Design and Performance of the Lead-Concrete Geiger Tower Array within the HEGRA Experiment

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Abstract

The HEGRA experiment is a hybrid installation characterized by four different types of detectors (scintillator counters, open Čerenkov counters, Čerenkov telescopes and Geiger towers) located within one detector array. The Geiger towers are built with the objective to measure the local energy deposition and to reconstruct and identify muon tracks. In addition each tower may serve as an independent high resolution muon flux monitor. With these properties the Geiger towers are operating as geometric and energetic calibration instruments for the other detector components and as additional independent measurement instruments with respect to the γ-hadron separation and the measurement of the chemical composition. In this paper the design, the performance, and the basic principles of the data analysis of the lead-concrete Geiger towers are described.

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1 Introduction

Among the primary aims of the HEGRA (High Energy Gamma Ray Astronomy) experiment located at the ORM (Observatorio de Roque de Los Muchachos) La Palma (Canary Islands, Spain) are the detection of directed and diffuse cosmic γ radiation, the measurement of the chemical composition, and the observation of time-variations in any of the cosmic ray components. For this purpose the HEGRA detector (Fig.1) is being built on the Roque de Los Muchachos at an altitude of 2200 m a.s.l. as a multicomponent detector on an array of 180×180 m^2 with a total coverage of about 3%. The assembly of the final HEGRA array [1] was carried out during the last three years and will be finished in Summer 1996. During this phase the detector was already taking data for detector studies and physics analyses. Presently four different types of detectors are involved in continuous data taking. With three (finally five) Čerenkov telescopes (and one prototype) [2] a search for high energy photon point sources is performed with a photon energy threshold of less than 1 TeV. The search is guided by theoretical expectations and low energy satellite observations [3]. A matrix of scintillator counters [7] [4] measures the direction and lateral particle distribution of air showers with a primary γ energy threshold of 35 TeV, while the matrix of open Čerenkov counters (AIROBICC) [8] [5] contributes a measurement of the shower direction and the light distribution with an energy threshold for primary γ's of 14 TeV. Finally matrix of 17 tracking calorimeters (Geiger towers) with a spacing of 30 m is designed for the measurement of the electron and muon content, the energy distribution, and the direction of the shower. With respect to the development of an air shower this sub array is working as a tail catcher calorimeter. In contrast to the other components the Geiger towers do not contribute to the trigger.
With the combination of detectors realized in HEGRA thus a variety of properties of each shower are measured. Due to independent measurements of identical or closely related quantities consistency checks of the relevant properties are provided. In the case of the Geiger towers the determination of the shower direction by reconstructing muon tracks can be compared to results of the other three detector components. In addition the determination of deposited electromagnetic energy can be related to the measurement of the scintillator

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[8] 49 for the analysis presented here, finally 85

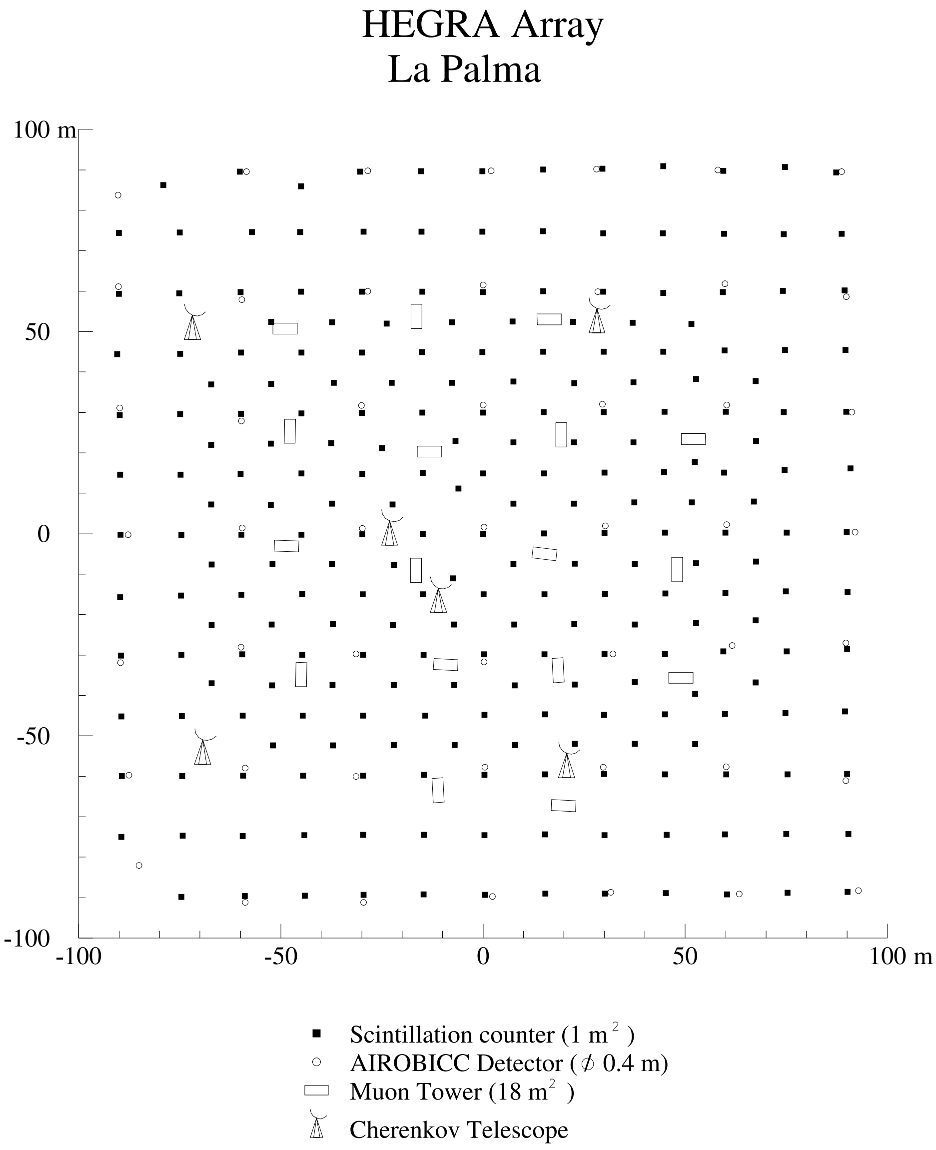

Fig. 1. Present layout of the HEGRA detector array at La Palma.

matrix.

