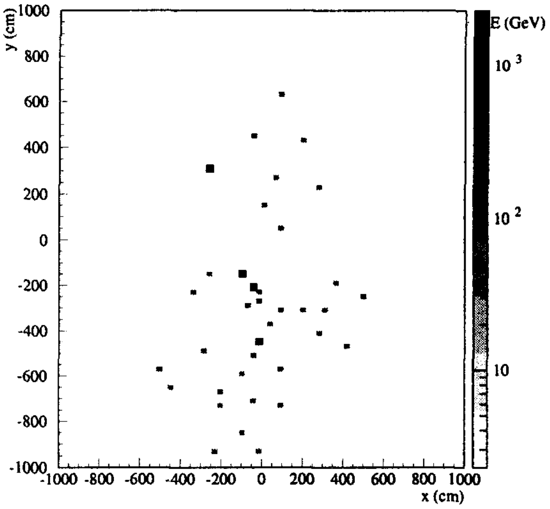

Figure 1. Example for a measured, elongated hadronic shower core with $\lambda_4 = 0.82$. The reconstructed primary energy is about $6 \cdot 10^{15}$ eV.

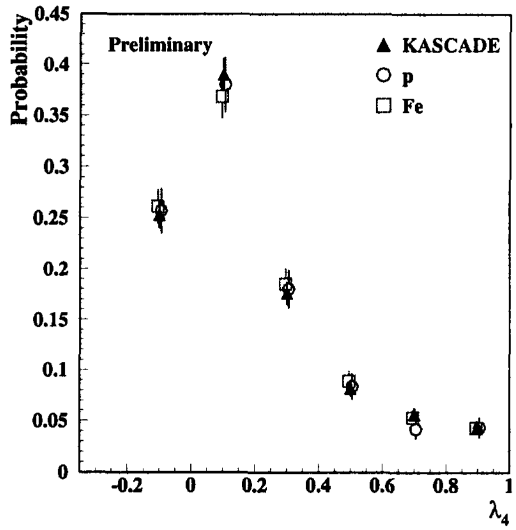

Figure 2. Measured distribution for the parameter λ_4 compared to results from simulations for primary protons and iron nuclei.

as well as the number of electrons and muons is obtained from these detectors.

Main part of the central detector system is a 320 m^2 hadron calorimeter, formed by 4000 t iron, lead, and concrete absorber material, with a thickness of 11 hadronic interaction lengths. The absorber is interspaced by nine layers of ionization chambers filled with the liquids TMS or TMP[4]. In total, 11 000 ionization chambers are installed, each containing four independent channels with a size of 25×25 cm^2. The fine segmentation of the read-out allows to reconstruct individual hadrons of EAS ($E_h \geq 30$ GeV), measuring their point and angle of incidence as well as their energy. A layer of plastic scintillators below the third absorber layer serves as a fast trigger and to determine the arrival times of hadrons.

3. Transverse momentum in hadronic interactions

The geometrical structure of the hadronic shower core is investigated in order to study the transverse momentum transfer in hadronic interactions [5]. The quantity

$$\lambda_N = \frac{\Sigma_{i \neq k \neq j}^{N} cos 2\phi_{ij}^{k}}{N(N-1)(N-2)}$$

is used to characterize the structure of the shower core. N is the number of hadrons, ϕ_{ij}^k is the angle between straight lines connecting the i^{th} and j^{th} hadron with the k^{th}. The parameter λ_N equals 1 for hadrons aligned along a straight line and tends to $-1/(N-1)$ for an uniform distribution. In the present analysis the parameters λ_4, taking into account the four hadrons with the highest energy, and λ_N, including all hadrons, are calculated.

As an example a measured hadronic shower core is shown in Fig. 1. The reconstructed primary energy amounts to about $6 \cdot 10^{15}$ eV. Each point represents an individually reconstructed hadron. The four hadrons with the highest energy, represented by black squares, indicate an elongated core with $\lambda_4 = 0.82$.

