GAP-97-005, Auger project technical note:* Simulations of the proposed Auger water Čerenkov ground array

Clement Pryke
Enrico Fermi Institute, University of Chicago, USA

January 9, 1997

Abstract

Simulations of a giant array of water Čerenkov detectors have been developed. These allow the output from shower simulation to be converted into simulated raw experimental data on the basis of specific assumptions regarding array layout, detector design, and front end electronics. The data is then analyzed in a similar manner to real data, and experimental performance predictions are made. This work is on-going; the current status and results are presented.

1 Introduction

To make further progress in the study of the highest energy cosmic rays ($> 10^{19}$ eV) an increase of orders of magnitude over the acceptance of current instruments will be required [1]. The largest experiments to date are the Akeno giant air shower array [2] with an acceptance of ~ 200 km^2 sr, and the Fly's Eye [3] (now decommissioned) with a similar time averaged aperture at the highest energies. The High resolution Fly's Eye detector (HiRes) currently under construction will achieve a figure of $\sim 1,000$ km^2 sr [4]. An international collaboration has been formed under the name of the Auger Project [5]

*This paper was prepared for the proceedings of the ICRR International Symposium on Extremely High Energy Cosmic Rays held in Tokyo, Japan in September 1996.

to build a next generation instrument with twin northern and southern hemisphere observatories having a combined acceptance of $\sim 14,000$ km^2 sr. Such a system would collect $\sim 10^4$ events per year of energy $\geq 10^{19}$ eV, and ~ 100 of energy $\geq 10^{20}$ eV.

The Auger proposal is to couple the traditional ground array technique with Fly's Eye style air fluorescence detectors in a *hybrid* system. During dark nights the two detectors will observe the same events in parallel yielding a sub-set of very high quality data, but most importantly allowing a detailed study of the random and systematic errors to which each technique is subject — something which has not been possible in the past.

Since each ground detector installation entails many fixed costs independent of the detector area (electronics, deployments etc.) and the number of stations required for a given array coverage is inversely proportional to the square of the array spacing, it is important that this distance be as large as possible. It is also a design requirement that the array be near fully efficient for showers $\geq 10^{19}$ eV. A hexagonal grid of water tanks 10 m^2 in area and 1.5 km apart satisfies this constraint, and still has enough triggered stations (15–20) at $\sim 10^{20}$ eV for the unambiguous event reconstruction demanded by the somewhat controversial nature of these showers. Figure 1 shows the Auger design; ≈ 1600 water tanks are spread over an area of ≈ 3000 km^2, and overlooked by three air fluorescence stations.

To determine the numbers stated above, and to access the experimental performance of the proposed ground array system, an increasingly sophisticated system of simulation codes has been developed [5, 6]. Simulations of the fluorescence detector system operating with a generic ground array have been developed in parallel [7]. The current state of the ground array simulations, and reconstruction of the resulting artificial data are presented in this paper.

2 Generation of simulated data

The process of generating simulated ground array data has been described previously [5, 6]. It will be briefly reviewed with emphasis on those things which have changed since previous descriptions.

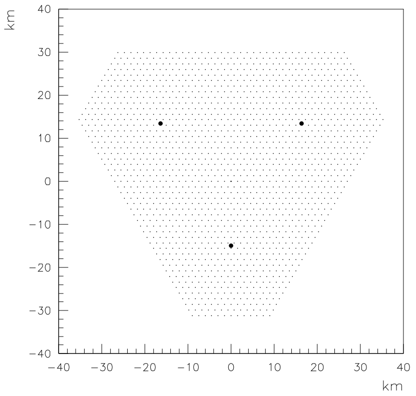

Figure 1: Layout of an Auger observatory. Small dots indicate water tanks; large dots indicate the fluorescence detectors. The distance between water tanks is 1.5 km.