This paper is organized as follows. In chapter 2 the function principle, the hardware and the readout system of the Geiger towers are presented. The Monte Carlo simulation of this detector component is described in chapter 3. The basic analysis procedure and the related detector performance are discussed in the sections 4.1 to 4.3 and in section 4.4 a general comparison of experimental and Monte Carlo data in terms of the output of a neural net used for the physics analysis is presented.

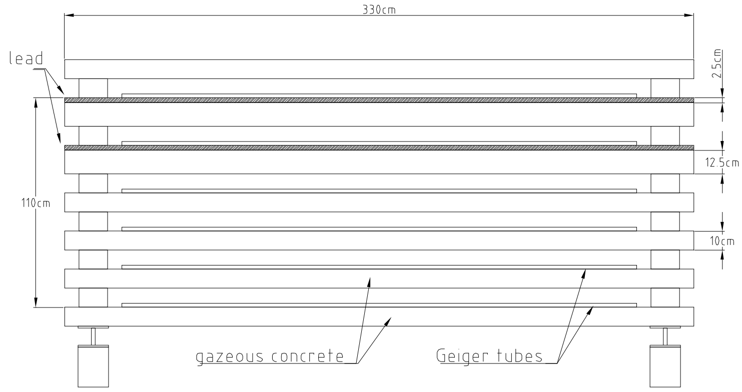

Fig. 2. Front view of a Geiger tower.

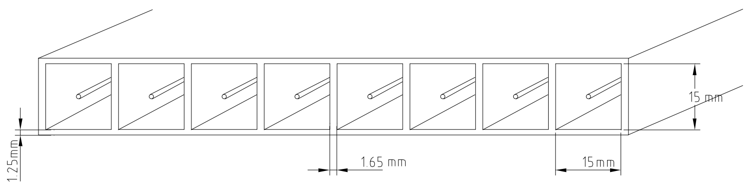

Fig. 3. Cross section of a Geiger octotube.

2 Function Principle, Hardware and Readout

Each Geiger tower consists of six planes of Geiger tubes placed in a support structure of gaseous concrete ($\rho = 0.8$ g/cm^3) and has an active surface of about 16 m^2 (Fig.2). The upper two planes are each followed by a layer of 2.5 cm (4.5 radiation lengths) of lead. The distance between planes amounts to about 20 cm. Each plane measures 6.0×2.73 m^2 and consists of 160 aluminium Geiger tubes with a length of 6 m and an inner quadratic profile of 1.5×1.5 cm^2 (Fig.3) each. Due to their multi-layer structure and the rather large active area, the hit information in the 6 layers of each tower provides information about particle density and energy distribution in different distances to the shower core. According to their geometrical setup the Geiger towers may be divided into two different function zones. With the lead layers below the first and second Geiger plane, the upper planes work as a calorimeter, while the lower planes serve to reconstruct directed information such as tracks of muons or tracks of a small amount of remaining hadrons and of hit pattern of electron

Fig. 4. Typical event as seen by the Geiger tower array. The light and shaded towers are oriented orthogonally to each other. The shower core is located near tower 6, reconstructed tracks are indicated by a line in the towers 8 and 12.

or photon induced showers classified as tracks (see sect. 4.1) (Fig.4).

A central mixing facility supplies the Geiger towers via a net of copper tubes with a gas mixture of 98.9% Argon, 1.0% Propane and 0.1% Freon. The system is kept under pressure to avoid air penetration and the flow rate is 6 l/h per row of 320 Geiger tubes (two planes) connected sequentially. On one side of the tower the gas connections for the Geiger tubes and on the opposite side the readout electronic and its power supply are located. A positive high voltage of about 1150 V is supplied to the wire through the electronic readout board which receives the Geiger pulse obtained on the wire through a coupling capacitor. This voltage leads to a current of about 1 μA per Geiger tube. To protect the interior setup of the tower blinds on the frontages, roofing material on the top, and metal shields on the sides have been installed. Like the

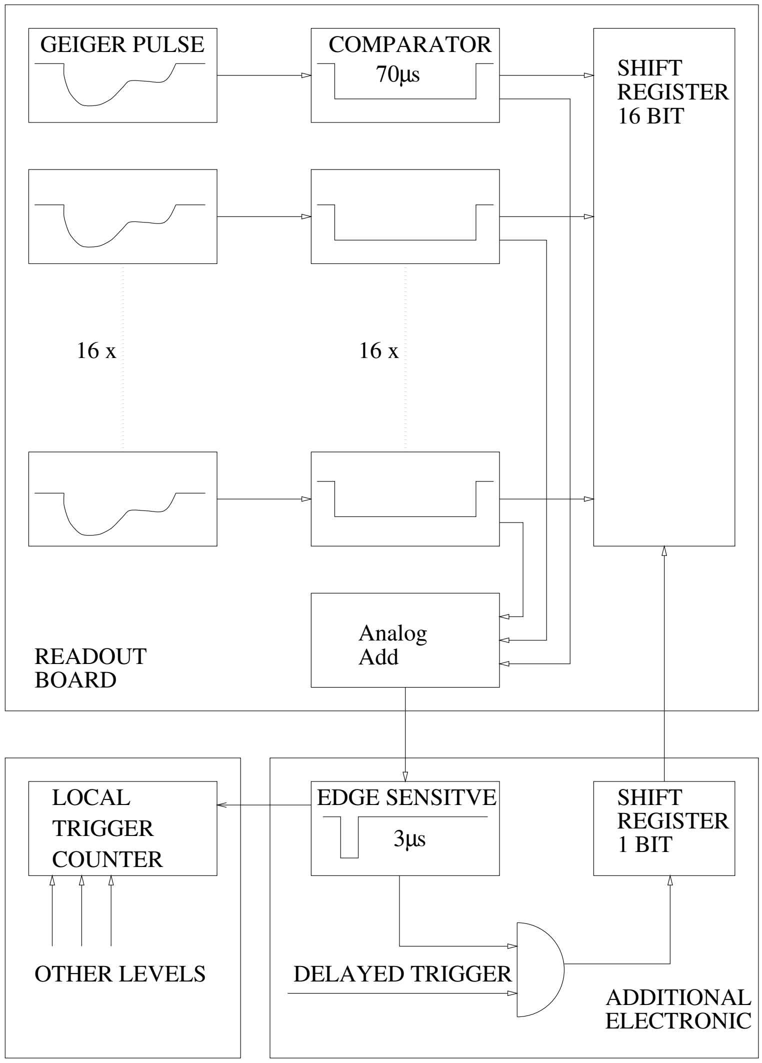

Fig. 5. Schematic drawing of the readout logic.

Geiger tubes the readout boards have been taken from the Fréjus underground detector after its shutdown. A detailed description of these components can be found in [6].

