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Hadrons in a calorimeter measured in air showers and at an accelerator

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Properties of hadronic cascades in a calorimeter are studied for two detectors, one exposed to hadrons up to 350 GeV at the CERN SPS accelerator, the second one, the hadron calorimeter of the KASCADE-Grande experiment registers cosmic-ray induced hadrons. The data obtained are compared to results of Monte Carlo simulations using the GEANT/FLUKA code.

1. Introduction

To measure properties of high-energy cosmic rays and to study the development of extensive air showers in the atmosphere the multi detector set-up KASCADE-Grande [1, 2] measures simultaneously the electromagnetic, muonic, and hadronic shower components. In particular, hadrons are measured by an iron sampling calorimeter [3] with the lateral dimensions 16×20 m^2. It consists of 9 layers of liquid ionization chambers and a layer of plastic scintillation counters to provide fast trigger signals interspaced between a 4000 t iron absorber. A lead filter above the absorber serves to suppress the electromagnetic component of air showers. In total, 11 000 liquid ionization chambers are installed. Each chamber has the dimensions $50 \times 50 \times 1$ cm^3 and contains four independent electronic channels. A feed-back preamplifier is mounted directly on the chamber in order to reduce noise pick-up. The detectors are filled with the room-temperature liquids tetramethylsilane (TMS, $Si(CH_3)_4$) or tetramethylpentane (TMP, C_9H_{20}).

With this detector the hadronic shower component is investigated in detail. Basis for these investigations is a precise energy calibration of the detector in a three step procedure [3]. First, an electronic calibration. Second, the conversion from the charge yield to deposited energy is derived from the signal of incident muons.

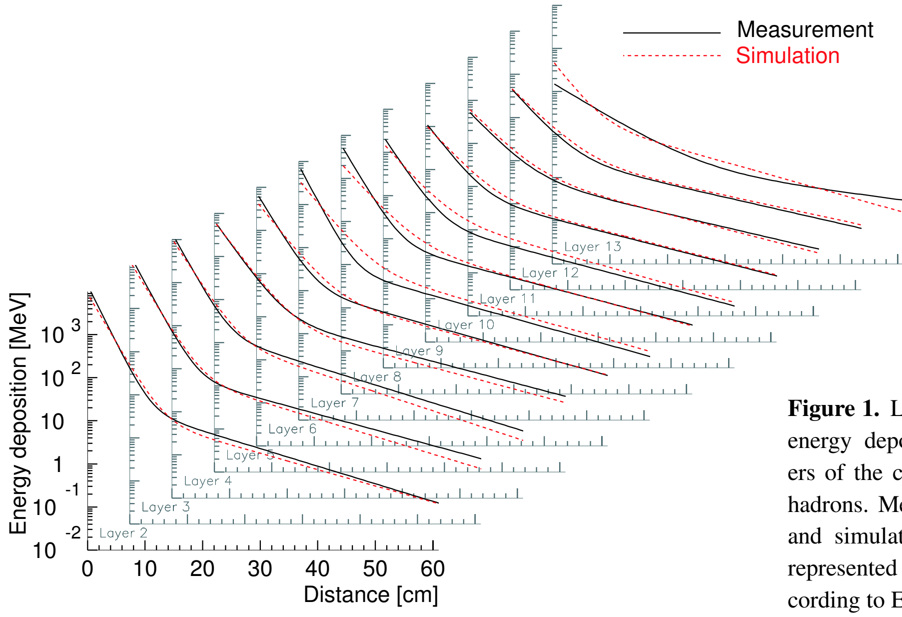

Figure 1. Lateral distribution of the energy deposition in different layers of the calorimeter for 300 GeV hadrons. Measurements (solid lines) and simulations (dashed lines) are represented by parameterizations according to Eq. (1).

Finally, the conversion from energy deposition to incident hadron energy is based on simulations of the detector response with the GEANT code [4] using FLUKA [5] to describe hadronic interactions.

For a direct verification of the calibration chain a test calorimeter with a set-up similar to the KASCADE calorimeter has been exposed to hadrons (pions and protons) up to 350 GeV at the CERN SPS accelerator [6]. It had the lateral dimensions 1×1 m^2 and consisted of 15 layers of liquid ionization chambers. The first two where separated by a 5 cm lead filter, all subsequent layers by a 10 cm iron absorber, each. In the following some results of this calibration measurements are presented and the data are compared to air shower measurements with the KASCADE calorimeter.