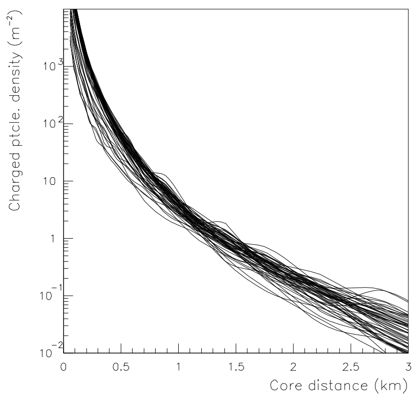

Figure 2: Lateral distribution of charged particles from 10^{-7} thinned, proton initiated MOCCA shower simulations. Density is normalized to primary energy of 10^{19} eV.

2.1 Shower simulation

The starting point for the Auger ground array simulation procedure is the MOCCA air shower code written by Hillas [8]. This is a detailed four dimensional program in which cascade particles are generated and tracked as they move through the atmosphere towards ground level, undergoing interactions and decays. A special technique known as thin-sampling is employed as it is not possible to track every shower particle at high primary energies ($> 10^{16}$ eV) using practical computing resources. In this technique only a sub-set of particles is followed, and these are assigned weights to compensate for those not followed. Normally all particles are followed down to an energy called the thinning threshold, defined as a fraction of the primary energy.

To predict the performance of a widely spaced ground array it is necessary to consider the nature of the shower particles at large core distances (> 1 km). For a hexagonal array with spacing 1.5 km there will be only 1 detector at a shower plane core distance of < 750 m for a vertically incident shower. Due to the steeply sloping power law form of the lateral distribution only a small fraction of the total particles fall at large core distances (few %).

For a given level of thinning there is a distance beyond which the statistics of the simulation output become unacceptable. In this regime artificial fluctuations due to the computational limitations dominate over any real physical fluctuations. It has been common practice to get around this problem by averaging over many shower simulation runs with the same initial parameters [5, 6]. Of course this also removes any physics induced fluctuations resulting from differences in the first interaction points, and variations in the first few generations of cascade development. If these average showers are then used to predict experimental performance the results will represent a "best case" scenario.

For this work, a set of 100 showers has been generated with the thinning threshold set at 10^{-7} of the primary energy. This provides sufficient statistics at large core distances that the showers may be input into the array simulation procedure individually. The showers were sampled from the energy spectrum $\frac{dN}{dE} \propto E^{-2}$ with $10^{19} < E < 10^{20}$ eV. This is approximately one power flatter than the true spectrum; otherwise very few high energy events would be generated. The spectrum of zenith angles for a fully efficient ground array is $\frac{dN}{d\theta} \propto \sin\theta\cos\theta$. Events were generated with $\theta < 60°$. Half the events were proton initiated, the other half being iron nuclei. The generation of each event took ≈ 36 hours on 200 MHz R4400 CPUs.

Figure 2 shows the lateral distribution of charged particles for the complete set of proton showers. It is believed that most of the residual fluctuations are physical in origin, and not an artifact of the simulation process. However, some artificial component clearly remains. Hence the resulting predictions of experimental performance may be regarded as "worst case".

2.2 Particle re-sampling

The shower simulation output files are each summarized into an array having 20 logarithmic bins of shower core distance ($50 < r < 5000$ m), 30 logarithmic bins of particle arrival time ($10 < t < 10^4$ ns), and 40 logarithmic bins of particle energy ($0.1 < E < 10^7$ MeV). Gamma rays, electrons and muons are stored separately, positive and negative charged particles being binned together. Hence for each core distance bin the time dispersion, and energy spectra of the shower particles are preserved, as well as any correlation between these quantities.

A shower core position is then selected on the array grid at random. The summary array is used to generate a re-sampled list of particles striking all

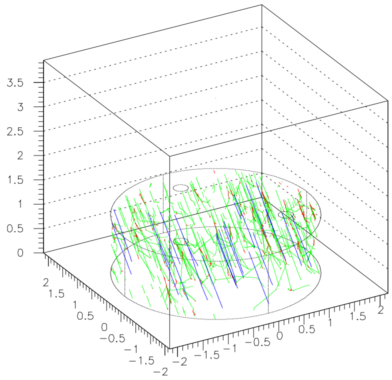

Figure 3: Illustration of detector simulation for a sample of shower particles.