To adapt the readout system which was designed for low fluxes of charged particles and respective low trigger rates to the high readout rates in a surface experiment, the original Geiger pulse level controlled system is supplemented by an edge sensitive secondary readout electronic. (Fig.5)

The original 16 channel readout board applies a voltage level to the parallel input of a CMOS shift register for the duration of a Geiger pulse (approx. 70 μs) and also sends a current signal of standard amplitude to a 16 channel summing network (on board). This signal is used by the new edge sensitive secondary 10 channel readout board which supplies a signal for the duration of 3 μs after the starting edge of each Geiger pulse of this board. If this signal is in

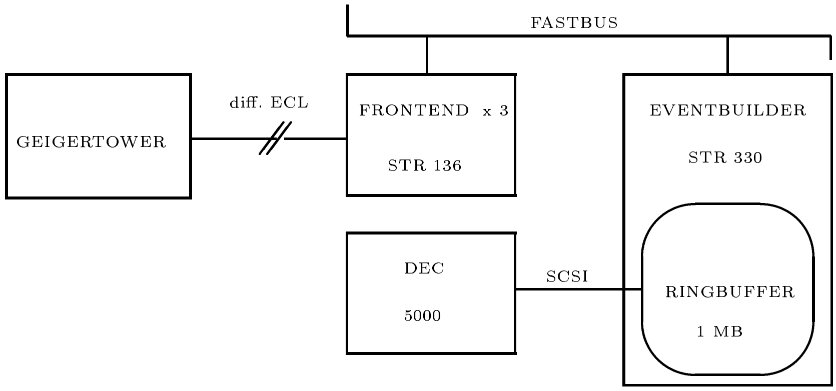

Fig. 6. Schematic drawing of the readout system.

coincidence with the (delayed) trigger pulse from the other sub arrays a voltage level is applied to the parallel input of an additional CMOS shift register. Therefore the total readout electronic system consists of $(10 \times 16 + 10) = 170$ channels per plane. The combination of both systems enables the shortening of the sensitive time period from 70 μs to 3 μs and thus the reduction of accidental background hits by a factor of 23.

If at least three of the four lower planes simultaneously show the 3 μs signal provided each time one of the Geiger tubes of a certain plane has fired, a local trigger pulse is counted per tower by an independent readout system. The condition is fulfilled with a rate of about 2.5 kHz mainly due to single muons (66%) with an energy above 300 MeV. The remaining flux is composed of hadrons, electrons, and photons. The rate corresponds to an integral muon flux of 0.58 ± 0.05 (min cm^2 sr)$^{-1}$ in one tower while a flux of 0.53 ± 0.02 (min cm^2 sr)$^{-1}$ is expected at an altitude of 2200 m due to Monte Carlo based interpolation of measurements at 0 m and 3000 m [7]. The measured flux is sensitive to atmospheric conditions like pressure (measured: (-0.08 ± 0.01)%/mBar), negative (measured: (-0.1 ± 0.03)%/C°) and positive temperature effect [8], as well as the working parameters of the Geiger tubes (gas composition, gas flow, and high voltage), so that this rate monitors the quality of each tower continuously.

The data are read out using a FASTBUS system in combination with a DECstation 5000/20 as controlling and monitoring device (Fig.6). The FASTBUS system consists of two DATA latches STR 136, one CONTROL latch STR 136 and a FASTBUS master CHIPS. Each of the 102 Geiger planes is connected to one of the DATA latches. The CONTROL latch handles the serial read out of the 170 channels per plane. The data are stored in the triple ported RAM of the FASTBUS master which is organized as a ring buffer. The ports are the (unused) FASTBUS-slave port of the STR 330 and an special IO port (X-bus) used for SCSI communication. Furthermore a portion of the address space of the STR 330 is used for data transfer to the DEC Station without applying load to the STR 330. The dead time ranges from 1 to 4 msec per event depending on the size of the event. This leads to a maximal trigger rate of about 200 Hz. A typical HEGRA trigger rate of 20 Hz yields about 600 MByte of Geiger tower data per day.

As control facility for each trigger the signal from each single tube is added and the sum displayed continuously for all towers and finally stored with the data. Malfunctions can thus be detected and removed by the operator and inefficient or noisy Geiger tubes can be easily detected in the software data analysis. It should be pointed out that by this setup per tower only a two dimensional projection of each shower is recorded. As neighbouring Geiger towers are oriented orthogonal to each other, for muon rich showers also a quasi three dimensional reconstruction is possible.

3 Monte Carlo Simulations

The Geiger towers are simulated by a detector Monte Carlo program based on the GEANT 3.21 [9] code. The data taken with the Fréjus test detector (an iron sampling calorimeter with a similar structure as the Geiger towers) when calibrated in the electron and hadron beams at DESY and Bonn were used to check the reliability of the Monte Carlo code. Furthermore the test detector data was modelled by a second independent Monte Carlo program based on the EGS code [10] with a special treatment of low energetic particles. Good agreement of the test detector response and the two different Monte Carlo calculations (Fig.7) was obtained. Based on this the number of Geiger tower tubes fired by single particles of an electromagnetic shower was calculated in dependence on their energy. The incident angle of the electrons was randomly distributed between 0° and 30°. It was found that the detector response is nearly linear between 50 MeV and 2 GeV. At higher energies saturation of the Geiger cells and geometric (side and rear) leakage effects set in. The corresponding energy resolution is basically determined by statistical fluctuations of the number of hits at a given particle energy leading to a $1/\sqrt{E}$ behaviour. Saturation and leakage effects are forcing the resolution to converge to a constant value. The energy resolution can be described with an accuracy of about 30% up to 5 GeV by

$$\frac{\sigma_E}{E} = A + \frac{1}{B \cdot E^C} \tag{1}$$

with $A = 0.10 \pm 0.03$, $B = 0.12 \pm 0.01$ and $C = 0.49 \pm 0.02$.

