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Search for elongated spatial structures in hadronic shower cores with KASCADE

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Abstract.
In this analysis the structure of hadronic shower cores is investigated with the KASCADE calorimeter. The energy, position, and direction of incidence for individual hadrons above 50 GeV are measured. In parallel, the spatial structure is studied using the simulation program CORSIKA with the hadronic interaction model QGSJET. First results are presented for the showers with primary energies above 5 PeV. Elongated cores are observed more frequently than expected from random coincidence. This proves that KASCADE is sensitive to hadronic interaction producing elongated structures. Alignment can be found in both data sets - measurements and simulation. No significant deviation between them or hints for new physics have been found so far.

1 Introduction

A finely segmented hadron calorimeter designed to study air shower cores is located in the center of the KASCADE EAS experiment (Klages et al. 1997). It is capable to measure energy, positions and direction of individual hadrons and, therefore, allows to search in hadronic cores for unusual structures. They could be signatures of certain properties of high-energy interactions of cosmic-ray particles with the air nuclei, and might allow to test hadronic interaction models. Structures of special interest are elongated hadronic cores. Experiments using X-ray emulsion chamber techniques at mountain altitudes, such as Pamir (Borisov et al., 1984, 2001), Kanbala (Xue et al., 1999) or in the stratosphere, like CONCORDE-ECHOS (Capdevielle, 1997, 2001) have reported on gamma hadron families showing strong geometrical alignment. Various interaction models have been tested in order to reproduce the observed phenomena and possible physics mechanisms were discussed (Mukhamedshin, 1994, 2001). The current status of these investigations is reflected in the following conclusion: ”The alignment of superfamilies cannot be explained by the QCD-jet production but results from some new physical mechanism of coplanar emissions of particles in strong interactions” (Borisov et al., 2001). A search for elongated hadronic cores in the data registered by the KASCADE calorimeter and a comparison with simulated results may give some additional hints towards an explanation of the phenomena mentioned above.

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2 Experimental Set-up and Measurements

The KASCADE experiment, located at the Forschungszentrum Karlsruhe (Germany), measures with high precision all three components of an EAS. A large number of shower parameters is provided on event-by-event basis. An array of 252 scintillator stations, located on a 200×200 m^2 field, gives information about the electromagnetic and muonic (E_μ $>$ 230 MeV) component. Three additional muon detectors (with thresholds of 0.49, 0.8 and 2.4 GeV) are operated in the Central Detector and the Muon Tunnel. The hadronic component is measured by a 16×20 m^2 iron calorimeter (Engler et al., 1999), being the main part of the Central Detector system (Fig. 1). The detector is equipped with 11 000 liquid

