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The Soudan 2 Honeycomb Calorimeter
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THE SOUDAN 2 HONEYCOMB CALORIMETER

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Abstract

Soudan 2 is an 1100-ton honeycomb tracking calorimeter which is being constructed to search for nucleon decay. The detector consists of finely segmented iron instrumented with long drift tubes, and records three spatial coordinates and dE/dx for every gas crossing. Excellent event reconstruction capability, particle identification and muon sign and direction determination give superior rejection of the neutrino background to nucleon decay in many modes. The first 620 tons of Soudan 2 are now in steady operation, with completion planned for 1992. Detector performance has been studied using cosmic ray tracks and a charged test beam calibration. Results on detector performance and detector response are described in this paper.

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1 Introduction

The Soudan 2 experiment is located in an underground laboratory 710 m. beneath Soudan, Minnesota. The detector consists of an 1100-ton fine grained tracking calorimeter surrounded on all sides by a two-layer active shield of proportional tubes. Its primary goal is to search for nucleon decay in modes which may be dominated by neutrino-interaction background in other experiments. It may also be used as an excellent long baseline neutrino oscillation detector, in conjunction with a neutrino beam from the Fermilab Main Injector.

The large amount of information recorded for each event allows neutrino interactions to be clearly distinguished from nucleon decay events in modes like $p \rightarrow \nu K^+$ and for nucleon decay into three or more charged tracks. Although the 1100-ton mass limits sensitivity to the 10^{32} years level, its excellent background rejection could enable Soudan 2 to identify nucleon decay in modes which have previously suffered from requiring large background subtraction.

The Soudan 2 experiment began contained event data acquisition with the first quarter of the main detector (275 tons) in July 1988, and has accumulated a total exposure of 0.34 fiducial kton-year to date. The first 620 tons are now in operation. Completion of the 1100-ton detector is planned for 1992.

The performance of the main detector calorimeter modules has been studied using cosmic ray muon tracks, both on the surface and underground. Results of module performance studies are presented in the paper.

A charged particle test beam, at the Rutherford Laboratory ISIS accelerator, has been used to study detector response to low energy particles. The test beam studies have provided the energy calibration for electromagnetic showers and tracks, and have measured the ability of Soudan 2 to identify muon charge and direction.

2 Detector Description

The completed Soudan 2 detector [1)] will consist of 256 identical 4.3 ton calorimeter modules, which are being constructed at Argonne National Laboratory and the Rutherford Appleton Laboratory. The modules are placed in a rectangular parallelepiped 2 modules high x 8 modules in the east-west direction x 16 modules along the axis of the cavity (north-south direction), yielding a dimension for the full detector of 5x8x16 m. This layout is illustrated in figure 1.

Each module is composed of 240 layers of 1m x 1m x 1.6 mm corrugated steel sheets interleaved with an insulated *bandolier* assembly of 1 m long x 0.5 mm thick x 15 mm diameter resistive Hytrel drift tubes (see figure 2). The insulation consists of two layer of 125 μm mylar, laminated together with long pockets to accommodate the drift tubes, and 0.5 mm thick polystyrene inserts which are vacuum formed to fit the steel corrugation. The steel sheets and the *bandolier* are stacked up for 240 layers (2.5 m) to form 4.3 ton modules. In doing this the bandolier is fanfolded back and forth with steel sheets interleaved. The stack is then compressed with about 15 tons of force. Each module is enclosed in a gas-tight sheet steel enclosure consisting of welded sideskins to maintain compression and removable covers to allow access to the wireplanes and stack faces.

The basic detection element of the experiment is shown in figure 3. It is a resistive ($\sim 4\text{x}10^{12}\Omega - cm$) plastic Hytrel tube (made by DuPont Corporation), one meter long with an inner diameter of 15 mm and a thickness of 0.5 mm. Each module consists of 7560 drift tubes. A linearly graded electric field is applied along it by 21 1.5 mm wide copper electrodes (see figure 2). These have a voltage of -9 kV at the middle of the tube and 0 V at the two ends. The resistive tube then grades the voltage between electrodes, creating a uniform axial drift field of 180 $volt/cm$ inside the tube. The tubes are filled with 85% argon, 15% CO_2 and 0.1% of H_2O (from the plastic). When a charged particle passes through the tube it ionizes the gas: the liberated electrons then drift (with a velocity of 0.6 $cm/\mu sec$) up to 50 cm to the ends of the tube where they are collected and amplified on a 50 μm diameter anode wire (gold plated tungsten).