While the investigation of single particles served to examine the Monte Carlo description of single Geiger towers, the following comparison between the full Monte Carlo expectation for air showers and the measured data aims at a determination of their physical applicability. With the air shower Monte Carlo

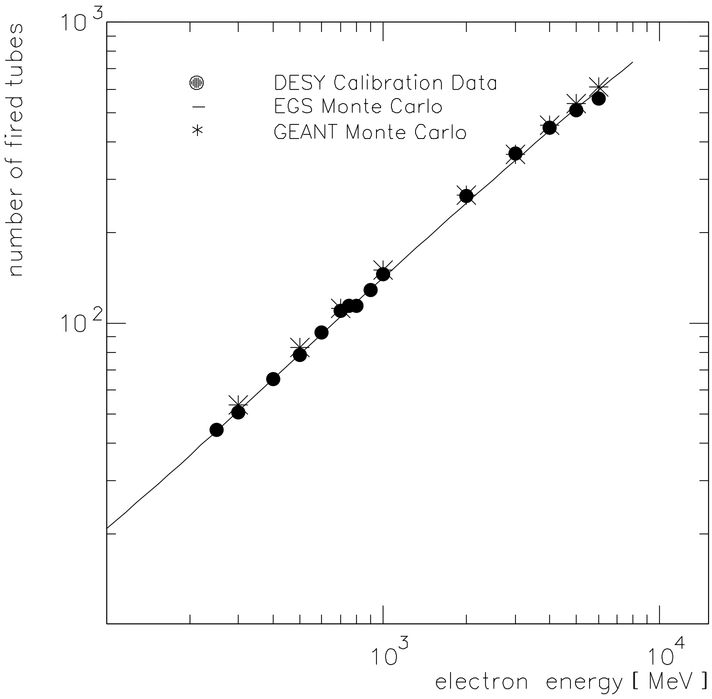

Fig. 7. The detector response of the test detector as measured at the electron beam at DESY including the two independent Monte Carlo calculations.

generator CORSIKA [11] hadron induced air showers with energies between 5 TeV and 10 PeV and zenith angles between 0° and 30° were generated taking into consideration the chemical composition and the power laws describing the energy dependence as given in [12]. The particle output of this program was tracked by the detector Monte Carlo. In analogy to the single electron case the total deposited electromagnetic energy inside each Geiger tower, which in this case is composed of the contributions of many low energetic particles, can be reconstructed with an accuracy of $\frac{\sigma_E}{E} = 40\%$ (Fig.8). Due to the large area covered by the Geiger towers the energy contained in the shower tails at the altitude of the HEGRA array can be determined with an accuracy of about 20%.

To check the compatibility of the combined CORSIKA and detector Monte Carlo calculations with experimental data, we examined the Geiger tower response for events with at least 13 triggered scintillator huts and core positions reconstructed in an area of 100×100 m^2 around the array centre. In Fig.9 (a-c) the mean number of hits in the first, second, and third-to-sixth plane per tower are shown as a function of showercore distance. In Fig.9 (d) the mean number of reconstructed tracks per Geiger tower is shown. Experimental data and Monte Carlo calculations are in good agreement.

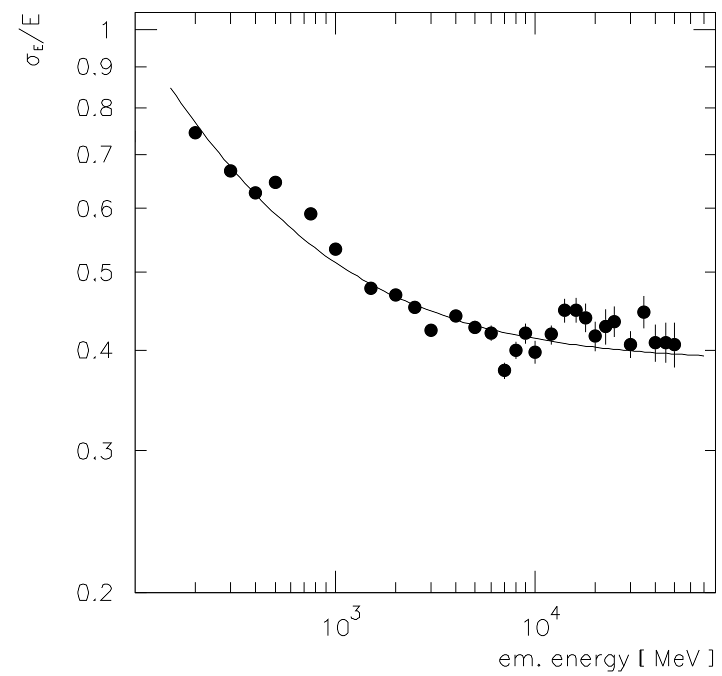

Fig. 8. The energy resolution of a single Geiger tower in case of incoming air showers.

As a further check the lateral distributions of the electron and muon component measured with the Geiger towers can be related to scintillator data. The measured number of hits in the first plane of the Geiger towers is compared to the result of the NKG (Nishimura - Kamata - Greisen) approximation [13]

$$\rho_e(N, r, s) \;=\; \frac{\Gamma(4.5 - s)}{2\pi\ \Gamma(s)\ \Gamma(4.5 - 2s)} \quad \frac{N}{r_m^2} \quad \left(\frac{r}{r_m}\right)^{s-2} \quad \left(1 + \frac{r}{r_m}\right)^{s-4.5} \tag{2}$$

which describes the lateral distribution of electromagnetic particles in the shower front if shower size N and age parameter s are both determined with the scintillator array; r denotes the distance from the core position and r_m the Molière radius in air at the HEGRA site (103 m). Both distributions are found to be in good agreement (Fig.10). To allow the identification of N with the number of hits in the first plane without taking into account saturation effects, this comparison is restricted to showers with $N < 10^4$, since an extension of N enlarges the saturated region near the shower core. The agreement implies that separate determinations of shower size and age parameter are possible with the Geiger tower array.

The measured lateral distribution of muons follows the equation given by Greisen [13] (see Fig.10)

$$\rho_\mu(N, r) \;\sim \left(\frac{N}{10^6}\right)^{0.75} \; r^{-0.75} \; \left(1 + \frac{r}{320}\right)^{-2.5} \tag{3}$$