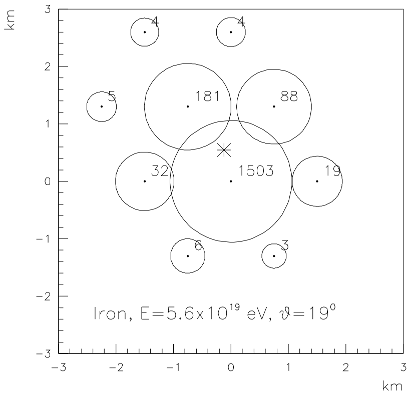

Figure 4: Simulated hit pattern of a large event on the Auger grid. Ten stations are triggered.

detectors at core distances of < 5 km. These are discrete lists of particles, each having energy, arrival time, and coordinates of the entry position into the detector volume.

2.3 Detector simulation

The water Čerenkov detector proposed for the Auger arrays is a $10 \text{ m}^2 \times 1.2$ m deep cylindrical volume of water viewed from above by three 200 mm diameter photomultiplier tubes (pmts). The tanks are to be lined with a diffusively reflective white material, and filled with clean water. A detailed simulation of tank behaviour has been developed, and several prototype units constructed. Testing of the detector simulation code against calibration data from a prototype detector is described in a companion paper [9].

Figure 3 shows a sample of shower particles passing into a detector. Each particle interacts and radiates Čerenkov photons; each photon is ray-traced until it is absorbed in the water, by the lining material, or reaches a pmt. A list of photoelectron release times is output.

2.4 Electronics simulation

From the list of photoelectron release times a pmt output trace is constructed, taking into account the behaviour of practical front end electronics. In this work it is assumed that the incoming charge is integrated in time intervals of 10 ns, and recorded by a waveform digitizer. The Auger concept demands that the detectors be pseudo-autonomous; the first level trigger being generated by each detector individually on the basis of local information only. Here it is assumed that a time-dispersion trigger is used. The waveform is clipped at a low level (few pe) and the clipped signal integrated. If the integral exceeds a given threshold then a trigger is generated. Such a trigger responds well to the time dispersed soft electromagnetic particles of an air shower event observed far from the core, but can be made insensitive to the high rate of single muon background events (~ 2 kHz).

The error of event time stamp electronics is also accounted for. The formation of higher level triggers by cross-correlation of low level event times, and the operation of the radio data network responsible for reading out the data to a central location is not modeled. Figure 5 shows some waveform traces for a large event. Note the time delay between the shower particles starting to arrive and the trigger condition being met (at time=0). In the detectors closest to the core the number of particles is very large and the waveform takes on a smooth appearance; far from the core individual spikes due to energetic particles can be seen against lower level signal caused by soft particles.

Figure 4 shows the footprint of this shower on the ground. The radius of the circles is proportional to the logarithm of the time-integrated signal; the numbers are in units of vertical equivalent muons (VEM). At the end of this stage simulated ground array event data is available for re-analysis.

3 Event reconstruction

A simple, "first-pass" event reconstruction algorithm has been developed for Auger ground array events. This is based around the log likelihood fitter "amoeba". We define the times t_{10} and $t_{10/50}$ as the arrival time of 10% of the total signal, and the time interval between the 10% and 50% points respectively. The signal recorded by a detector is denoted by ρ, and measured in units of VEM m^{-2}.