Measured values for λ_4 are presented in Fig. 2 for showers with primary energies above 5 PeV. The results are compared to results of simulated showers using CORSIKA/QGSJET, initiated by

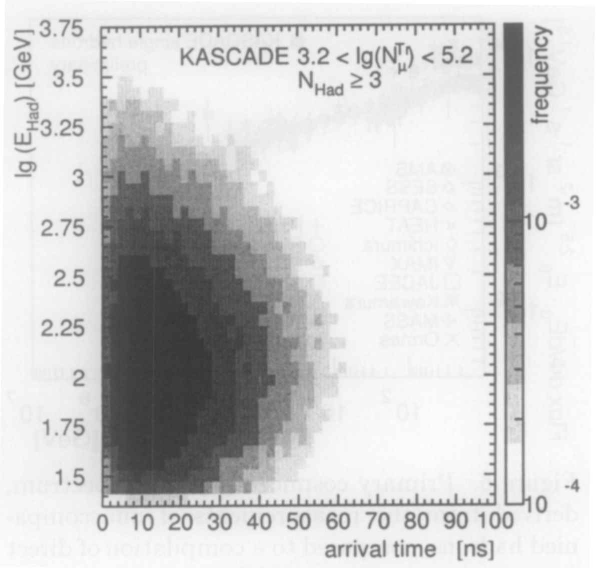

Figure 3. Measured reconstructed hadron energy vs. arrival time.

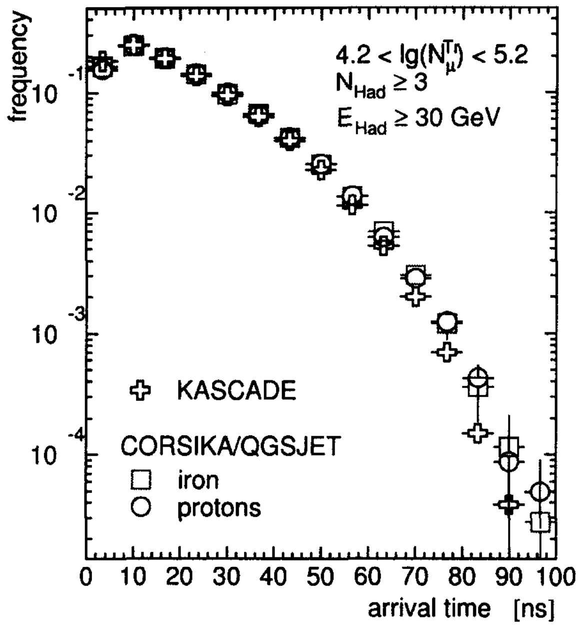

Figure 4. Measured arrival time distribution compared to simulations for primary protons and iron nuclei.

protons and iron nuclei. Elongated events with large λ_4 parameters can be found with equal probability in measured and simulated distributions. In conclusion, the simulations reproduce the measurements well.

A further method to check the transversal momentum transfer in EAS is the investigation of the arrival times of hadrons at ground level. On their way through the atmosphere hadrons undergo several interactions, in each process an average transversal momentum $\langle p_\perp \rangle \approx 400$ MeV is exchanged, resulting in a zigzag path of the hadrons through the atmosphere. For this reason hadrons are expected to arrive several tens of ns later at ground level than the shower front.

The measured hadron energy for hadrons with $E_h \geq 30$ GeV vs. their arrival time for showers with at least 3 reconstructed hadrons is displayed in Fig. 3. The times are measured relative to the first particle hitting the detector. The muon number N_μ^{tr} corresponds to an energy $E_0 \approx 0.3$ to 30 PeV. For hadrons with energies around 100 GeV delays of more than 60 ns are registered, indicating that these particles undergo many interactions in the atmosphere.

The measured arrival time distribution for primary energies between 3 and 30 PeV is shown in Fig. 4. The data are compared to results of simulations for primary protons and iron nuclei. Over the whole range the measurements are reproduced well by the simulations. No unexpected number of delayed hadrons can be observed. Also, no significant difference between light and heavy primaries can can be inferred from the graph.