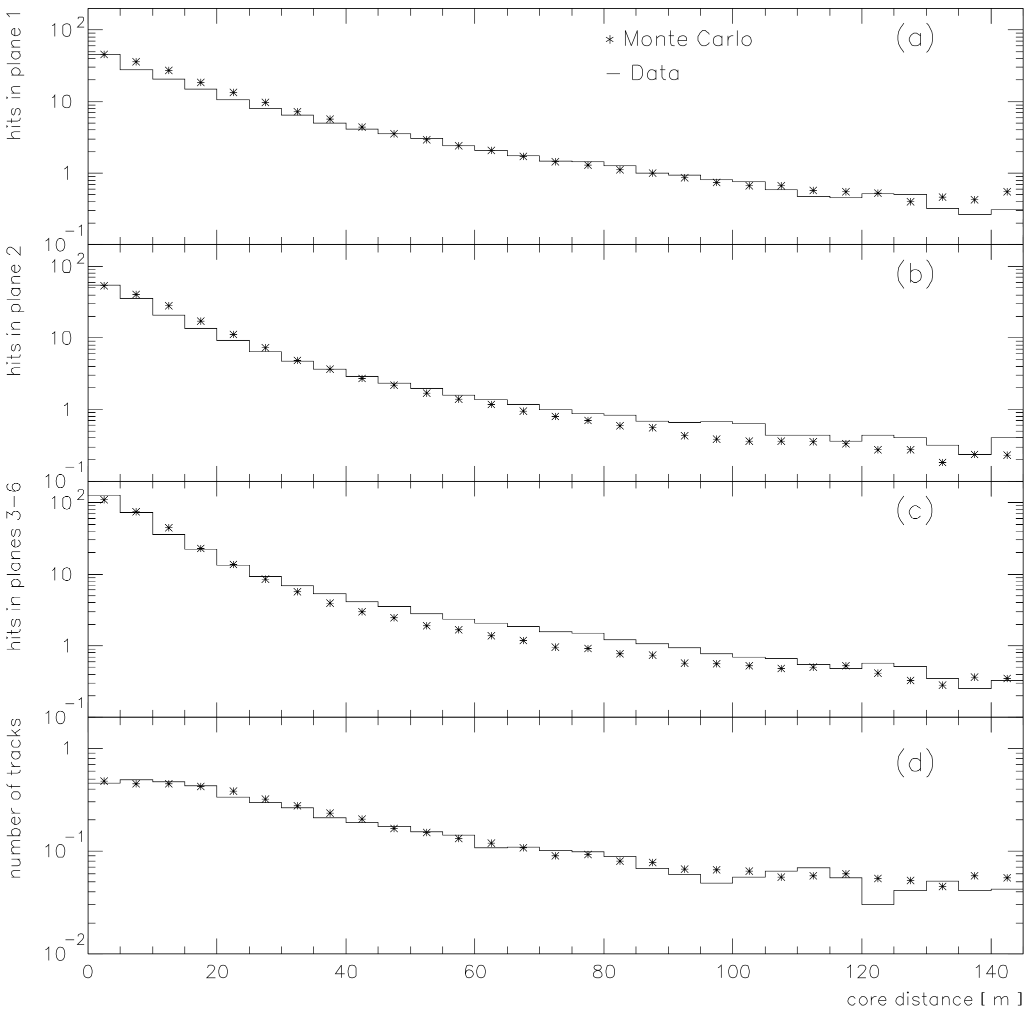

Fig. 9. (a) The mean number of hits in the first plane, (b) the mean number of hits in the second plane, (c) the mean number of hits in the third to sixth plane, and (d) the mean number of tracks per tower are shown for data and Monte Carlo as a function of the core distance.

where the parameters N and r are extracted from scintillator data.

4 Data Analysis and Detector Performance

4.1 Reconstruction of secondary particles

A distinct characteristics of the Geiger towers is the ability to trace secondary particles and to determine their identity to a certain extend. For each Geiger tower tracks are found by applying the following algorithm to the recorded

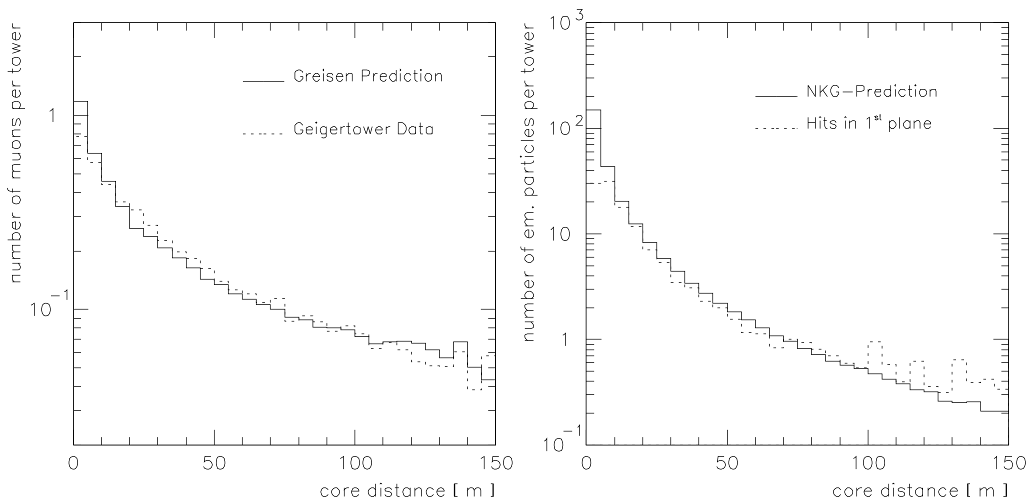

Fig. 10. A comparison between the measured number of muons and the measured number of hits in the first Geiger tower plane, and the expectation based on the measurements of the scintillator array and theoretical approximations.

hit pattern: Adjacent hits separated by not more than one Geiger tube form a so-called cluster with an assigned error corresponding to the cluster width. Looping over all pairs of clusters and requiring at least four clusters to lie on a straight line all track candidates are determined. In the next step all track candidates are fitted using weighted linear regression. In order to reject fake tracks which share more than one cluster with other track candidates, the actual number of clusters per track and the χ^2 value are evaluated and compared.

Obviously the track reconstruction efficiency of secondary particles, *e.g.* penetrating muons, depends on the complexity of the hit pattern. Due to high particle densities saturation effects in a tower located close to the shower core may conceal the clear features of penetrating particles. The reconstruction efficiency is therefore an increasing function of core distance due to the rapid fall of the electromagnetic particle density (Fig.11). Since the experimental setup and the search algorithm is optimized for muons, it is interesting to study the muon purity for a set of reconstructed tracks. This has been done for proton showers with energies above 30 TeV and a spectral index of 2.7. As shown in the inset of Fig.11 the muon purity is increasing with core distance while the fraction of fake tracks dominates the core region due to the decreasing particle density. The fraction of electromagnetic sub showers within the Geiger towers causing a track-like hit pattern decreases with the core distance due to their strong correlation with the shower core.
Although unspecific track reconstruction is aimed for (see sect. 4.4), one can use the detailed hit pattern to distinguish between muons and other tracks. For this purpose we use a feed-forward neural net [14] with an 18-15-1 geometry. The input parameters are the cluster width (6 parameters), the cluster