The tubes are arranged in a hexagonally closed packed array as shown in figure 2. The anode wires run vertically in a plane 10 mm from the tube ends and are spaced every 15 mm so that they are aligned with the centers of the tubes. Cathodes pads are connected in horizontal strips orthogonal to the anode wires 5 mm behind then, and are aligned with the tubes. Thus it is possible to identify which tube a signal came from, since the anodes and cathodes provide a two-coordinate grid centered on the tube ends.

The Soudan 2 detector is read out by 16128 anodes wires and 30720 cathodes strips. Signals from preamps on each wire and strip are bussed together in groups of 8 to reduce the number of ADC channels. The resulting 5888 channels of ionization signals are digitized by 6-bit flash ADC's every 200 ns and stored in RAM's. This provides both a pulse height profile of the signal and measures the drift time down a tube, thereby giving the z coordinate of the hit. Therefore, three correlated spatial coordinates and a dE/dx measurement are recorded for every charged particle crossing of a drift tube.

The raw data pulse patterns at the ADC inputs are continuously compared with programmable trigger conditions to detect localized clusters of hits in the drift tubes. Since every readout channel contributes equally, the trigger requirement is uniform throughout the detector volume. Efficiency is high for muons above 230 MeV/c momentum and falls linearly to zero at 90 MeV/c (for muons which do not have a visible decay). The electron (shower) triggering threshold is about 50 MeV. The rate of random triggers from natural radioactivity is less than 0.5 Hz in the full detector under these conditions.

The main detector is surrounded on all sides by a 2-layer array of extruded aluminum proportional tubes [2]. This active shield is mounted against the cavity walls to signal the presence of cosmic ray events in the cavity and the surrounding rock. Cosmic ray muons can create contained event candidates by entering the detector through the spaces between main detector modules, or by creating neutrons and K_L^0's in the nearby rock which penetrate to the interior without leaving tracks. Such neutral particle production is almost always associated with charged particles which are detected in the shield. Candidates for nucleon decay should not have associated hits in the active shield. Because the 1700 m^2 shield has nearly 3.5 times the area of the main detector it also increases the effective area for studies of multiple-muon cosmic ray events.

Some advantages of the Soudan 2 detector compared with previous proton decay detectors are:

- The honeycomb geometry gives a more uniform spatial response than a parallel plate detector and much better track and vertex resolution than water cerenkov counters. The result is high quality pictorial event information.
- The ionization measurement yields particle identification (e.g. proton-pion/muon separation) not available in some other detectors.
- The ionization measurement yields track direction information from the ionization rise at the stopping end of the track.
- μ^- absorption in iron gives a track charge information not available in a water cerenkov detector. (Stopped μ^+'s decay visibly in Soudan 2.)
- Muon trigger thresholds are lower than in any other proton decay detector.
- The observation of shower development yields better low energy electron-muon separation that in water cerenkov detectors.

3 Module Performance

The response of the detector is continuously monitored by analysing the data from the cosmic ray muons which trigger the experiment at a rate of about 0.3 Hz. A sample of tracks accumulated over several weeks is used to measure the detailed response in the region of nucleon decay or neutrino interaction candidate events. In order to optimize the operating parameters (e.g. gas and electronic gains), a few modules were initially operated on the surface where the cosmic ray flux is high enough to do high statistics studies rapidly. Some of the results on detector performance of the modules operated on the surface are presented in this section.

For the study of tube efficiency the cosmic ray muon trajectories were fitted. By comparing the number of hit tubes crossed by the trajectory with the number predicted to be hit by a muon trajectory, the tube efficiency is determined. Such a definition not only considers if the tube is working, it also includes the anode-cathode matching efficiency and the track fitting efficiency. Moreover, the efficiency will be decreased due to deviations of the actual tube position from its nominal position. In the case of perfect geometry, for Monte Carlo data, the tube efficiency is 85%. Under actual operating conditions the mean tube efficiency is of the order of 75%. The mean tube efficiency is very uniform throughout a module, as is shown in figure 4, where the efficiency is plotted along the cathode direction. The variations seen in figure 4 are correlated with the pulse height variations along the cathodes. The maximum tube efficiency one can reach is 80% when the pulse height is big enough, but the modules were operated at the knee of the efficiency plateau to remain in the proportional gain region.

