Investigation of Geometrical Structures in the Hadronic Shower Core

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Abstract

The geometrical structure of high-energy hadrons in shower cores measured with the KASCADE calorimeter is analyzed. The angular correlation, especially the degree of alignment, is quantified by means of the commonly used parameter λ_4. The λ_4 distribution obtained by KASCADE is comparable to that derived by other experiments. The analysis shows that the observed λ_4 distribution is not linked to angular correlations due to jet production at high energies. The dependence on the transverse momentum p_t in the simulation of hadronic interactions is marginal. In contrast to λ_4, the maximum distance d_4^{max} between the most-energetic hadrons reveals a sensitivity both on p_t and the primary mass.

1. Introduction

High-energy hadrons in the cores of extensive air showers offer a unique possibility to study interaction features well beyond the kinematic and energy region of earthbound colliders. At primary energies around and above the *knee*, the observation of aligned structures in air showers has motivated many experimental and theoretical investigations, including discussions about sensitivity to specific interaction features as jet formation or hints to new physics (see e.g. [2,4] and references therein). The degree of alignment is commonly described by the parameter λ_4 quantifying the angular correlation between the four most-energetic

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particles (or particle families)

$$\lambda_4 = \frac{1}{24} \cdot \sum_{i \neq j \neq k}^{4} \cos 2\varphi_{ij}^k \quad (1)$$

where φ_{ij}^k denotes the angle between the connecting lines of hadron k to i and j. Possible values range between $\lambda_4 = -\frac{1}{3}$ (isotropic distribution) and $\lambda_4 = 1$ (perfect alignment). Events are usually termed "elongated" for $\lambda_4 \geq 0.8$. Another observable is the distance d_4^{max}, which is defined as the maximum distance between one of the four considered hadrons to the geometric center of the other three. As this quantity is correlated to the hadron lateral distribution, some sensitivity to hadronic interaction features can be expected. In the following, both observables will be analyzed using KASCADE [1] data and CORSIKA [5] simulations.

2. Data Preparation

The shower size, direction, and core position are determined by the KASCADE array. Only events with the core well contained in the hadron calorimeter [3] are accepted; additionally, at least four hadrons with energies ≥100 GeV have to be reconstructed. Using data from May 1998 to April 2001, 4489 events survived the cuts. After transformation to the shower plane, λ_4 is evaluated for each event. Simulations have been performed with CORSIKA using the QGSJET01 [7] hadronic interaction model for proton and iron induced showers for a primary energy slope of −2.7, followed by a detailed detector simulation.

3. Results

In Fig. 1a, good agreement of simulations and measurement can be seen, especially for elongated events. Despite the much smaller energy per nucleon in case of iron showers, no significant difference between proton and iron induced showers is observed. To investigate the correlation between λ_4 and jet production in high-energy interactions, the azimuth angles of the four hadron positions in each event were sampled randomly. The KASCADE data could be reproduced if the lateral distribution of these hadrons follows the measured one (see Fig. 1b, label "RANDOM"). More detailed studies revealed that even unphysical changes in p_t assumed in shower simulations for the secondary particle production only marginally influence the λ_4 distribution [6].

The λ_4 distributions measured by KASCADE and the emulsion chamber experiment PAMIR [2] agree to each other (Fig. 1c), although PAMIR is located at high altitude and the data refer to so-called "gamma families" with a higher energy threshold. Finally, within the statistical uncertainties no energy dependence of the rate of elongated events could be found (Fig. 1d).

