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MUON/ELECTRON SEPARATION FOR ATMOSPHERIC NEUTRINO INTERACTIONS *

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Abstract

A study has been made of the ability of the Soudan 2 nucleon decay detector to distinguish between showering and non-showering particles, utilizing several different pattern recognition techniques. This work has direct application in the determination of the ν_μ/ν_e ratio for atmospheric neutrino induced events. The results of the application of these techniques to Monte Carlo data and to calibration data from the ISIS test beam are presented.

Introduction Cosmic ray air showers produce both ν_e and ν_μ neutrinos with typical energies of 1 GeV from pion, muon, and kaon decay. Standard cosmic ray Monte Carlos make predictions for the fluxes of ν_μ's and of ν_e's produced by the air showers. Some of these atmospheric neutrinos will interact in large underground detectors. Two of these detectors have reported anomalies in the ratio of ν_μ/ν_e charged current events observed, seeing a deficit of ν_μ induced events.[1,2] If this observation is confirmed, it may have implications for the existence of neutrino mass and neutrino oscillations.

The significance of any reported anomaly in the ν_μ/ν_e ratio depends on understanding possible systematic effects in muon/electron identification. The ability to calibrate the detector response to tracks and showers is an important tool in this identification. Ultimately, the accuracy of the measured ν_μ/ν_e ratio will depend on the accuracy of corrections applied for track/shower separation.

The Soudan 2 Detector and Calibration The Soudan 2 nucleon decay detector is a 900 ton modular fine-grained tracking calorimeter which has been described previously.[3] One of the 4.3 ton modules has been set up at the ISIS test beam at the Rutherford Appleton Laboratory. There it has been exposed to muons, electrons, protons and pions with momenta of 140 MeV/c and above.[4] The general features of the muon tracks and of the electron showers are in agreement with similar events produced by the Soudan 2 Monte Carlo simulation. Figure 1 shows the XY views of the reconstructed hits produced by a typical ISIS test beam muon track and by an electron shower at

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momenta of 236 Mev/c. At this momentum, a muon track has on average, 10 hits, while an electron shower has 16 hits, with large statistical variations.

Track/Shower Separation Techniques The methods outlined here depend upon generating a large set of Monte Carlo tracks and showers (muons and electrons). We chose to start with Monte Carlo events in order to later use the test beam data as a direct unadjusted measure of separation performance. These Monte Carlo events are used to tune several different pattern recognition 'engines' to recognize the differences between tracks and showers. Before they can be used, the events must be partially reconstructed. The anode and cathode pulses must be matched to create 3-dimensional hits, and the hits must be grouped together. Each hit group is assumed to consist of either a track or a shower. The job of the pattern recognition is to assign a classification of 'track' or 'shower' to each hit group. Automated reconstruction algorithms, tuned to match the way a human operator would reconstruct the events, were used to reconstruct the Monte Carlo training set events.

For hit groups with $N_{hits} \leq 3$, there is not enough information present to make a decision. At momenta above approximately 500 MeV/c ($N_{hits} \approx 40$ for tracks), the track/shower separation capabilities of the Soudan 2 detector approach 100%. Therefore, the following techniques have been optimized for track/shower separation in hit groups with $3 < N_{hits} < 40$. Furthermore, to take into account the energy dependence of the track/shower separation efficiency, each hit group is first categorized according to N_{hits} into one of 4 bins; $3 < N_{hits} \leq 10$, $10 < N_{hits} \leq 20$, $20 < N_{hits} \leq 30$, or $N_{hits} > 30$ before the track/shower determination is made. A different pattern recognition engine was tuned to specialize in each of these four N_{hits} regimes.

Two polynomials are fit to each hit group; one fit in the XY projection and another in a projection involving Z. A set of seven 'attributes' are then calculated using these fits. The attributes are quantities that embody some aspect in the geometric pattern of hits which can be used to differentiate tracks from showers. Most of the attributes are quantities based on how much the individual hits in the hit group deviate from the fits. The natural range of values for each attribute is rescaled to produce a consistent range of -1 to 1 for all attributes. As an example, Figure 2 shows the distributions of RMS_{xy} (an attribute defined as the RMS of the hits with regard to the fit in the XY projection) for both tracks and showers in N_{hits} regime 2.

The four pattern recognition engines used were:

- Cuts After examining the distributions for each attribute in each N_{hits} regime, cuts were defined on each attribute and optimized to best discriminate tracks from showers. When classifying hit groups, the hypothesis of 'track' was assumed, unless any of the hit group attributes failed a cut. Since the hit group had a chance to fail any of the seven cuts and be called a shower, the cuts were placed out on the tails of the track distributions.

- Maximum Likelihood In this method, the attribute distributions are transformed into probability distributions by simply normalizing the area to 1. When classifying a hit group, the likelihood that the observed value of an attribute would be produced by a hit group that was in reality a track is read off the appropriate probability distribution. Similarly, the likelihood that the attribute value was produced by a shower hit group is read from a different distribution. The likelihoods read from the track or shower distributions for each of the seven attributes are multiplied together to get the final likelihoods for the track hypothesis and for the shower hypothesis. The hypothesis with the largest likelihood is chosen as the classification.

- Nearest Neighbor This method is best visualized by considering each training hit group to be plotted as a point in a seven dimensional space, with the coordinates given by the values of the attributes. Ideally, the track and shower hit groups are separated into distinct regions of this space. During classification, the point corresponding to the candidate hit group is also plotted in this space, and the closest neighboring point is found. If the closest point was from a hit group that was associated with a track, the candidate hit group is called a track, otherwise it is called a shower.