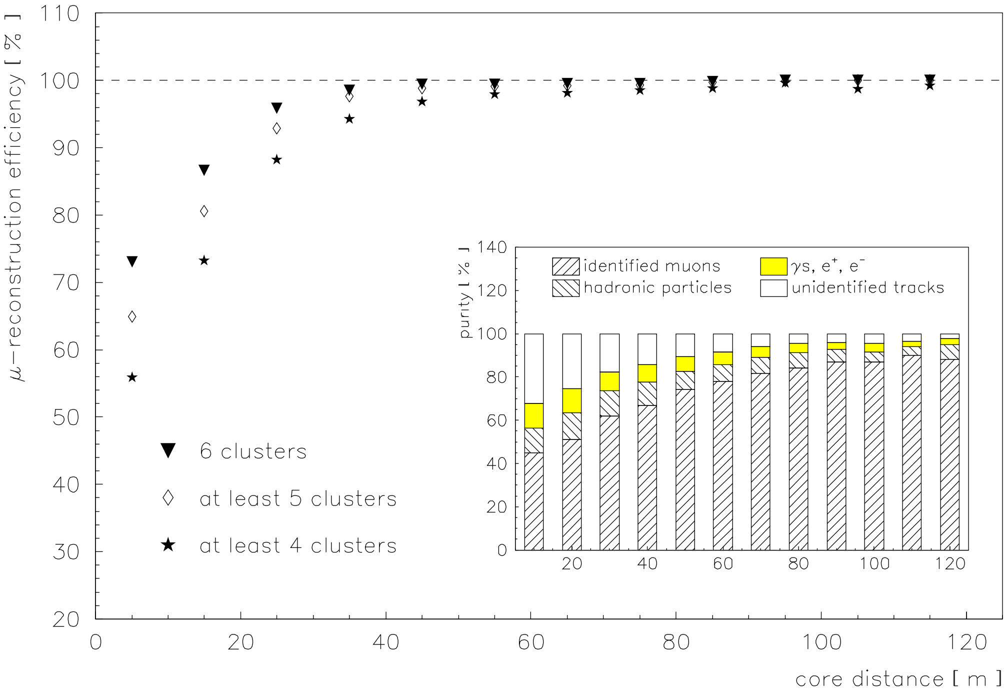

Fig. 11. Reconstruction efficiency as a function of the core distance r_c. The number of clusters defining a track can vary from 4 to 6. In the Monte Carlo calculations proton showers in the energy range from 30 TeV to 500 TeV and with a differential spectral index of 2.7 were used. The inset shows the fractions of different particle species for all reconstructed tracks as a function of r_c.

residua (6) being the distance between the center of a cluster and the fitted track position, the multiple scattering angles (5), and the final track angle with respect to the zenith (1). The numbers in brackets correspond to the maximum number of input parameters. The separation power plotted in Fig.12 reaches 82% for the optimal cut value of $v_{\rm opt} = 0.51$ for which the muon efficiency is still 85%.

4.2 Direction Measurement

The distribution of the directions of secondary muons is peaked around the direction of their primary particle. Using muon tracks reconstructed in the Geiger towers, the HEGRA experiment has the unique possibility to cross-check the absolute pointing of its four components based on the pure geometry of the Geiger towers. For this purpose the difference between the (projected) direction of a muon-like particle and (a) the direction of the shower axis in Monte Carlo calculations, (b) the direction from AIROBICC data reconstruction, (c) the direction from scintillator data reconstruction, and (d)

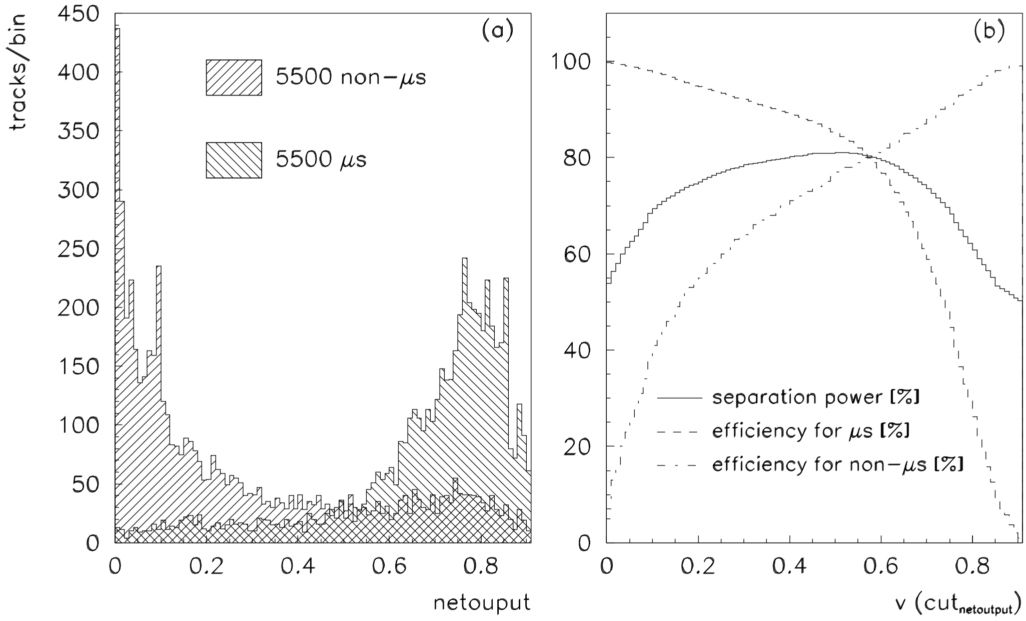

Fig. 12. (a) shows the output of the neural net for 5500 μ and 5500 non-μ tracks (including fake tracks). Defining v as a cut on the net, (a) is used to determine the separation power of the neural net approach and the individual efficiencies for muon- and non-muon tracks in (b). The optimal cut value is $v_{\rm opt} = 0.51$.

Table 1
Projected directions of different HEGRA detector components

Detector	Width (σ) [°]	$\delta\sigma$ [°]	Shift (d) [°]	δd [°]
AIROBICC	1.2	0.014	0.02	0.01
SCINTILLATOR	1.4	0.02	0.21	0.02
Č-Telescopes	2.1	0.11	0.7	0.08
Monte Carlo	0.8	0.01	0.01	0.01

the nominal Čerenkov telescope direction are investigated (Fig.13). While the peak area is fitted by a Gaussian the background can be well described by a second order polynomial. The results are in acceptable agreement with the expectation, though Tab.1 shows that for the case of a comparison with the scintillator array and the telescope directions systematic effects have to be investigated [9] . The multiple determination of the shower direction allows systematic checks of the accuracy of single detector components which might be influenced by systematic effects in each component and facilitates the location of errors. Moreover, it is possible to offline verify the telescope pointing.