2. Results

The lateral distribution of the energy in an hadronic cascade seems to consist of two components, a strongly collimated component at distances closer than 20 cm to the cascade axis and a more weakly attenuated component at larger distances, see [3]. Simulations show that the latter (flat component) consists of low-energy neutrons. In this work, two exponential functions are used to describe the energy density ρ_E as function of distance r to the center of the cascade

$$\rho_E(r) = C_1 \exp(-r/r_1) + C_2 \exp(-r/r_2). \tag{1}$$

A parameterization of measured data with this function is shown in Fig. 1 for different layers in the calorimeter for 300 GeV hadrons. The two components can easily be distinguished. As can be recognized from the figure, the energy distribution falls steeply as function of distance. Within the central 15 cm the energy density decreases by about three orders of magnitudes. Hence, for a fit of Eq. (1) to the data the integral over Eq. (1) has been calculated within the boundaries of each electronic channel (25×25 cm^2), the resulting functions are shown in the figure for measured and simulated data. The measurements show that the parameters r_1 and r_2, the widths of the cascade, within the energy of the two components falls off by a factor of $1/e$, are almost independent of the energy of the incident particle. For the inner component r_1 increases approximately linearly

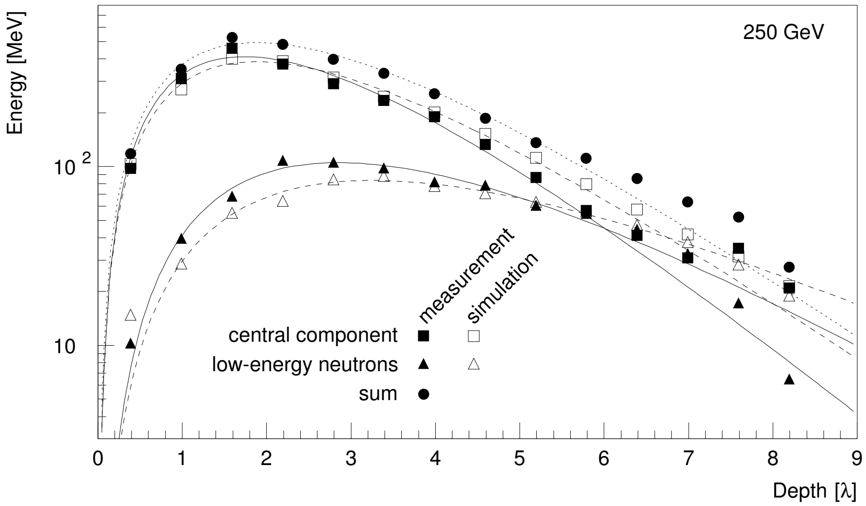

Figure 2. Longitudinal profile of the energy deposition for 250 GeV hadrons. The contributions of the central and the low-energy neutron components are shown separately. The accelerator data are compared to simulations using GEANT/FLUKA. The lines indicate fits to the data points according to Eq. (2).

as function of depth in the detector from 1.5 cm at a depth of 0.4 hadronic interaction lengths (λ_i) to about 2.5 cm at 7 λ_i. A similar behavior is obtained for the outer (low-energy neutron) component, the values for r_2 increase from about 9 cm at 0.4 λ_i to almost 14 cm at 7 λ_i. Overall, the simulated energy deposition agrees well with the measured data within the statistical uncertainties.

Integration of the curves in Fig. 1 gives the energy deposition in each layer. The longitudinal profiles of the energy deposition for the two components are shown in Fig. 2 for hadrons with an energy of 250 GeV. The longitudinal behavior is approximated by the function

$$E_{dep}(t) = A \cdot t^{\mu} \cdot \exp(t/\lambda_0), \tag{2}$$

where t is the depth in the absorber, λ_0 the attenuation length at large depths, μ characterizes the grow of the particle multiplicity in the cascade, and A is a normalization constant.

