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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 fine segmented hadron calorimeter designed to study the 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, in particular, 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 a 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). Search for elongated hadronic cores in the data registered by the KASCADE calorimeter and comparing with simulated results may give some additional hints towards an explanation of the above-mentioned phenomena.

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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 $200 \times 200\,\mathrm{m}^2$ field, gives information about the electromagnetic and muonic ($E_\mu >$ 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). Between its 9 active layers, containing 11 000 liq-

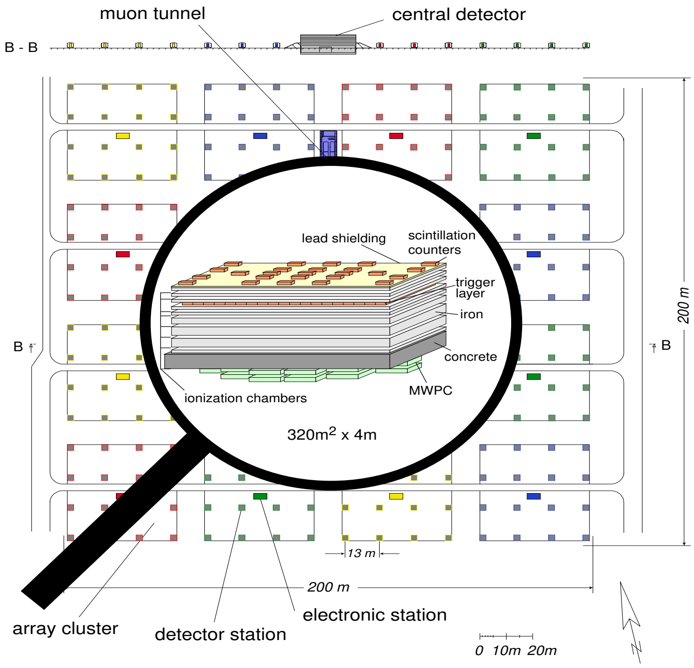

Fig. 1. Location of the hadron calorimeter within the KASCADE experiment.

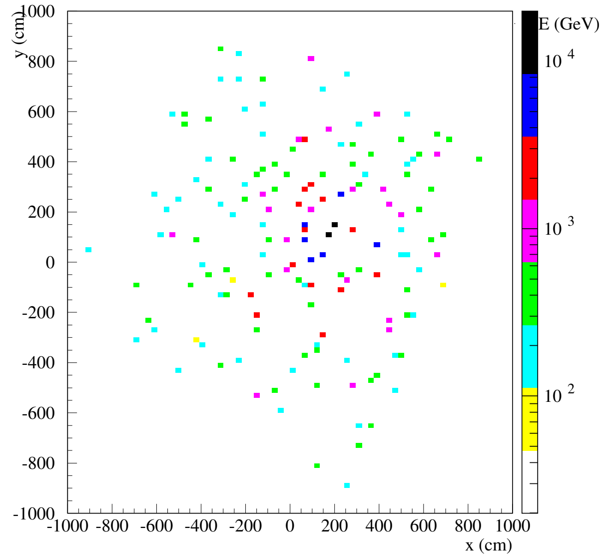

Fig. 2. Example of a measured hadronic shower core with λ_4 $=-0.11$. Reconstructed primary energy is about $2{*}10^{16}$ eV.

uid ionization chambers, the absorber thickness varies from 12 to 36 cm. The thickness of the iron stack corresponds to 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 $25{\times}25$ 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 registred between 1.01.1997 and 1.03.2000. The following cuts were applied to the data: The shower core position had to be reconstructed in the center of the calorimeter, with a distance of at least 3 m from its boundaries. Additionally, *truncated muon numbers* (Glasstetter R. et al., 1999) of $\log(N_\mu^{tr})>3.5$, zenith angles $\theta < 30°$ and at least four hadrons with 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

To describe the asymmetry of the high-energy hadronic shower cores we apply the λ parameter, introduced as an alignment criterion by the Pamir Collaboration (Borisov et al., 1984) :

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

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 λ_N parameter 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 a λ_4 parameter was calculated, taking into account the 4 most energetic hadrons in the shower core. In Fig. 2. the example of a typical shower core with λ_4 = -0.11 is shown. An example of an elongated event is given in Fig. 3 (λ_4 = 0.82).

In Fig. 4 the λ_4-distribution of the data together with results of two sets of random generated hadron positions are presented. These tests show how the λ_4 parameter is distributed for isotropic events. In the first test (RANDOM1 in Fig. 4), 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. This is repeated for a large number of events. 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 in Fig. 4.). Both tests are consis-

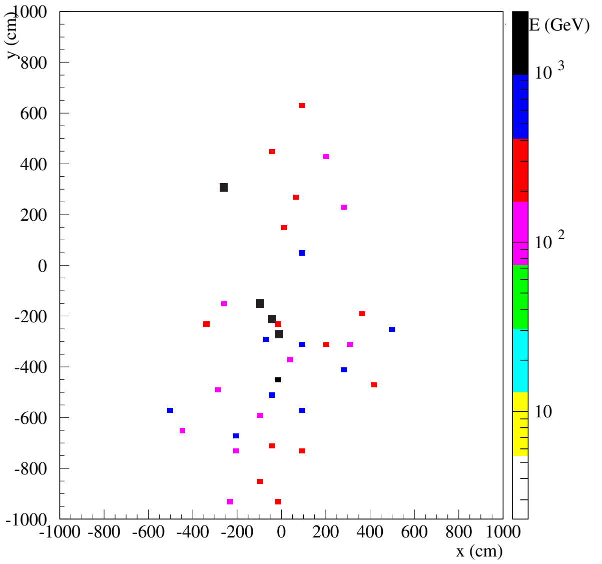

Fig. 3. Example of a measured hadronic shower core with λ_4 =0.82. Reconstructed primary energy is about $6{*}10^{15}$ eV.

tent 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.