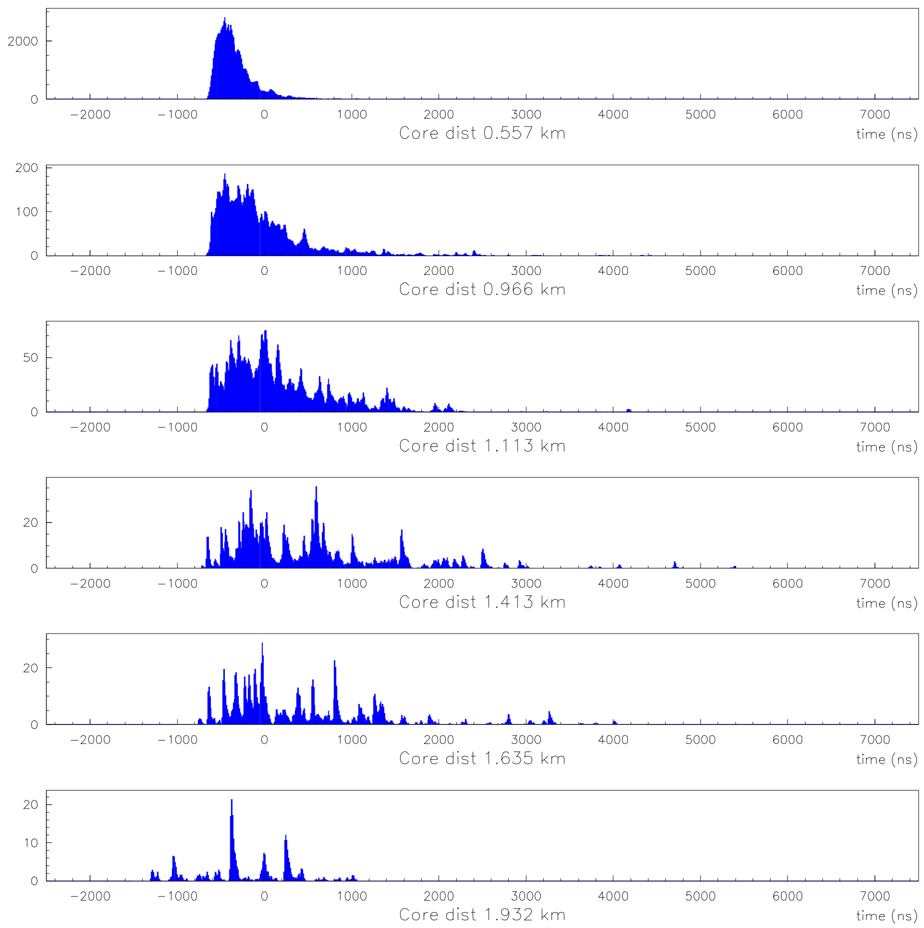

Figure 5: Simulated waveform recorder output traces for the large shower shown in figure 4. Each trace is the summed signal of the three pmts.

Event reconstruction proceeds as follows:

- Data for a single shower event is read in and ρ, t_{10} and $t_{10/50}$ determined for each triggered detector.
- A plane fit is made to the t_{10} times to obtain approximate starting values for shower incidence angles (θ, ϕ).
- A "center of gravity" of the ρ values is made to obtain starting values for (x, y) the coordinates of the core position.
- An iteration loop starts (2 cycles). First a fit for (θ, ϕ) is made using t_{10} on the assumption that the shower front is spherical in space. A fixed curvature radius R of 10 km is used at this stage, and the t_{10} values are weighted by the corresponding ρ values. Then a fit for (x, y) and shower energy E is made to the ρ values using the lateral distribution function for water Čerenkov detectors determined by the Haverah Park (HP) experiment [10]. A fixed lateral distribution slope η is used at this stage (as predicted from the HP relations).
- A final fit to t_{10} is made with (θ, ϕ) and R as free parameters.
- A final fit to the signal values is made with (x, y), E and η as free parameters.
- A fit to the $t_{10/50}$ values is made on the assumption that this quantity varies linearly with core distance, and is zero at the core.

It is not expected that the above is optimal; much work remains to be done. Figure 6 shows the fit results for the shower shown in figures 4 and 5.