4. Unaccompanied hadrons

Unaccompanied hadrons are events for which only one hadron has been reconstructed in the calorimeter. These hadrons originate mostly from small, proton induced EAS with energies around $10^{11} - 10^{13}$ eV, where either most of the EAS has already been absorbed in the atmosphere or the leading hadron made only a few hadronic interactions. For primary protons the hadron suffers in average only 3.6 ± 1.9 interactions for the selected unaccompanied hadrons as compared to 6.4 ± 1.8 interactions for all showers.

This event selection is very sensitive to the in-

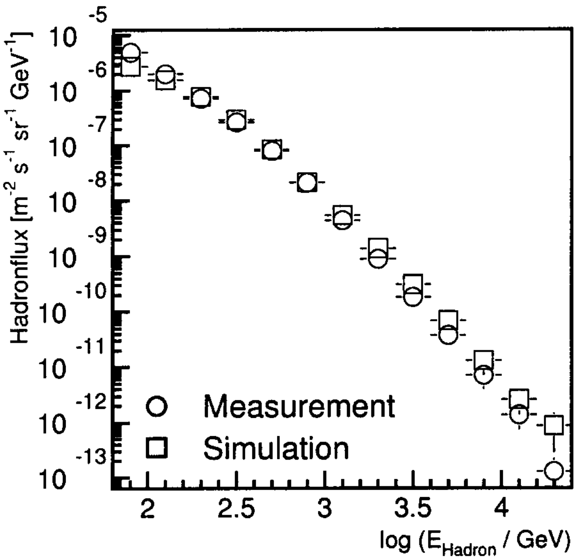

Figure 5. Measured flux of unaccompanied hadrons at ground level compared to results of CORSIKA/QGSJET simulations, preliminary.

elastic hadronic cross section. The measured flux of unaccompanied hadrons is presented in Fig. 5 as function of hadron energy. In addition results of CORSIKA/QGSJET simulations are shown. The flux on top of the atmosphere of primary protons, helium, oxygen, and iron nuclei as obtained by direct measurements (see [6]) has been taken into account in the simulations.

The measured flux at detector level has been converted to the flux at the top of the atmosphere. Since the selection of unaccompanied hadrons enriches primary protons as primaries, the flux obtained is basically the flux of primary protons. The values obtained are compared in Fig. 6 to a compilation of direct measurements [6]. The reconstructed flux is compatible with the direct measurements. This analysis provides a very crucial test of the inelastic cross sections of hadronic interactions in the atmosphere for the energy interval of 100 GeV to 100 TeV.

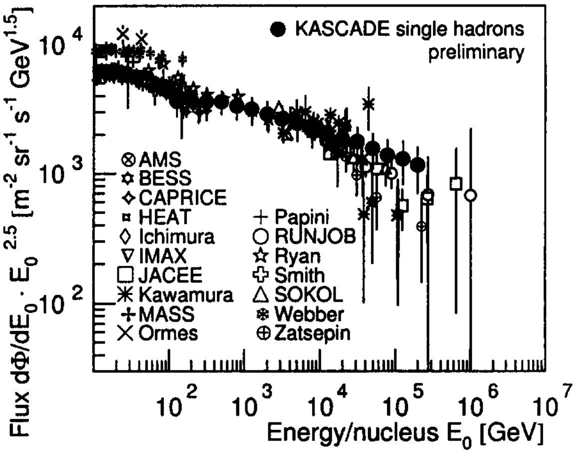

Figure 6. Primary cosmic–ray proton spectrum, derived from the measurements of unaccompanied hadrons, compared to a compilation of direct measurements taken from [6].

5. Conclusion

The present investigations indicate that the transverse momentum transfer in hadronic interactions is described correctly in the model QGSJET. The primary cosmic–ray proton spectrum has been reconstructed from the measured flux of unaccompanied hadrons compatible with direct measurements, indicating a correct modeling of the inelastic hadronic cross section up to 10^5 GeV.

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