Cosmic Ray Anisotropy with KASCADE

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Abstract

The anisotropy of cosmic rays with energies in the region of the knee in the energy spectrum is investigated in three different perspectives based on the arrival directions of about 150 Mio. extensive air showers measured by KASCADE. The different analyses are a harmonic analysis of the right ascension distribution and a point source search of showers above 0.5 PeV as well as an autocorrelation analysis of showers above 100 PeV. All three analyses agree inside the statistical limits with an isotropic distribution of the arrival directions of cosmic rays.

1. Introduction

The origin of the knee in the cosmic ray (CR) energy spectrum at about 4 PeV is still under discussion, various theories can be found in literature. Restrictions to these theories can be given by measurements of the anisotropy of the primary CR. While well below 0.5 PeV many experiments reported amplitudes of the first harmonic of the right ascension distribution of CRs of about 10^{-3} or lower [3], the measurements in the interesting knee region suffer from the low flux of CRs. Some theories also predict a mass dependent change of the amplitude and phase at the knee. Results of an analysis with KASCADE concerning this questions can be found in Chapter 3.

Since charged CR are deflected by the galactic magnetic field and photons are absorbed by the CMBR no point sources are expected to be seen in the

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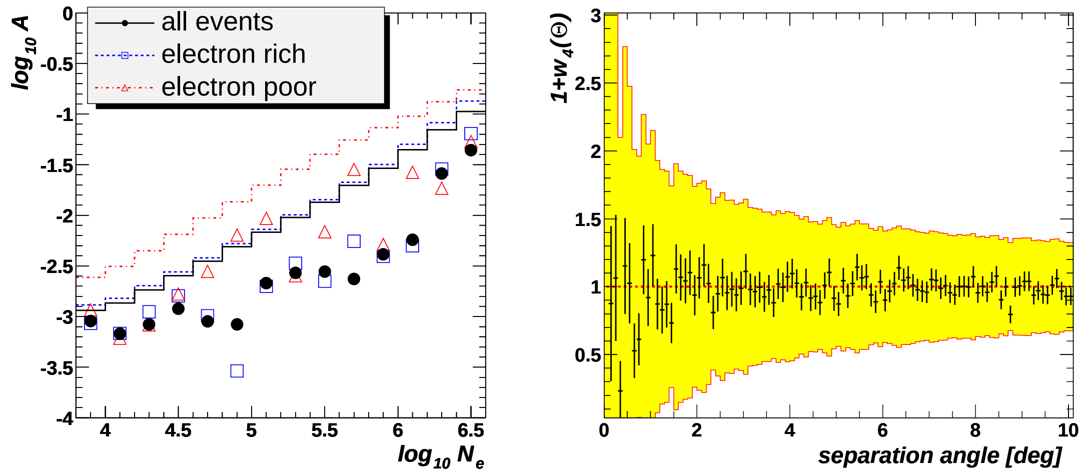

Fig. 1. Left: Rayleigh amplitudes. Right: autocorrelation of the 1000 largest showers.

considered energy region. At large energies the deflection in the magnetic field decreases substantially, point sources could there effect a clustering in the arrival directions. This will be investigated in Chapter 4 and 5.

2. KASCADE: Experiment and Reconstruction

The KASCADE experiment [1], located at the Forschungszentrum Karlsruhe, Germany (110 m a.s.l., 49.1° N, 8.4° E), is designed to measure extensive air showers (EAS) in the energy range of about 0.5 to 100 PeV. In the present analysis data from the 200x200 m^2 field array of KASCADE are used. Electron and muon numbers, shower core and shower direction of EAS are reconstructed from the energy deposits and arrival time measurements of the scintillator counters in the 252 detector stations. Shower directions, which are of particular interest in this anisotropy analyses, are determined by evaluating the arrival times of the first particle in each detector station and the total particle number per station. The reconstruction accuracy of the shower direction is steadily increasing with the number of electrons N_e per shower, from 0.5° at $\log_{10} N_e = 4$ to 0.1° at $\log_{10} N_e = 6$. A comparison with independent measurements from other detectors of KASCADE and Monte Carlo studies shows no systematic error in the reconstruction of the the shower direction. The data set of about 150 Mio. showers was recorded on 1400 days of operation between May 1998 and December 2002

3. Large Scale Anisotropy - Harmonic Analysis

The large scale anisotropy is investigated by the Rayleigh formalism [6], which delivers beside the amplitude A and phase Φ of the first harmonic of the arrival direction distribution in right ascension α also an estimate of the probability $P_{fluc}(n, A)$ of measuring a random fluctuation from a uniform distribution in α with n events. The amplitude A and phase Φ are influenced by changes in the event rate, e.g. by interruptions in the data taking, or atmospheric influences. To minimize these effects, only data taken over full sidereal days with all detector stations of the field array running are considered. This reduces the number of events in this analysis by about a factor of five corresponding then to 300 sideral days of operational time. To check for a correlation of the amplitude A with the primary mass, the data is divided into electron rich (preferentially light primaries) and electron poor (preferentially heavy primaries) events by a simple linear cut in the muon to electron size ratio at a value of $\log_{10} N_{\mu,tr}/\log_{10} N_e = 0.78$. Fig. 1 (left) shows the amplitude A of the first harmonic for the whole data set (filled points), electron rich showers (open squares) and electron poor showers (open triangles) as a function of electron size N_e (covering an energy range of $E_0 \approx 5 \cdot 10^{14} - 5 \cdot 10^{16}$ eV, the knee position is in the region of $\log_{10} N_e \approx 5.2 - 5.8$). The lines show the 90% confidence limit of $1 - P_{fluc}$. From these lines, the level of sensitivity to large scale anisotropy can be seen. All amplitudes in the three data samples are well consistent with fluctuations from a uniform distribution, no significant large scale anisotropy can be seen.