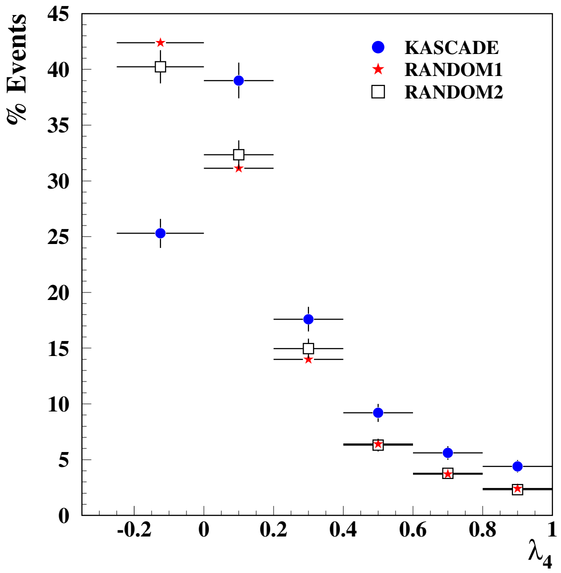

Fig. 4. Distribution of the λ_4 parameter for the KASCADE data and two random tests (see text).

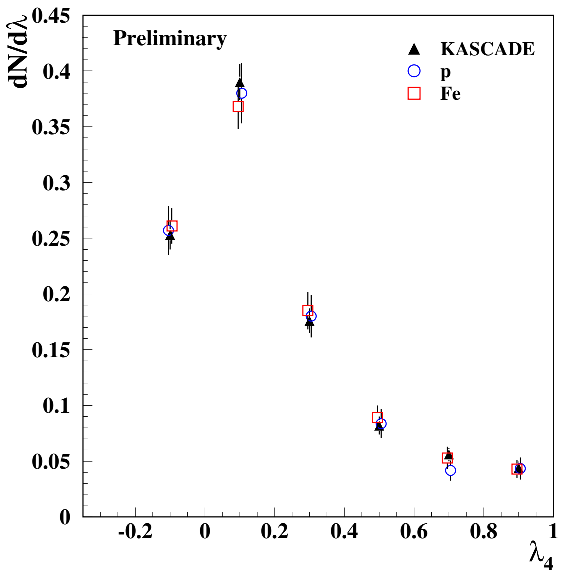

Fig. 5. Normalized distribution of a lambda parameter for KASCADE data and simulated showers with proton and iron primaries with $E_0 \geq 5$ PeV.

4 Simulations

In order to check the physical relevance of the observed alignment in the data, we compare them with simulations. Showers with the primary energy $E_0 \geq$ 5 PeV, initiated by protons and iron nuclei, and with a differential energy spectrum slope of -2.7, have been simulated. The CORSIKA version 5.644 (Heck et al., 1998) with the QGSJET model (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 λ_4 parameter was calculated and 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 specially flagged showers were selected. Grosso modo, showers with a high $<p_t>$ 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 selected 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 chosen is sensitive to such interactions. This gives a hint towards further investigations of the role of QCD jet production mechanism in the observed elongated hadronic shower cores in the KASCADE calorimeter.

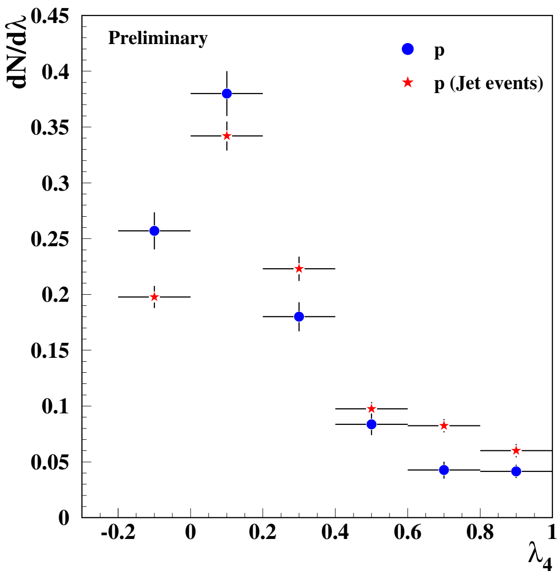

Fig. 6. Normalized distribution of a lambda parameter for simulated showers with a proton primary ($E_0 \geq 5$ PeV) for a standard QGSJet model and QGSJet where only events with jet production in the first interaction have been considered.

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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