- Neural Network In this approach, the seven attributes are fed to the inputs of a feed-forward neural network that has been trained to produce a single output of -1 for showerlike hit groups and 1 for tracklike hit groups. If the attributes of a candidate hit group evoke an output greater than 0 when presented to the trained network, the hit group is classified as a track, otherwise it is classified as a shower. Note that a different neural network was trained for each N_{hits} regime. During the training of the neural networks, a number of different training parameters and network configurations were tried, and only the trained networks exhibiting the best performance were kept. The theory and operation of neural networks is described in detail in several sources [5].

Also, an attempt was made to create a 'meta-engine' that used the outputs of each of the above four engines, each weighted by a confidence factor derived from further Monte Carlo testing, to make a final classification decision.

Results After being tuned as described above, the four pattern recognition engines were tested on an independent set of Monte Carlo events consisting of equal numbers of tracks and showers. The relative performance (in terms of the fraction of events correctly identified) of each of the classification engines is shown in Figure 3. The engines were also tested with muon tracks and electron showers from the 236 MeV/c ISIS test beam data. Because the test beam events must be laboriously reconstructed by hand by a human operator, only a small number have been tested. The performance of the engines on these test beam events is nearly identical to the performance seen while testing with Monte Carlo events.

Conclusions The performance of the engines are remarkably similar, with the best and worst engines differing by only about 10% in any N_{hits} regime. The Neural Network approach seems to hold the most promise, followed closely by the Maximum Likelihood method. More studies are underway on correlations between the outputs of the four engines, and on methods of combining the outputs to make a final decision. Also, more testing with ISIS test beam events is being carried out.

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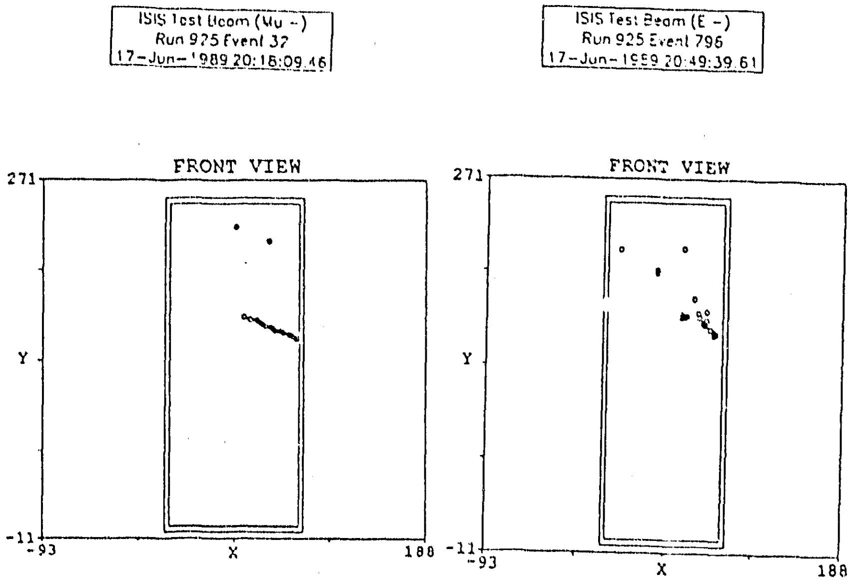
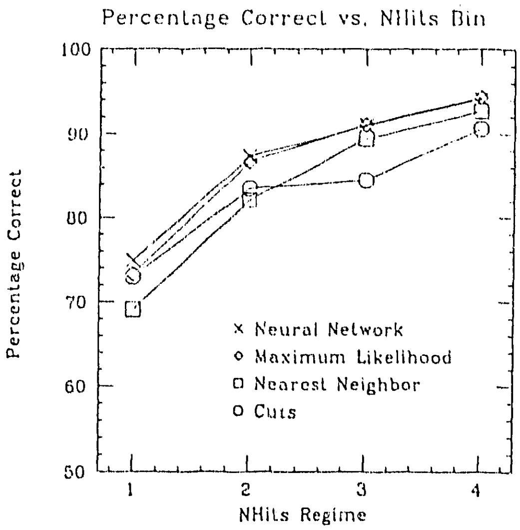


Figure 1. Reconstructed 236 Mev/c muon track (left) and electron shower (right) from the ISIS test beam. Only the XY projection is shown.



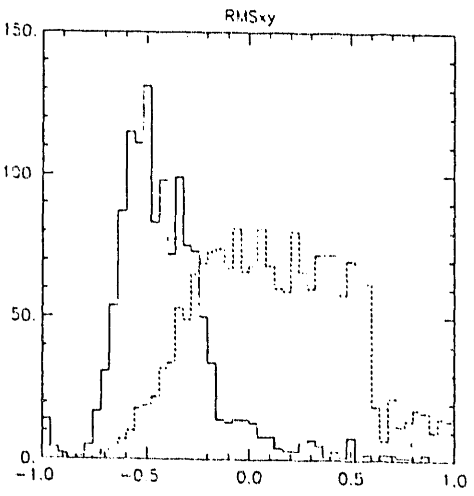


Figure 2. The distributions of RMS_{xy} attribute for the tracks (solid line) and showers (dashed line) for the training events in N_{hits} regime 2.

Figure 3. The percentage of correctly identified tracks and showers for each of the separation methods.

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