Typical attenuation lengths are of the order of 70 cm. For the pulse height distribution shown in figure 5 the attenuation lengths for each 50 cm drift region are 71 and 63 cm. Such attenuation of the pulse height is well understand in terms of diffusion along the tube and electron attachment due to O_2 contamination. Some variations from module to module can be observed, even with the same gas composition, due to imperfections in the electric field which show up as a difference in the effective radii of the tubes. In the absence of oxygen attachment, attenuation lengths are expected to be about 100 cm. The spatial resolution is determined by the anode and cathode spacing, the drift time digitization unit and the drift velocity. The spatial resolution is obtained from the RMS of the residual distributions, calculated by fitting cosmic ray muon tracks. The spatial resolution in the y direction is 0.47 ± 0.10 cm , compatible with the expectations from cathode separation. The same result is obtained in the x direction. However, the spatial resolution in z is 1.04 ± 0.24 cm, higher than expected from the time unit and the drift velocity. There are several factors affecting the z resolution: non uniform electric field, drift velocity variations, and wireplane-stack misalignment.

One of the main characteristics of the Soudan 2 detector is its ability to yield pulse height information for track direction determination and particle identification. To make maximum use of this information, the pulse height variation over the modules must be smaller than Landau variations (20%). Typical pulse height fluctuation along the wire plane are of the order of 30%, while in the drift direction, due to pulse height attenuation, 50% reduction on pulse height can be observed (see figure 5). However, these variations can be corrected by calibrating out the effects of measured pulse height attenuation, wire plane nonuniformities, module to module variations, atmospheric pressure, and gas composition. After pulse height calibration, 10% variation is obtained.

4 Module Calibration

At the Rutherford Laboratory's ISIS pulsed neutron source, a module was exposed to beams of positive and negative pions, muons, and electrons at momenta between 140 and 400 MeV/c, and protons at 700 and 830 MeV/c, for several angles of incidence. Analysis of the data is in progress but preliminary results are available on the detector resolution, ionization response, and particle identification. These studies have confirmed that the detector modules are performing as expected, and also have provide detailed response parameters which are then used in the Monte Carlo detector simulation.

The electromagnetic shower energy is determined by counting tube crossings (hits). Figure 6 shows the number of tube crossings as a function of the beam energy, for ISIS and Monte Carlo data. The non-linear dependence upon the energy reflects the high density of tube crossings at high energy. The measured energy resolution can be represented as (figure 7):

$$\frac{\Delta E}{E} = \frac{7.0}{\sqrt{E}} + 13.5\%$$

where E is given in GeV and the second term reflects the saturation of the number of hits.

Although the Soudan 2 detector is designed to be relatively isotropic, its geometry is not completely uniform. This fact will affect, at some level, the number of hits counted for shower energy measurement. Figure 8a shows the number of hits observed for different vertical incidence angles of the beam, for tracks perpendicular to the tubes. The maximum variation (8%) is obtained for small vertical angles. This variation is easily calibrated. The total amount of pulse height is independent of the vertical incidence angle as is shown in figure 8b. When the dependence upon horizontal angle (angle with the z direction) was measured, a variation of the number of hits was observed where the beam is almost parallel to the tubes (see figure 8c). The total amount of pulse height does not vary with horizontal angle(figure 8d). Therefore, the Soudan 2 detector is isotropic after some small corrections. The small detector anisotropy observed is confirmed with the Monte Carlo and does not compromise the energy resolution.

A sample of $\pi^{0\prime}s$ produced in charged pion interactions has been reconstructed. The events were selected by scanning for events with two well separated showers. The π^0 peak is centered at $136 \pm 3\ MeV/c^2$ and has an RMS of $40\ MeV/c^2$ (see figure 9). When the vertex is known it is possible to distinguish electrons from photons by measuring the distance between the vertex and the first hit (conversion length). If the distance is smaller than 4 cm the probability to be a electron is 8 : 1. for a distance larger than 4 cm the shower is a photon with a probability of 14 : 1.

Muon momentum is calculated from the range obtained by measurement of the muon track length (L) and using a mean detector density (1.6 g/cm^3). The average length for 245 MeV/c muons is 40.6 cm, with $\frac{\Delta L}{L} = 20\%$, giving a momentum resolution of 8%. This resolution is independent of momentum for the ISIS energies.