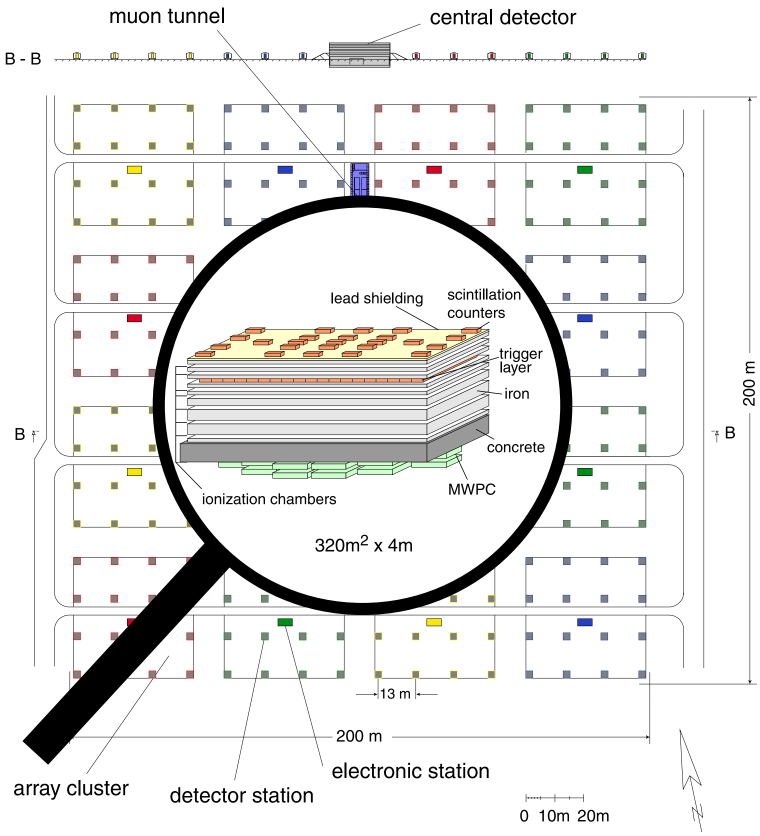

Fig. 1. Location of the hadron calorimeter within the KASCADE experiment.

ionization chambers, arranged in 9 layers above, between, and below the absorber. The latter consists of 4 000 t iron, concrete, and lead with a total thickness of 11.5 nuclear interaction lengths for vertical protons, ensuring a reasonable shower containment up to 25 TeV hadron energy. On average, 97.5 % of the energy is deposited in the calorimeter at this energy. Each chamber is read out by four 25×25 cm^2 pads.

The hadron energy reconstruction accuracy changes from 20 % at 100 GeV to 10 % at 10 TeV. The reconstruction efficiency approaches unity for hadrons of 100 GeV. The accuracy in position determination for hadrons of 100 GeV equals to 14 cm and reaches $\approx$ 10 cm for 1 TeV, and the hadron zenith angle accuracy improves from 12° at $E_H = 100$ GeV to 5° at $E_H = 1$ TeV.

3 Analysis

For the present analysis about 7.0 million showers with at least one reconstructed hadron have been considered. They have been registered between January 1997 and March 2000. The following cuts were applied to the data: The shower axis has been reconstructed in the center of the calorimeter with a distance of at least 3 m from its boundaries. Additionally, *truncated muon numbers* (Glasstetter et al., 1999) of $\log(N_\mu^{tr})>3.5$, zenith angles $\theta < 30°$ and at least four hadrons with an energy $E_H \geq 500$ GeV are required. The muon number corresponds to a primary energy $E_0 > 10^{15}$ eV. 1417 events survived these cuts and are used for the following analysis. The hadron positions are transformed into a plane perpendicular to the shower direction.

3.1 Asymmetry parameter

Several quantities may be used to characterize the geometrical structure of high–energy hadronic shower cores. As an example, we apply the parameter λ, introduced by the Pamir Collaboration (Borisov et al., 1984):

$$\lambda_N = \frac{\Sigma_{i\neq k\neq j}^{N} cos2\phi_{ij}^{k}}{N(N-1)(N-2)} \quad (1)$$

where N is the number of hadrons, and 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 in the case of complete alignment of N hadrons along one straight line and tends to $-\frac{1}{N-1}$ for an isotropic distribution of hadrons in a plane.

3.2 Aligned events

For our data sample the parameter λ_4 was calculated, taking into account the 4 most energetic reconstructed hadrons. In Fig. 2. the example of a typical shower core with λ_4 = -0.11

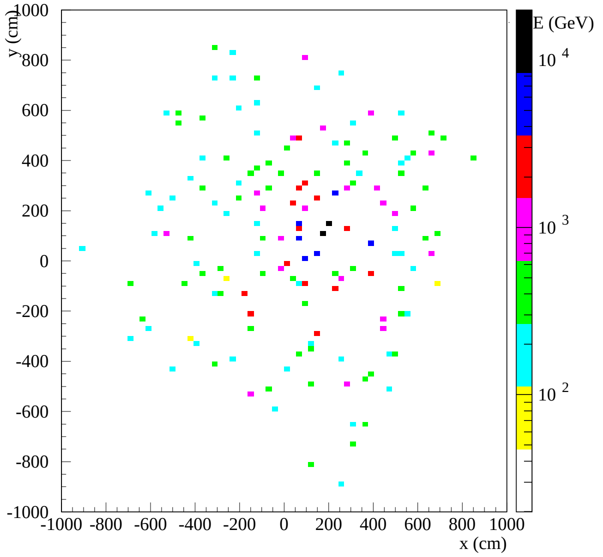

Fig. 2. Example of a measured, isotropic hadronic shower core with $\lambda_4 = -0.11$. Reconstructed primary energy is about $2 \cdot 10^{16}$ eV.