The inner component reaches its maximum at a depth of $1/(\mu\lambda_0) \approx 1.5\ \lambda_i$. The low-energy neutrons penetrate deeper into the absorber and reach their cascade maximum at about 2.5 λ_i. The exponential attenuation at large depths is for the low energy neutrons significantly weaker as compared to the central component. Due to this effect, the low energy neutron component, which is suppressed by about a factor of five in the region of the cascade maximum, equalizes with the central component at large depths (typically around $\sim$ 6 λ_i). Also depicted are results from simulations using the GEANT/FLUKA codes. For the central component, the simulations follow the measurements up to about the maximum of the cascade and the exponential attenuation is less pronounced in the simulations. For the low-energy neutron component the simulated showers penetrate slightly deeper into the absorber and, in addition, the attenuation at large depths is weaker than for the measured cascades. The total energy deposition, obtained as sum of the two components, is shown in the figure as well.

An important check of the calibration procedure is the comparison of the data acquired at the accelerator compared to hadrons measured in air showers. A subset of hadrons has been selected from cosmic-ray induced events, namely unaccompanied or single hadrons. These are debris of small showers interacting at high altitudes. Most particles have been absorbed in the atmosphere and only one hadron has been reconstructed in the calorimeter. These hadrons should behave like artificially accelerated hadrons, but much higher energies are reached. For example, the most energetic single hadron detected so far at KASCADE-Grande has an energy of 67 TeV. The energy spectrum of these hadrons follows a power law [7]. Narrow intervals $\Delta\,\mathrm{lg}(E/\mathrm{GeV}) = 0.1$ have been selected for a comparison with accelerator data at fixed energies.

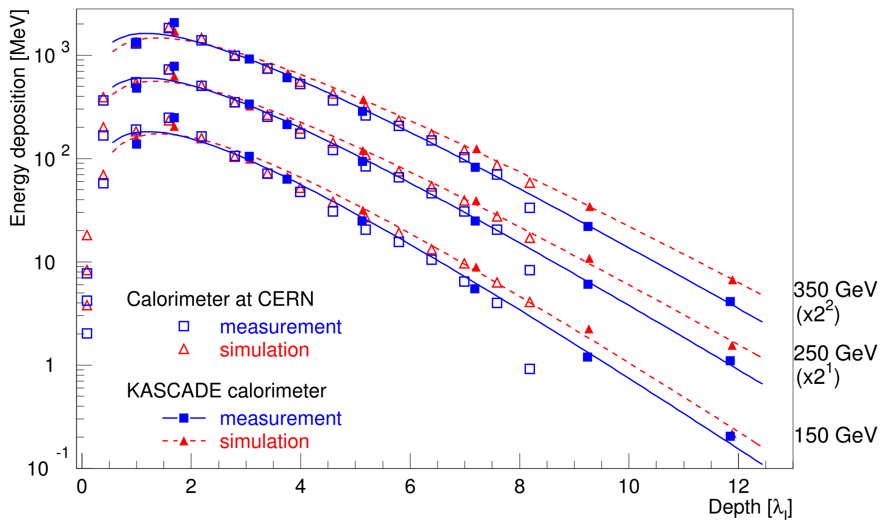

Figure 3. Longitudinal energy deposition in a calorimeter for hadrons with energies from 150 to 350 GeV. Measurements at an accelerator are compared to air shower data.

For these hadrons the longitudinal profiles of the energy deposition are compared to the results from the accelerator measurements in Fig. 3 for three different hadron energies. The different sampling structures of the two calorimeters can be noticed, the test calorimeter had a homogeneous sampling, while the absorber thickness increases as function of depth for the KASCADE calorimeter. The cascade development of the artificially accelerated and the cosmic-ray induced hadrons agrees very well. An important result, since this verifies the calibration chain applied for the air shower measurements.

The results of a GEANT/FLUKA detector simulation for both event classes are depicted in the figure as well. The two simulation sets agree well with each other. Nevertheless, a comparison to the measurements exhibits a difference at large depths. The attenuation of the simulated cascades beyond the maximum is weaker as compared to the measurements, a behavior already observed for the individual components in Fig. 2. For both, measurements and simulations, the position of the cascade maximum increases as function of energy by about 0.67 λ_i/decade, but the maximum is shifted deeper into the absorber by about 0.1 λ_i for the simulations.

In **summary**, the accelerator measurements proof the validity of the calibration chain for the KASCADE-Grande hadron calorimeter and deficiencies in simulations of the cascades, as pointed out earlier [3], have been confirmed.

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