Soudan 2 can distinguish between stopping positive and negative muons because most negative muons are captured by iron nuclei and do not decay visibly. The decay positrons from positive muons are usually detected. Figure 10 shows the number of extra hits at the ends of tracks for samples of negative and positive muons. Two or more shower hits are observed at the end of 85% of the positive muon tracks. No hits are observed for 75% of the negative muon tracks. The expected ionization response of a slowing muon is observed. Figure 11 shows the mean pulse height along the muon trajectory from the end of the tack. Crude measurement of the track direction (choosing the end with the higher mean ionization on the last 5 hits as the stopping end), yields the correct direction 78% of the time.

An algorithm is under development to separate electron showers from muon tracks. It distinguishes between electrons and muons using the residuals of points from a smooth trajectory fit. the number of hit tubes not on a smooth trajectory and their distribution along the trajectory. the number of non-hit tubes and the largest contiguous set of non-hit tubes on the smooth trajectory fit. The efficiency of identifying muons is essentially constant with momentum and equal to 95% (for both μ^- and μ^+). The efficiency of the algorithm for identifying electrons is dependent on the energy and is equal to the muon efficiency for 400 MeV/c. and falls to 83% at 185MeV/c. At our lowest energy calibration point (140 MeV/c). the electron identification efficiency is 60%. This is because such low energy electron tracks do not often exhibit large showers.

5 Conclusions

The Soudan 2 detector is collecting data and is working well. The detector performance is continuously monitored using cosmic ray muon tracks. By exposing one of the modules to a charged particle beam at ISIS, various detector capabilities have been measured: muon charge identification, direction determination, track pattern recognition, and track energy measurement has been calibrated. The large amount of information for each contained event will be of great value in separating neutrino interactions in Soudan 2 from nucleon decay event candidates.

References

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2. W. P. Oliver *et al.*, *A rugged 1700* m^2 *Proportional Tube* Array, Nucl. Instr. and Methods **A276** (1989) 371.

Figure Caption

Figure 1: Soudan 2 main detector and active shield layout.

Figure 2: *Bandolier*, insulation sheets(inserts) and corrugated steel assembly (stack).

Figure 3: Cutaway view of a single drift tube. The drift field is generated by the application of graded voltages on a series of 21 copper electrodes (the polystyrene inserts are not shown).

Figure 4: Typical mean tube efficiency variation with cathode numbers.

Figure 5: Typical pulse height variation along the drift direction.

Figure 6: Electron shower energy versus number of hits from ISIS data and Monte Carlo simulations.

Figure 7: Energy resolution for electron showers.

Figure 8: Mean number of hits (a) and mean total pulse height (b) for different beam momenta versus the vertical angle, and mean number of hits (c) and mean total pulse height (d) versus the horizontal angle.

Figure 9: Invariant mass distribution for two shower events in the π beam.

Figure 10: Number of shower hits at the end of $\mu+$ and $\mu-$ tracks.

Figure 11: Mean pulse height versus anode number (from the last anode in the μ trajectory).

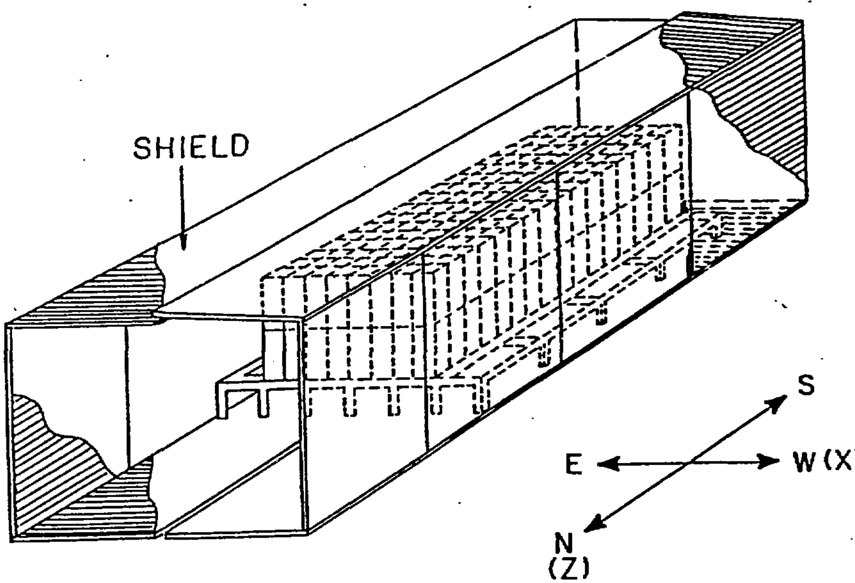


Figure 1.