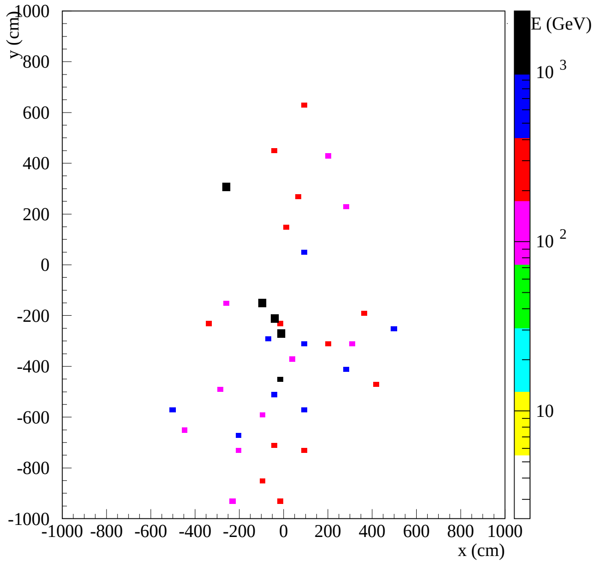

Fig. 3. Example of a measured, elongated hadronic shower core with λ_4 =0.82. Reconstructed primary energy is about $6 \cdot 10^{15}$ eV.

is shown. An example of an elongated event is given in Fig. 3 with $\lambda_4 = 0.82$.

The λ_4-distribution of the data together with results of two sets of random generated hadron positions are presented in Fig. 4. These tests show how the λ_4 parameter is distributed for isotropic events. In the first test (RANDOM1), four positions of hadrons within the fiducial area of the calorimeter are randomly chosen from a uniform distribution in x and y, then the parameter λ_4 is calculated. The second test was done taking into account the real lateral distribution of hadrons in a shower core. Starting from the measured configuration of the hadrons, their azimuthal angles are randomly varied around the geometrical center-of-gravity and again λ_4 is calculated (RANDOM2). Both tests are consistent with each other. The comparison with the KASCADE data shows, that for λ_4>0.6 the frequency of the data points exceeds by $\approx 60\%$ the results of both tests. The measured distribution is significantly shifted towards larger values of λ_4, i.e., to non-isotropic events. Thus, we can conclude, that the observed alignment tendency in hadronic EAS cores is not a pure-chance phenomenon.

4 Simulations

In order to check the physical relevance of the observed alignment in the data, we compare them with simulations. Showers with a primary energy $E_0 \geq 5$ PeV, initiated by protons and iron nuclei, with a spectral index of -2.7, have been simulated. The CORSIKA version 5.644 (Heck et al., 1998) with the hadronic interaction model QGSJET (Kalmykov et al., 1997) was used. A full detector simulation using GEANT3 (CERN, 1993) was performed and the events were reconstructed with the same software procedures as were used for the data. Finally, the parameter λ_4 was calculated and is plotted in Fig. 5 together with the data. As it is seen there, the simulations fully reproduce our data points.

Since KASCADE — in contrast to the emulsion chamber experiments — is located nearly at sea level, it has to be checked whether we would by sensitive to elongated structures generated in the first interactions. For this purpose spe-

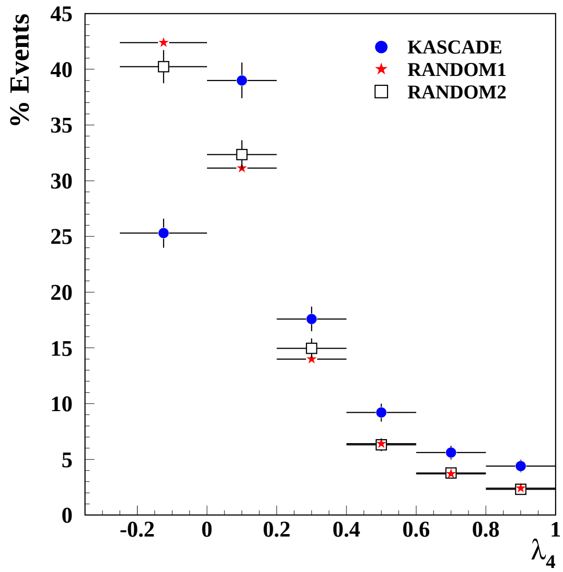

Fig. 4. Distribution of the parameter λ_4 for the KASCADE data and two random tests (see text).