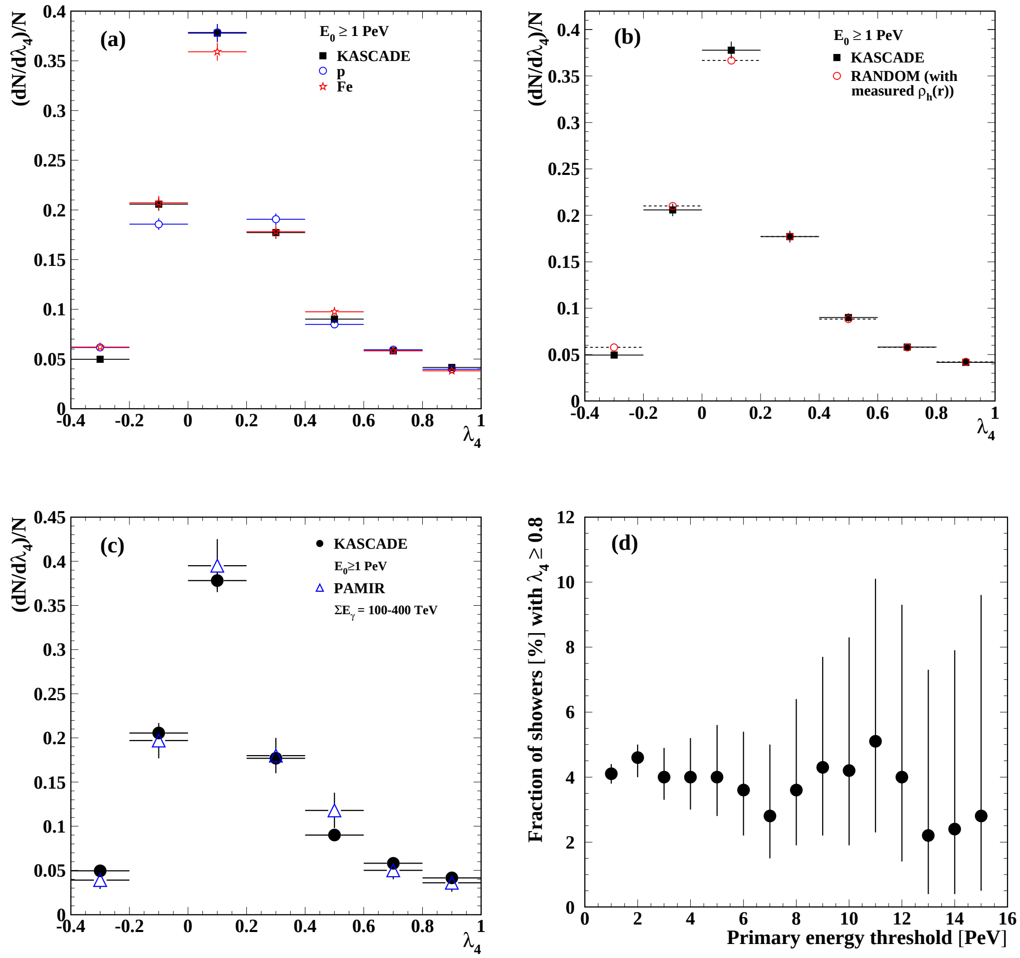

Fig. 1. λ_4 distributions: KASCADE data and (a) CORSIKA/QGSJET01 simulations for primary proton and iron showers, (b) random distribution based on the measured hadron lateral distribution, (c) PAMIR data [2]. In (d), the fraction of elongated events measured at KASCADE is plotted versus the primary energy.

The same KASCADE and CORSIKA data sets have been used to evaluate d_4^{max}. In Fig. 2a, the d_4^{max} distribution is given for the measurement and for simulations. The decrease towards larger d_4^{max} is enhanced by the limited detector size. A clear separation between proton and iron induced events is visible with the KASCADE data in between. The sensitivity of d_4^{max} to the primary mass can be used as cross-check of composition assumptions obtained for a given hadronic interaction model [6]. Moreover, d_4^{max} turned out to be quite sensitive to the p_t values employed in the hadron production. Simulation results are shown in Fig. 2b for a fixed primary energy of 5 PeV. Increasing (arbitrarily) p_t in secondary hadron production by a factor 2 clearly shifts the distributions towards larger d_4^{max} values. The average d_4^{max} values move for proton induced events from 3.4 m to 5.2 m and for iron induced showers from 4.8 m to 6.7 m.

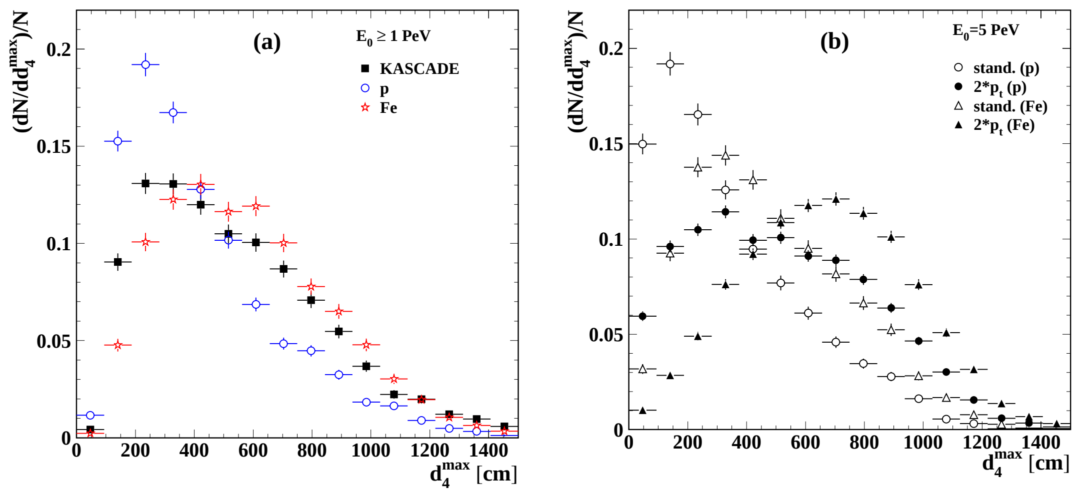

Fig. 2. d_4^{max} distributions: (a) KASCADE data compared with CORSIKA/QGSJET simulations for proton and iron showers, (b) CORSIKA simulations with standard and modified p_t (see text) for proton and iron showers of fixed primary energy.

4. Conclusion

The λ_4 distribution and the rate of elongated events of high-energy hadrons measured with KASCADE are well reproduced by simulations. They follow the expectations from a random azimuth distribution satisfying the measured hadron lateral distribution. No significant dependence on hadronic interaction features, in particular jet production at high energy, was found. No primary energy effect has been observed. In contrast, the d_4^{max} distribution is sensitive to the primary particle mass and the mean transverse momentum of secondaries in hadronic interactions. It can be used for consistency checks in composition analyses.

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References

1. Antoni T. et al., KASCADE Collaboration 2003, Nucl. Instr. Meth., submitted
2. Borisov A.S. et al. 1997, Nucl. Phys. B (Proc. Suppl.) 52B, 218; Capdevielle J.N., Slavatinsky S.A. 1999, Nucl. Phys. B (Proc. Suppl.) 75A, 12
3. Engler J. et al. 1999, Nucl. Instr. Meth. A 427, 528
4. Halzen F., Morris D.A. 1990, Phys. Rev. D 42, 1435
5. Heck D. et al. 1998, Report FZKA 6019, Forschungszentrum Karlsruhe
6. Iwan A. 2003, PhD thesis, University of Lodz (in Polish)
7. Kalmykov N.N. et al. 1997, Nucl. Phys. B (Proc. Suppl.) 52B, 17