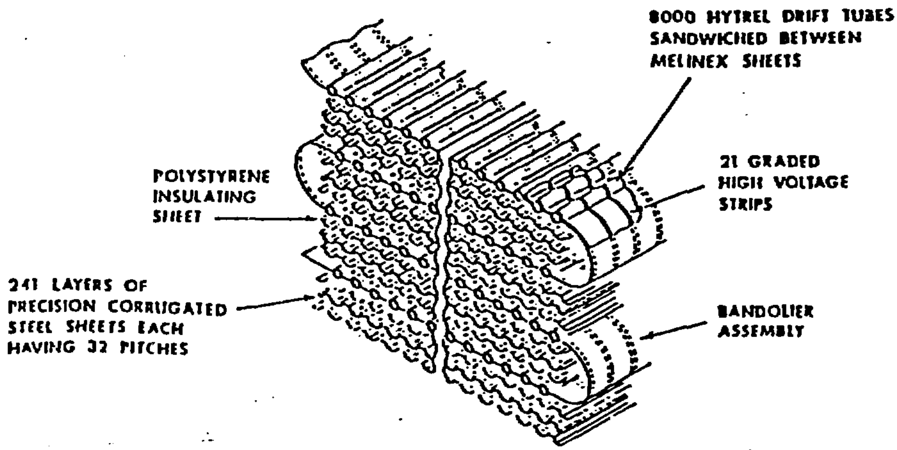


Figure 2.

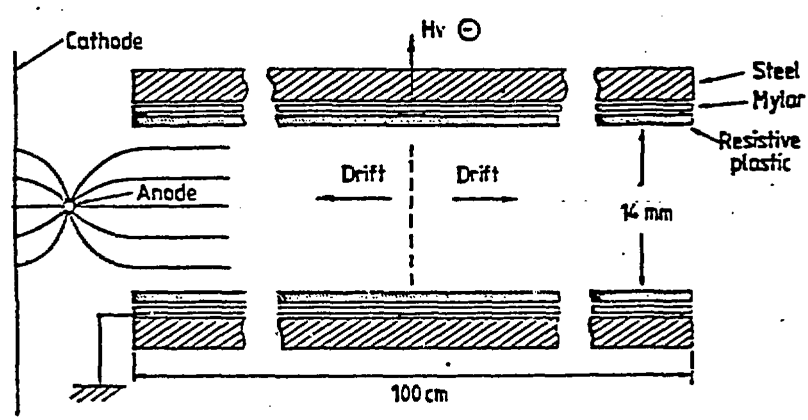


Figure 3.

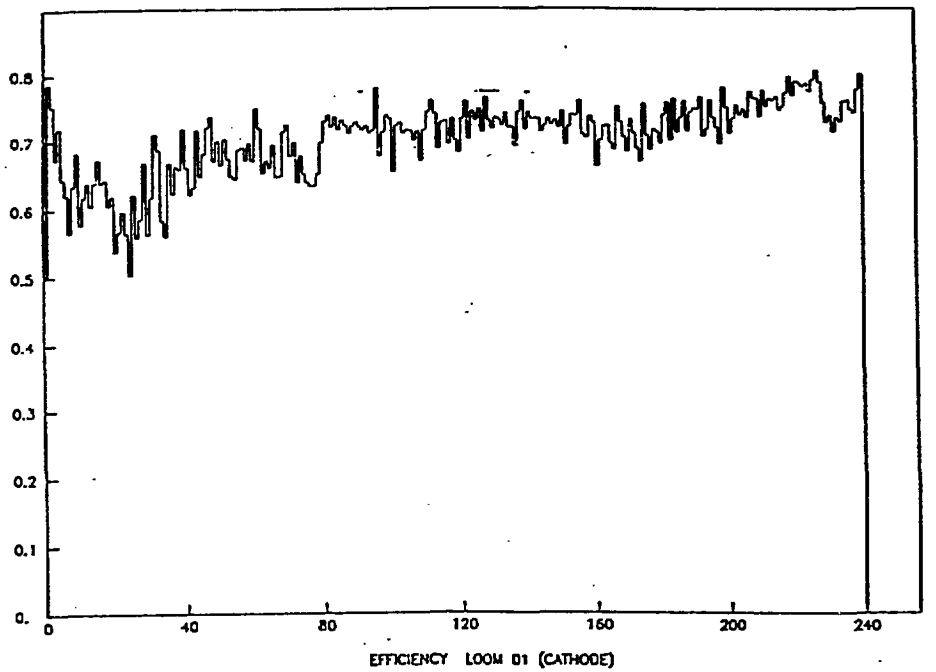


Figure 4.