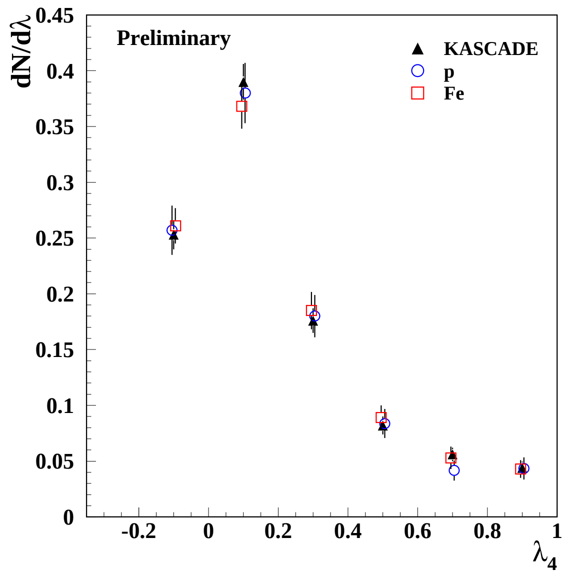

Fig. 5. Normalized distribution of a lambda parameter for KASCADE data and simulated showers with proton and iron primaries with $E_0 \geq 5$ PeV.

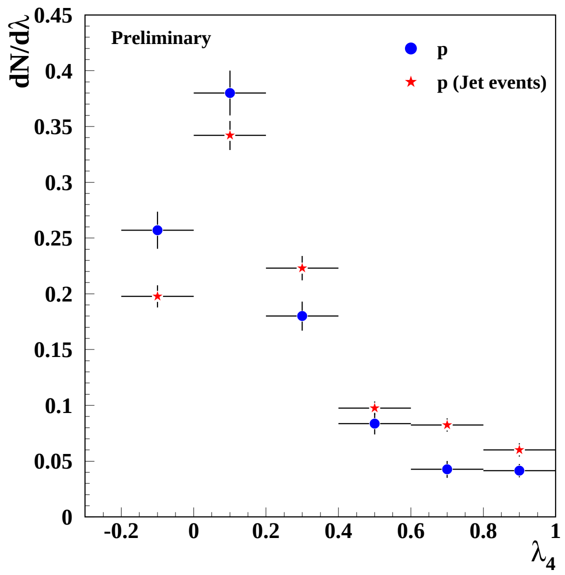

Fig. 6. Normalized distribution of a lambda parameter for simulated showers with a proton primary ($E_0 \geq 5$ PeV) for a standard QGSJet model and QGSJet where only events with jet production in the first interaction have been considered.

cially flagged showers were selected. *Grosso modo*, showers with a high–$\langle p_t \rangle$ jet (above a few GeV) of high-energetic hadrons in the first interaction are looked for. In Fig. 6 the corresponding λ_4 parameter of the flagged events is plotted together with the results obtained for all simulated events. A clear difference between those two distributions of the lambda parameter is seen. It signifies, that events with jet production exhibit a larger degree of hadron alignment, and that the method applied is sensitive to such interactions. This gives a hint towards further investigations of the role of QCD jet production and of elongated hadronic shower cores.

5 Conclusions

The preliminary study of the hadronic cores registered by the KASCADE calorimeter allows the following first conclusions:
1. Despite of its location nearly at the sea level, the KASCADE calorimeter is sensitive to hadron alignment phenomena generated in the first interactions.
2. To explain the observed elongation of events no necessity of new physics has been found so far. Instead, based on QGSJET simulations, normal QCD jet production seems to explain the observed degree of hadronic alignment.

Investigations using larger samples of data and simulated events are in progress. It is foreseen to include further observables in order to investigate the structure of the hadronic shower cores in coordinate and energy space.

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