Figure 7 shows the results for the full set of 100 shower events. Each MOCCA event is re-used three times to improve the statistics; since for each use the shower core is placed randomly with respect to the array grid it is probably justifiable to do this. The results are shown as scatter plots against input shower energy, and as distributions over the full energy range. The rms energy reconstruction error is $\approx 40\%$ for the proton events, and $\approx 20\%$ for iron, taken over the full energy range. This difference is to be expected as the development of iron showers fluctuates somewhat less than proton showers of equal energy. Angular reconstruction improves with increasing energy, which is also expected due to the increasing multiplicity of triggered

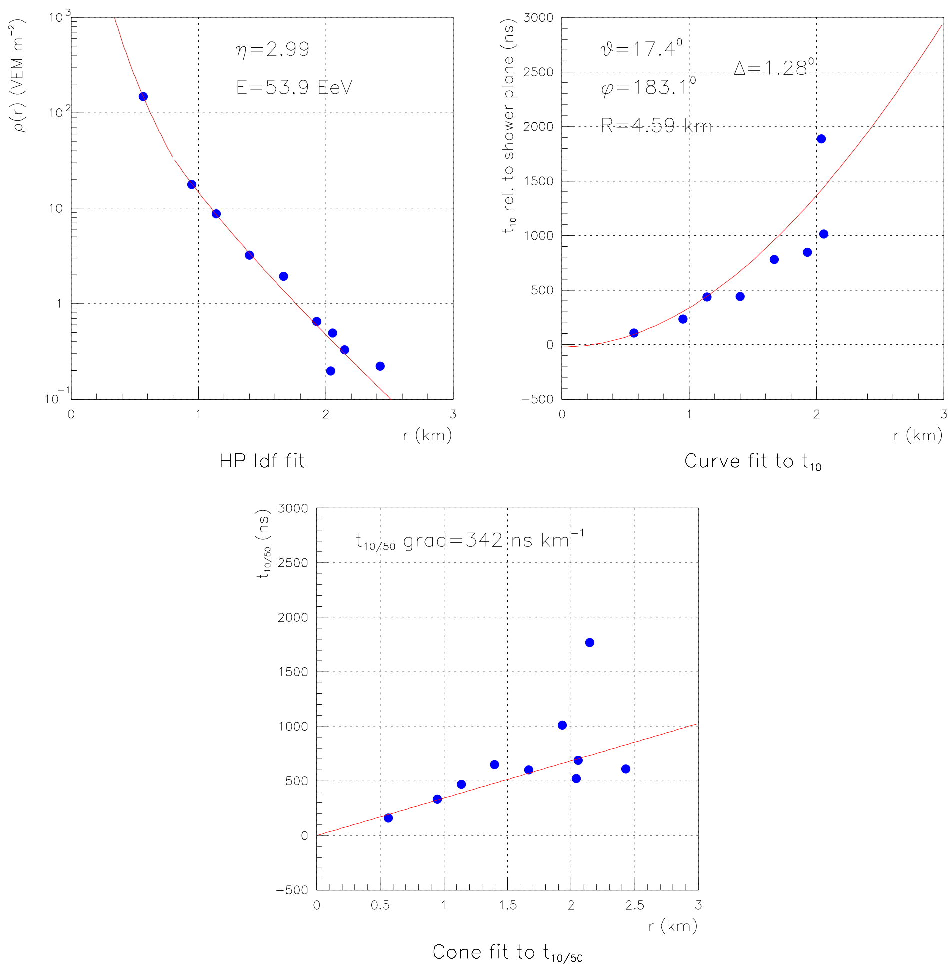

Figure 6: Reconstruction results for a single shower.