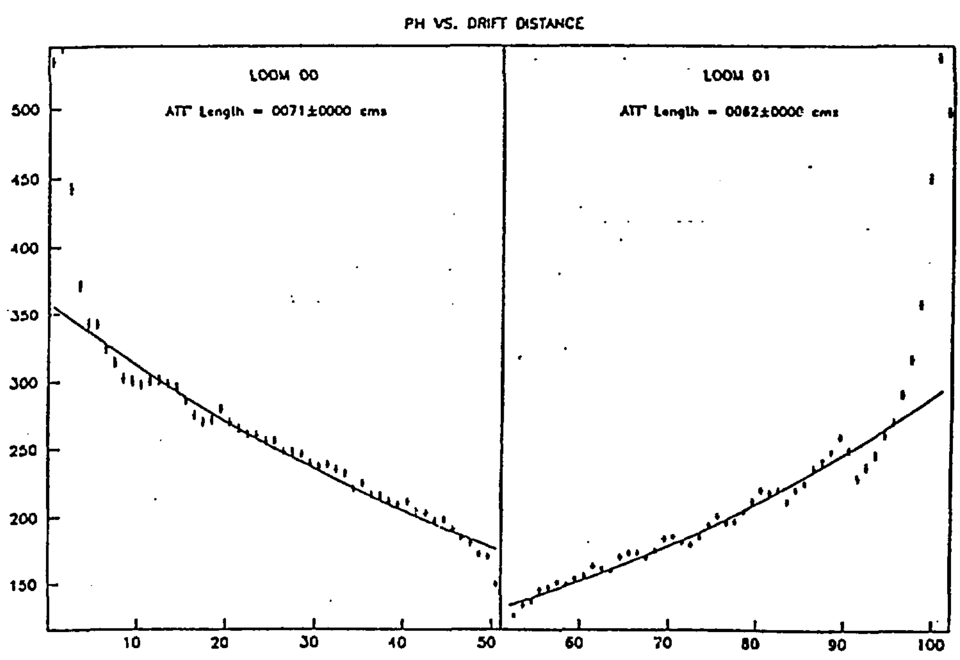


Figure 5.

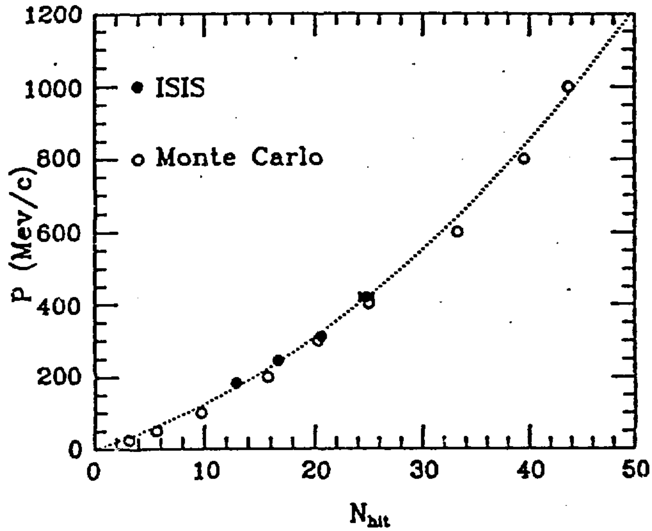


Figure 6.