4. Autocorrelation of EAS above 100 PeV

The 1000 largest EAS by muon size ($\log_{10} N_{\mu,tr} > 5.4$) measured by the KASCADE experiment correspond to primary CR energies around 100 PeV. A possible clustering of these EAS is analyzed using an estimator of the autocorrelation function according to [4]. It describes essentially the ratio of the probabilities of finding a pair of showers separated by a certain angular distance Θ in the measured data set and the one derived from an isotropic distribution: $1 + w_4(\Theta) = (DD - 2DR - RR)/RR$. DD, DR, RR denote the angular distance distributions of data-data, data-random and random-random events. To reproduce an isotropic background, random directions R are generated from the measured directions D using the shuffling technique [2], averaging over 1000 new artificial data samples. Fig. 1 (right) shows the $1 + w_4(\Theta)$ distribution. No significant deviation from the isotropic expectation which is exactly one can be seen. All points are well inside the estimation of the five sigma confidence area indicated by the shaded region.

5. Small Scale Anisotropy - Point Source Search

Small scale anisotropy is studied by comparing the measured arrival direction distributions in equatorial coordinates with an estimation of an isotropic background distribution. This background distribution is generated using again the shuffling technique averaging over 50 new artificial data samples. Significance maps with a bin size of 0.5° are generated from the deviations between these distributions using the formalism of Li and Ma [5] for different data cuts. Fig. 2 shows the distributions of significance from these maps for the visible sky

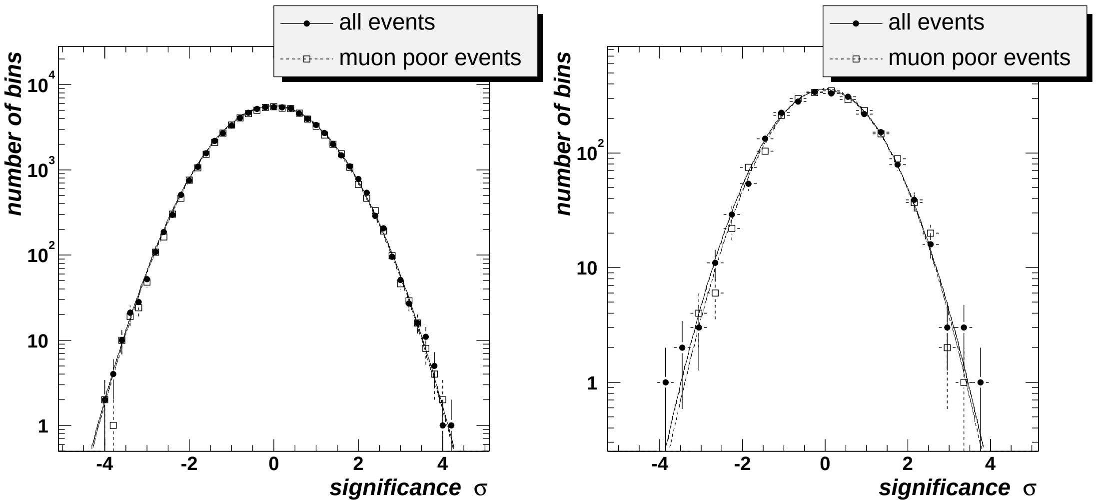

Fig. 2. Significance distribution of the visible sky of KASCADE (left) and of the sky inside a band of 6° around the galactic plane (right).

of KASCADE (left) and a band of 3° width around the galactic plane (right) for all events (filled squares) and a data sample of muon poor EAS ($N_\mu/N_e < 0.01$, open squares). This cut enhances the number of gamma ray shower candidates in the sample. Any deviation from isotropy would result in a distorted Gaussian distribution $N(0,1)$. Fits to the data points, indicated by the lines in Fig. 2, show a very good agreement of all four distributions with $N(0,1)$. Calculation of 90% upper flux limits for point source events yield values between $7 \cdot 10^{-11}$ and $1.5 \cdot 10^{-10}$ m^{-2} s^{-1} depending on declination and the applied data cut.

6. Conclusion

We present KASCADE results on anisotropy measurements of CRs with primary energies in the PeV region. An 90% upper limit of $A \approx 10^{-3} - 10^{-2}$ depending on the size and the primary mass of the EAS for the first harmonic amplitude of the right ascension distribution is given. The autocorrelation function of EAS with energies around 100 PeV is consistent with an isotropic distribution. No hints for point sources in the visible sky of KASCADE or an enhancement of the flux of CRs from the galactic plane is visible in the analyzed data sample, upper flux limits are determined to be below 10^{-10} m^{-2} s^{-1}.

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