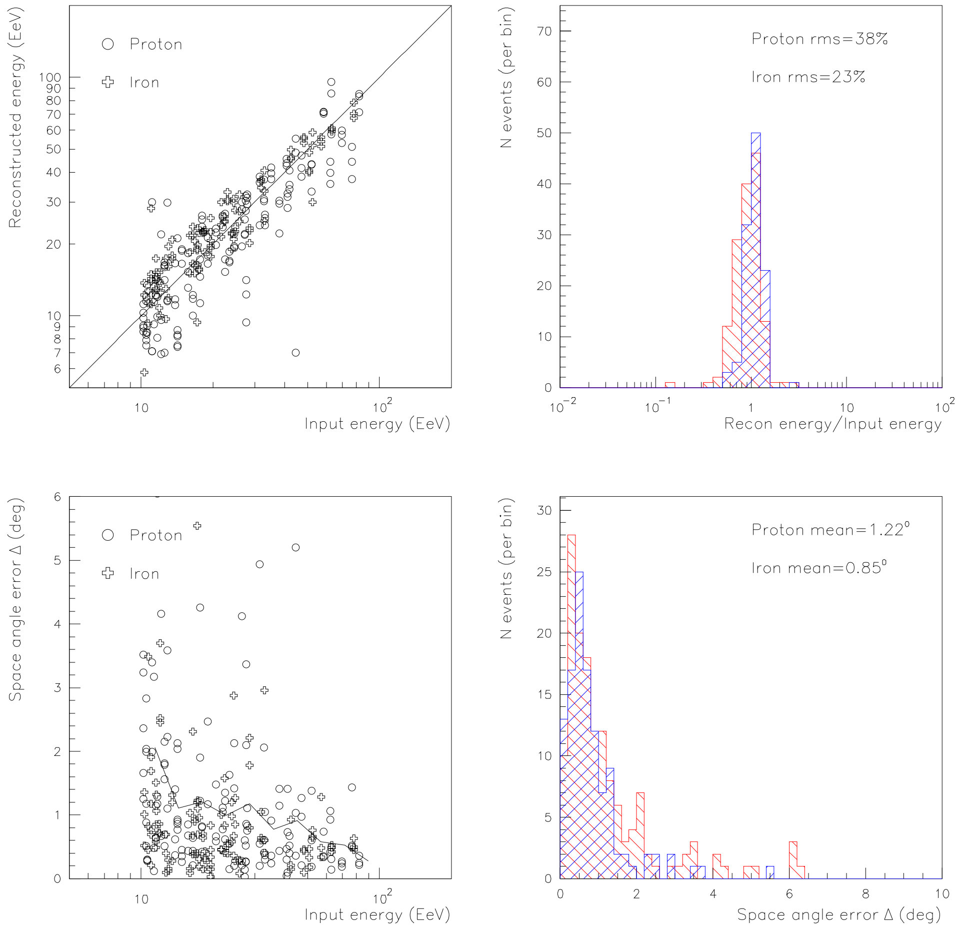

Figure 7: Reconstruction results for shower energy and incidence angle.

detectors. For all energies the mean space angle error is $\approx 1.2°$ for proton events, and $\approx 0.9°$ for iron.

Sensitivity to the nature of the primary particles is a key goal for the Auger project. It is at best difficult to achieve this using ground array data alone. There are several measurable parameters which in principle have sensitivity. Three of these are the lateral distribution slope parameter η, the radius of curvature of the shower front R, and the rate of increase of rise time $t_{10/50}$ with core distance. All of these are also expected to vary with zenith angle θ, but only slowly with shower energy. Figure 8 shows the results for these parameters plotted against the secant of the reconstructed zenith angle. In each case a linear fit has been made to the total data set and is seen to partially separate it into proton and iron components. A crude combined composition parameter has been devised and is also plotted. Although nearly independent from the reconstruction point of view, these quantities are sensitive to similar features of shower development, and hence taking an aggregate results in less than the ideal $\sqrt{3}$ improvement in separation.

It should be noted that the very detailed simulation of detector waveform traces shown in figure 5 has been developed to test the hypothesis that additional compositional information may be derived from analysis of the fine time structure of the signal. Shower muons have typical energy in the GeV range and produce sharp spikes. The more numerous, softer electromagnetic particles form a background of lower level signal. Work on this signal processing is on-going, and is not described here.

4 Conclusions

A detailed simulation of the proposed Auger water Čerenkov ground arrays has been developed. The resulting simulated data has been subjected to crude event reconstruction. Initial results indicate that energy resolution will be better than 40% random error, and angular resolution better than 1.5°. These figures will improve at the highest energies ($\geq 10^{20}$ eV) where the most critical interest of the project lies. It is expected that results will improve considerably with more intelligent reconstruction algorithms, and in particular that the out-lier events seen in figure 7 can be removed.