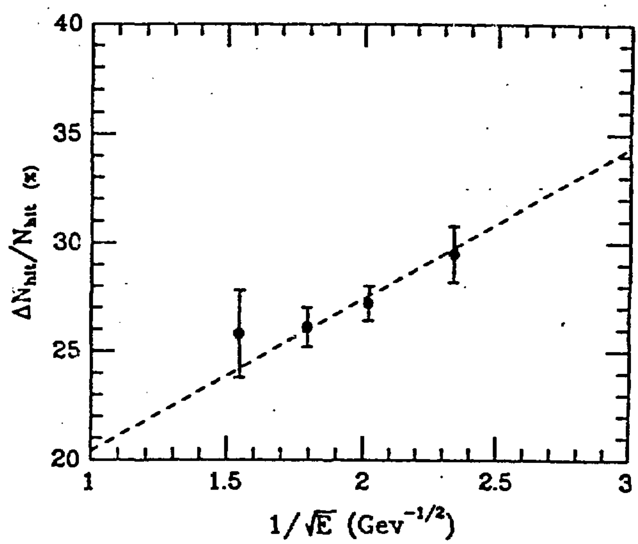
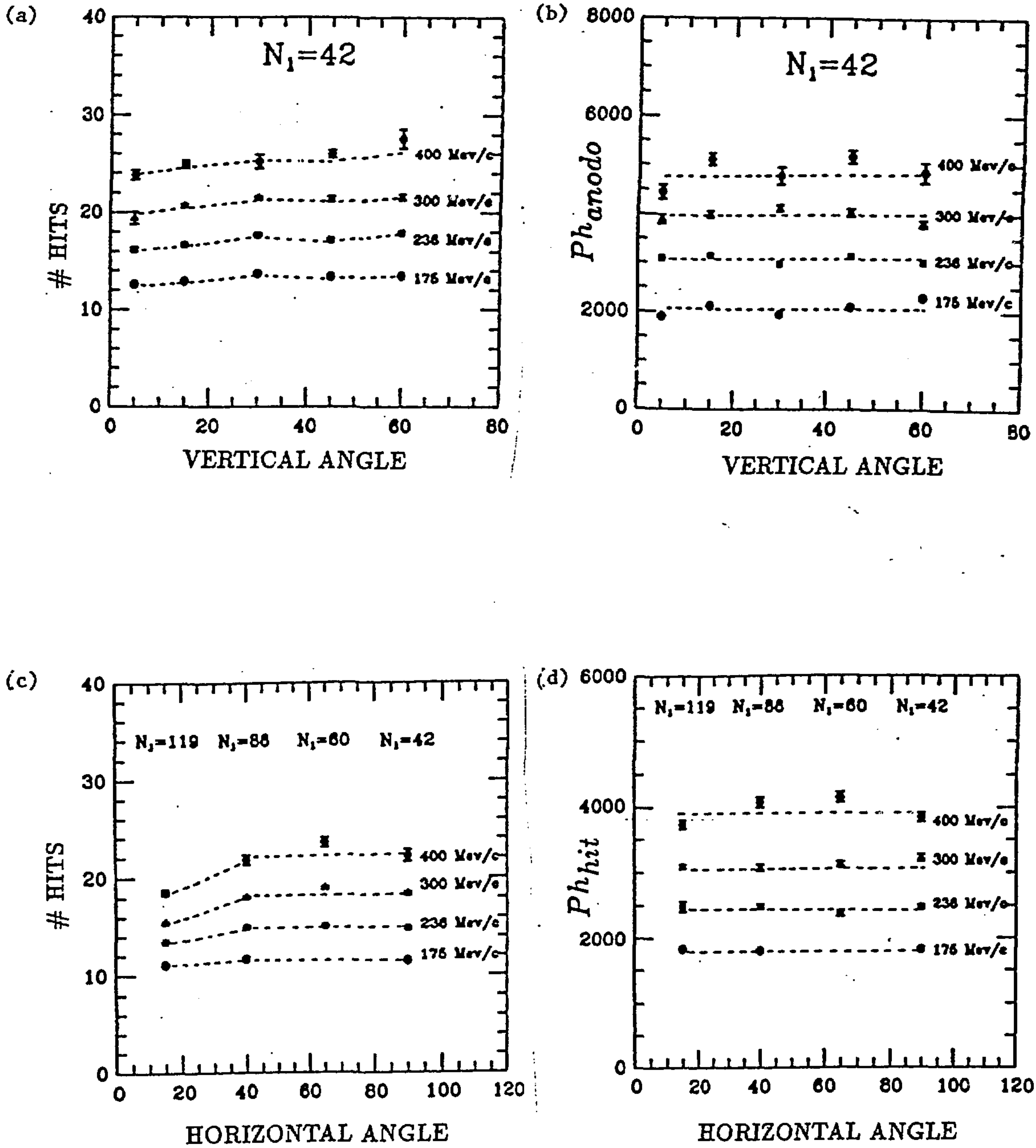


Figure 7.