[9] In Table 1 only statistical errors are given

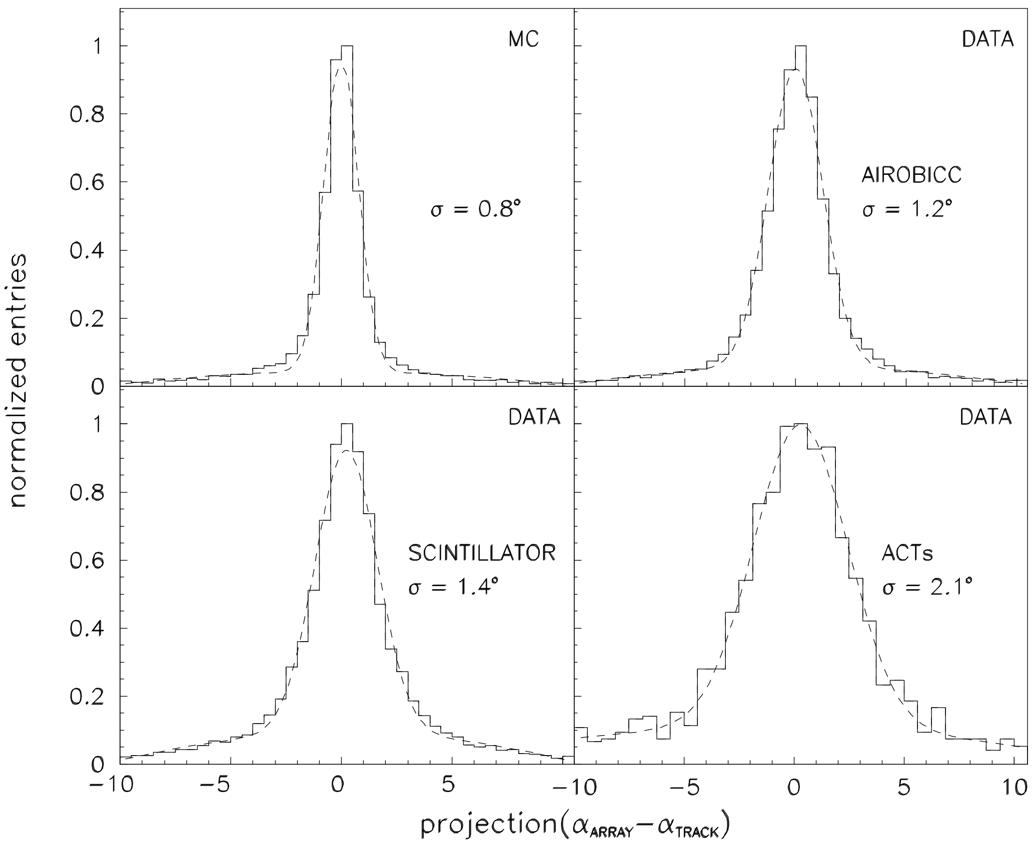

Fig. 13. The air shower directions as measured by different detector components are projected into the Geiger towers and compared with the reconstructed tracks for which we require at least four hits flagged by the edge sensitive readout electronic and a track quality value better than $v_{\rm opt} = 0.51$.

4.3 Core Determination

A further application of the neural net technique to the Geiger tower hit information shows that even the rather small number of 17 towers allows a reconstruction of the shower core with good accuracy.
We use a Monte Carlo trained neural net (NN) [14] as a plain fitting machine with a linear activation function between the hidden and output layer to obtain the x- and y-position of the shower core as desired output. For this 51-10-2 net the number of hits in the first and second layer and the averaged number of hits in the lower four layers are used as input information. After 500 training cycles using 2000 proton showers with the shower core randomly distributed over the array, the net reconstructs the core position of 3000 test showers with an accuracy of $\sigma \simeq 10\,\mathrm{m}$. The result is shown in Fig.14 for both Monte Carlo data, where the shower core position is *a priori* known, and experimental data, where the core position is taken from the scintillator array

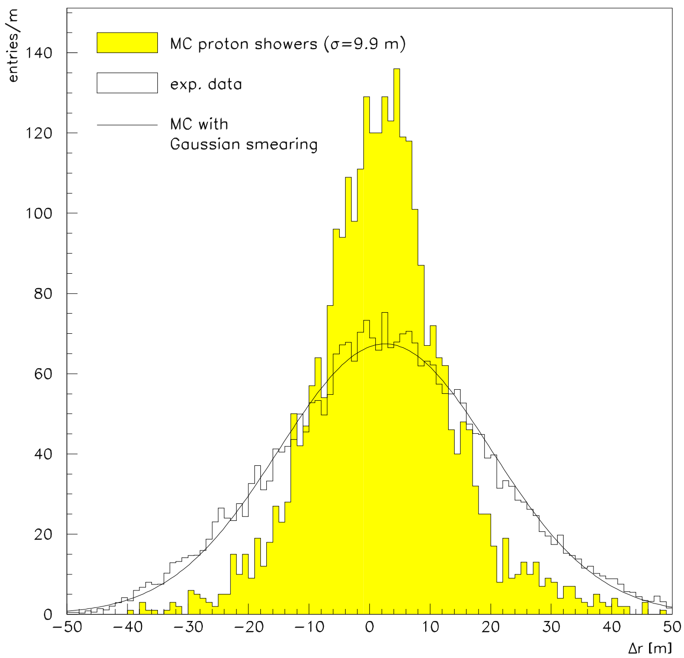

Fig. 14. The performance of the 51-17-2 net used as a plain fitting machine for shower core determination is shown. Δr is the residual difference between the reconstructed and the exact core position (Monte Carlo data) resp. the core position as reconstructed by the scintillator array (exp. data). The solid curve shows the expected residuum for a resolution of 7.7 m of the scintillator and 9.9 m of the Geiger tower array.

reconstruction. The Gaussian distribution of the Monte Carlo data (hatched) accurately fits the Gaussian distribution of the experimental data (histogram) after smearing it with the expected scintillator core reconstruction error of $\sigma = 7.7$m.