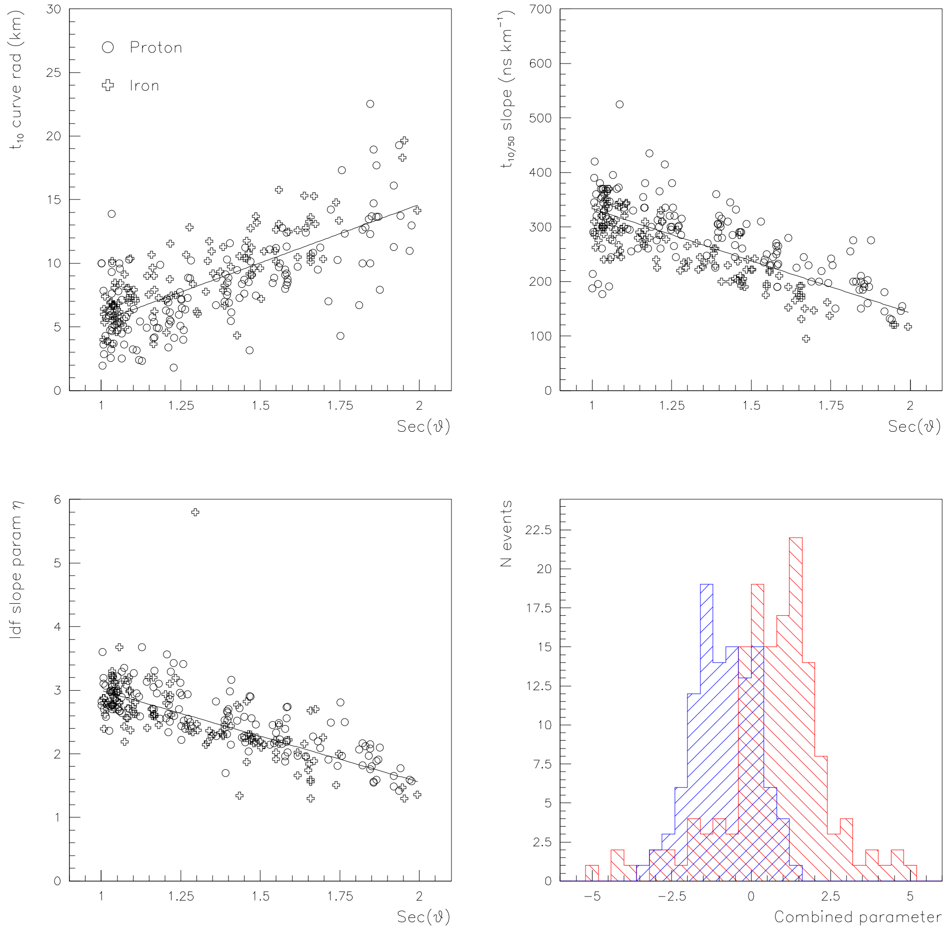

Figure 8: Reconstruction results for parameters sensitive to primary particle type.

5 Acknowledgements

The computing division of FNAL is thanked for the use of its facilities.

References

[1] A. Watson, *Nucl. Phys. B (Proc. Suppl.)* **28B** (1992) 3.

[2] N. Chiba et al, *Nucl. Instr. and Meth. in Phys. Res. A*, **311** (1992) 338.

[3] Baltrusaitis et al, *Nucl. Instr. and Meth. in Phys. Res. A*, **A240** (1985) 410.

[4] P. Sokolsky, these proceedings.

[5] The Auger Collaboration, "Design Report", FNAL, (1995).

[6] C. Pryke, PhD thesis, University of Leeds, (1996). Available from ftp://hep.uchicago.edu/pub/auger/pryke/clp_thesis.ps.gz

[7] B. Dawson et al, *Astropart. Phys.*, **5** (1996) 239.

[8] A. Hillas, Proceedings of ICRR Paris, **8** (1981) 193, and Proceedings of ICRR Rome, **1** (1995) 270.

[9] C. Pryke, these proceedings.

[10] R. Coy, G. Cunningham, C. Pryke, and A. Watson, *Astropart. Phys.*, in press.