(a)
N1=42
# HITS
VERTICAL ANGLE
400 Mev/c
300 Mev/c
236 Mev/c
175 Mev/c
(b)
N1=42
Ph anodo
VERTICAL ANGLE
400 Mev/c
300 Mev/c
236 Mev/c
175 Mev/c
(c)
N1=119 N1=86 N1=60 N1=42
# HITS
HORIZONTAL ANGLE
400 Mev/c
300 Mev/c
236 Mev/c
175 Mev/c
(d)
N1=119 N1=86 N1=60 N1=42
Ph hit
HORIZONTAL ANGLE
400 Mev/c
300 Mev/c
236 Mev/c
175 Mev/c

Figure 8.

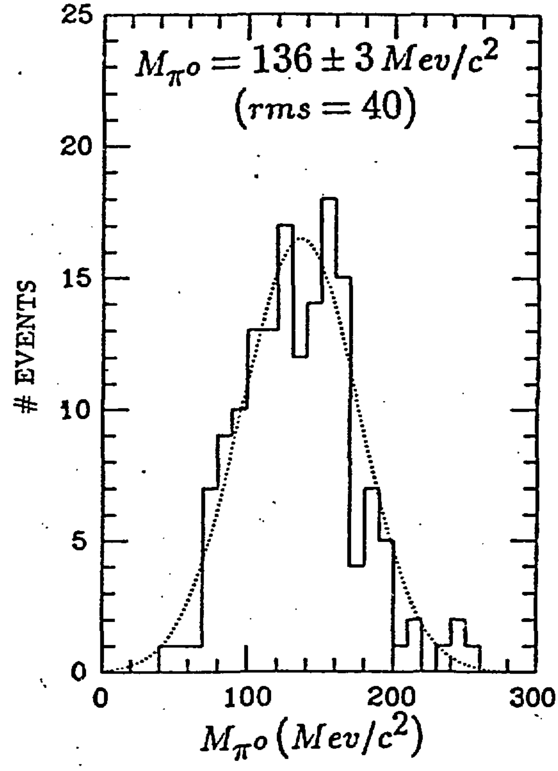


Figure 9.

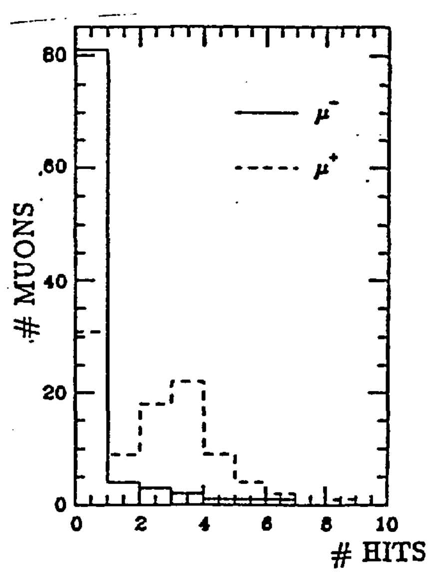


Figure 10.

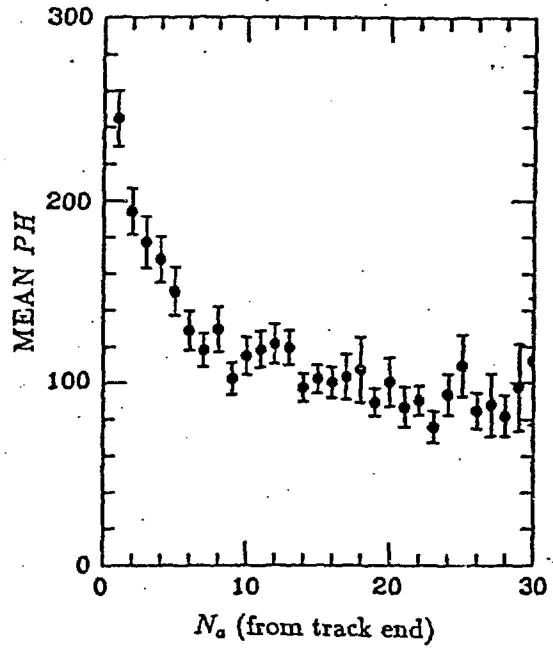


Figure 11.