4.4 γ-hadron separation

Due to the rather small detector sampling density the number of detectable muons (3 to 4 per hadronic shower) is too small for a sufficient stand alone hadron shower suppression. It is one of the main advantages of the Geiger tower array that it also measures particle density and energy distribution in different distances to the shower core, i.e. a calorimetric shower information. Furthermore high energy ($E > 250$MeV) $e^{\pm}$ and converting γs outside the shower core region ($r \geq 30\,$m), which both are reconstructed as punch through tracks, are strong indicators of hadron induced showers. Evaluating

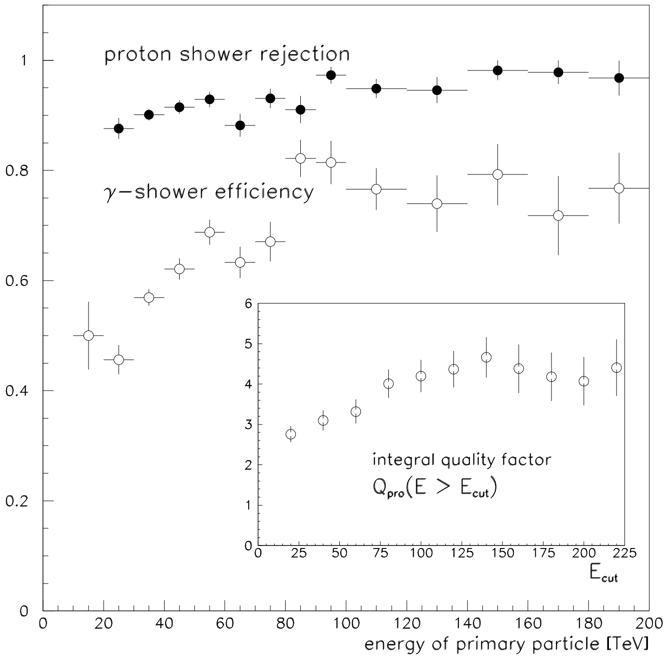

Fig. 15. Results of neural net analysis: γ-shower efficiency, proton shower rejection, and quality factor (inset) as a function of the primary particle's energy.

all available information, the Geiger towers allow a γ-hadron separation which considerably goes beyond ordinary muon counting [15].
This is again facilitated by a Monte Carlo trained feed-forward neural net [14]. In addition to the input values given above the number of tracks per tower are used as additional information. The net is trained to give the desired output "0" for γ and "1" for hadron-induced showers. Fig.15 shows the γ-shower efficiency and proton shower rejection as a function of the energy of the primary particle. This is achieved by the 68-17-1 net trained with a set of 1500 proton and 1500 γ-induced showers after a full detector simulation. For testing the net 4500 independent showers of each class are used.

Note that a NN trained to reject proton showers also rejects showers induced by heavy nuclei: the rejection power increases with increasing atomic weight (see [15] for a detailed description of this NN analysis).
It can further be shown that the γ-hadron separation based on Geiger tower data in fact intrinsically uses the reconstructed shower core position [15]. Application of γ-hadron separation increases the significance of excesses from point sources by a *quality factor* Q defined as $Q = \epsilon_\gamma/\sqrt{\epsilon_{\rm had}}$, where ϵ_γ and $\epsilon_{\rm had}$ are the fractions of γ and hadron showers passing the selection. The inset of Fig.15 shows the integral quality factor $Q_{pro}(E > E_{cut})$ for the separation of proton and γ-showers as a function of the lower energy boundary. In the relevant energy range between 30 and 500 TeV the net analysis leads to

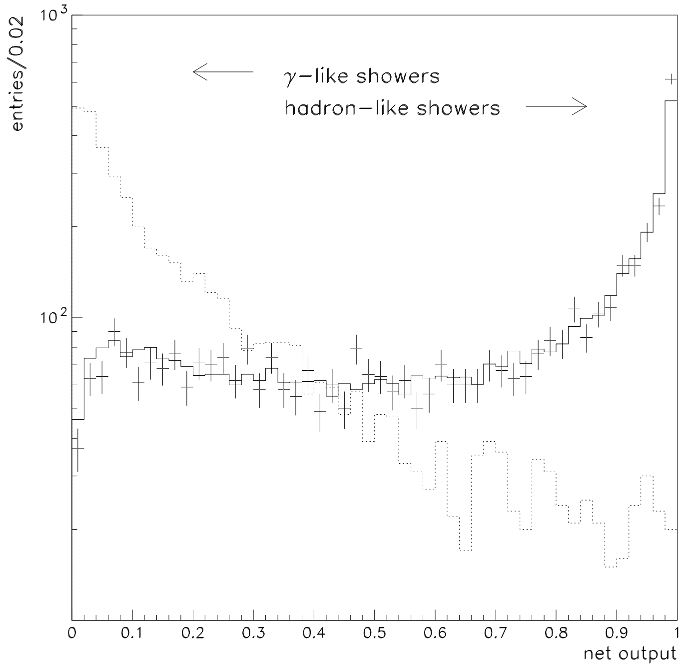

Fig. 16. Neural net output of 4500 Monte Carlo proton showers (dots with error bars), 4500 Monte Carlo γ-showers (dotted line) and experimental data (25000 events, normalized to the number of Monte Carlo proton showers).

a weighted overall quality factor of about 3. The trigger condition requiring a pre-defined minimum number of fired scintillator (or AIROBICC) huts is taken into account.

Confronting the NN output for Monte Carlo proton showers with experimental data (normalized to the number of Monte Carlo proton showers) in Fig.16 shows two important results: as expected the experimental NN output distribution can be explained without considering γ-induced showers due to the overwhelming dominance of hadron induced showers. This directly leads to a conservative upper limit on the isotropic flux of γ-rays: assuming all showers with a net output below a cut value $\xi_{cut} = 0.05$ to be γ-showers, the ratio of γ-rays to the total cosmic ray flux is $I_\gamma / I_{\mathrm{CR}} \leq 4.1 \times 10^{-2}(90\%\,\mathrm{CL})$ for $E \geq 40\,\mathrm{TeV}$. This limit was obtained using events taken during about 4 months of almost continuous data aquisition.

We also note here that the simulation of the detector's response to proton showers shows almost the same NN output distribution as for experimental data. The data simulation chain combining CORSIKA shower generation and GEANT detector simulation describes the dominant separation criteria to a satisfying degree.

5 Conclusions

The HEGRA Geiger towers are an appropriate detector component for a measurement of the energy and lateral particle distribution in air showers. Track reconstruction of charged particles and the distinction of muon- and electron-like particles is possible. By this means they facilitate the γ-hadron separation and the measurement of the chemical composition of primary cosmic rays. Since the absolute direction of the reconstructed tracks depends only on the tower geometry and the deposited energy is measured independently, they are a valuable tool for cross checking of the different detector components of HEGRA. Within one year of operation the performance of the detector has been studied with several monitoring tools. Results are compatible with expectations.

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