P-907 Answers to PAC questions

1. What are the major uncertainties in the cost estimate?

The major cost uncertainties are in the procurement of the magnet Jolly Green Giant, which is a high aperture magnet with uniform field, ideally suited to the placement of the TPC. Members of the collaboration have had experience in using this magnet on a previous experiment. The magnet has a shorted coil which needs fixing, the cost of which we have estimated in the proposal. The second magnet for analysis of high momentum particles can be procured from the surplus at the Tagged-Photon lab. If the Jolly Green Giant is not available, we will have to procure a large aperture magnet to house the TPC in. To build such a magnet from scratch would cost in the neighborhood of \$1 million.

The second uncertainty is the phototubes associated with the SELEX RICH. Some of them are owned by Fermilab and others by Russian Collaborators. We are hopeful we will be allowed to use these tubes for the refurbished SELEX RICH. The cost of the tubes is \$350 each and there are 3000 in the SELEX RICH. Redoing the SELEX RICH electronics is expected to cost \$45,000.

We plan to upgrade the DAQ for the TPC for \$55,000 to speed up some bottlenecks.

2. Discuss the priorities and amount of running time needed for each part of the physics program.

The TPC is capable of acquiring data at 100 Hz. We plan to use a 1% interaction (proton interaction lengths) target, which means that the one second spill of the beam should contain 10^4 particles of the species of interest. The dead time of the TPC is $16\mu sec$, i.e. an unreacted beam particle in the center of the TPC will be drifted out in 8 μsec. With these rates, we can tolerate a beam flux of 10^5 particles per spill without unreacted beam particles being superimposed in the TPC with the event of interest. At 100 Hz of data taking, with a 3 second Main Injector Cycle time, we will be able to acquire 10^6 events in 8.3 hrs. Using the canonical factor of 3 (10^7 seconds = 1 year), this takes 25 hrs of actual time.

Scaling law time requirements

We plan to take data with a 1% hydrogen target for beam energies 5,10,20,30..110 GeV/c for p,K^+ and π^+ at 12 momenta. With the above fluxes, and the particle mixes shown in the proposal, and using prescales to optimize data acquisition times, we will take 25 hrs per proton point throughout the momentum range. Pions take 25 hrs per point from 5 GeV/c to 70 GeV/c and then run into flux problems. Kaons take 25 hrs per point from 5 GeV/c to 40 GeV/c and then run into flux problems. We can speed up data acquisition at these high momenta by going to a 2% target and tolerating more stray beam particles in the TPC. With these provisos, the positive part of the scaling law experiment will require 900 hrs.

We plan to repeat the experiment with a negative beam of $\bar{p}$, K^- and π^- particles. The π^-'s take 25 hrs per point through out the momentum range, K^- runs out of flux by 30 GeV/c and $\bar{p}$ by 20 GeV/c. Employing the same techniques of increased beam fluxes and larger target thicknesses, we plan to push up the momentum reach of K^- to 80 GeV/c and $\bar{p}$ to 50 GeV/c. We would require 900 hrs for the negatives as well for a total of 1800 hrs (75 days) for the scaling law portion of the experiment.

MINOS time requirements

We need to acquire 10^7 interactions on the MINOS target which can be done in 250 hrs. We may need to repeat the measurement at a different angle of beam incidence (to take into account the beam optics at NUMI) which may lead to another 250 hrs.

Proton radiography time requirements

Proton radiography plans are to measure particle production at 8 momenta ranging from 5,10,20...100 GeV/c on the nuclei Be, C, Al, Cu, W, and Pb with positive and negative beams. In addition there will be a target empty run at each data point. We plan to acquire 10^6 events per beam momentum made up of a prescaled mix of beam particle species. This data is expected to take 142 days to acquire.

In addition, there will of course be an initial engineering run, where we get the apparatus functional. This is expected to last approximately 3 months.

3. What are the major sources of systematic error, both overall and point-to-point, on the measured distributions of hadron energies and angles? Are there additional systematic errors involved in predicting the MINOS beam characteristics from the P-907 measurements, such as targeting issues?

The targeting issues for MINOS are addressed in MINOS Question 2 (see below). In doing the measurement, one needs to do a factor of a few better than the 2% criteria numbers listed, i.e. one should measure the beam sigma to at least 10%, and the angle of beam on target to at least 0.1 milliradian. This should not be difficult to achieve.

The systematic error for momentum measurement comes from the knowledge of the magnetic field. Past experiments (BNL E766 and FNAL E690), in which some of our collaborators participated, have used the $K_s^0 \rightarrow \pi\pi$ and the $\Lambda \rightarrow p\pi$ decays to check the geometry and the magnetic field magnitude. The magnetic field of the Jolly Green Giant has been measured each time it was assembled it for an experiment. These measurements were made on roughly 100,000 points, 1" x 1" x 2" (x,y,z) lattice with three (Bx, By, Bz) field measurements good to 1 gauss (3000 gauss is the nominal peak field). The x and y extent filled the magnet aperture, and the z extent included the target region and the downstream region ("fringe" field). This has led to the most accurate measurement of the Λ mass (one part in 5E-6) (Hartouni 94, Particle Data Group). This was achieved using a sample of 20,000 Λ hyperons and fitting kinematically. We expect to record 2E7 interactions in the scaling law part of the experiment alone, so it should be possible to have a large enough Λ sample to calibrate our energy scale. The systematic error on the energy scale would then be given by that of the Λ mass, i.e 5E-6.

The systematic error in the angles are determined by the errors in the alignment and the survey. The TPC provides a contiguous, well surveyed detector volume that is well understood in past experiments. Note also that the TPC is temperature and pressure controlled, eliminating most of the possible x-z plane geometry changing mechanisms. Alignment with drift chambers is achieved by track fit residuals and is coupled to how well one measures the magnetic field. We feel the systematic error in angle measurements would be negligible for the final state particles. The beamline can be aligned to the rest of the apparatus using target empty runs.

Note that tke K_s^0 mass calculated from the $\pi^+\pi^-$ invariant mass has a large dependence on the opening angle, the Λ mass is mostly sensitive to the momentum resolution. Systematic variations in energy scale and alignment can be examined by looking at the K_s^0 and Λ masses as a function of momentum and angle.

Finally, the changes in the geometry of the spectrometer can be checked by comparing the K_s^0 or Λ mass reconstructed by the upstream spectrometer with the same for the downstream spectrometer. The K_s^0 and Λ inclusive cross sections are roughly 10% of the inelastic cross section. There should be a large sample of these particles in the data with which to make the necessary calibrations.

The third source of systematic error for MINOS comes from particle misidentification. i.e. how often do pions get identified as Kaons. Figure 1 shows the ring-radius distribution for pions and kaons (lower ring radii) for the SELEX RICH counter (J.Engelfried et al, Fermilab-Pub-98/299E, submitted to NIM A) for 95 GeV/c-105 GeV/c momentum. The separation between pions and Kaons is excellent and SELEX estimates a mis-identification rate of 4% for pion to fake a proton or kaon. The systematic error in this measurement is introduced by the error on the 4%. It should be possible to determine the fake probability to 2% or so using again Λ's and K^0's, given enough statistics, yielding a systematic error per pion of 8E-4. This should then be folded into the Monte Carlo to yield an overall systematic error from this source, but already one can see that it is likely to be negligible for MINOS needs.

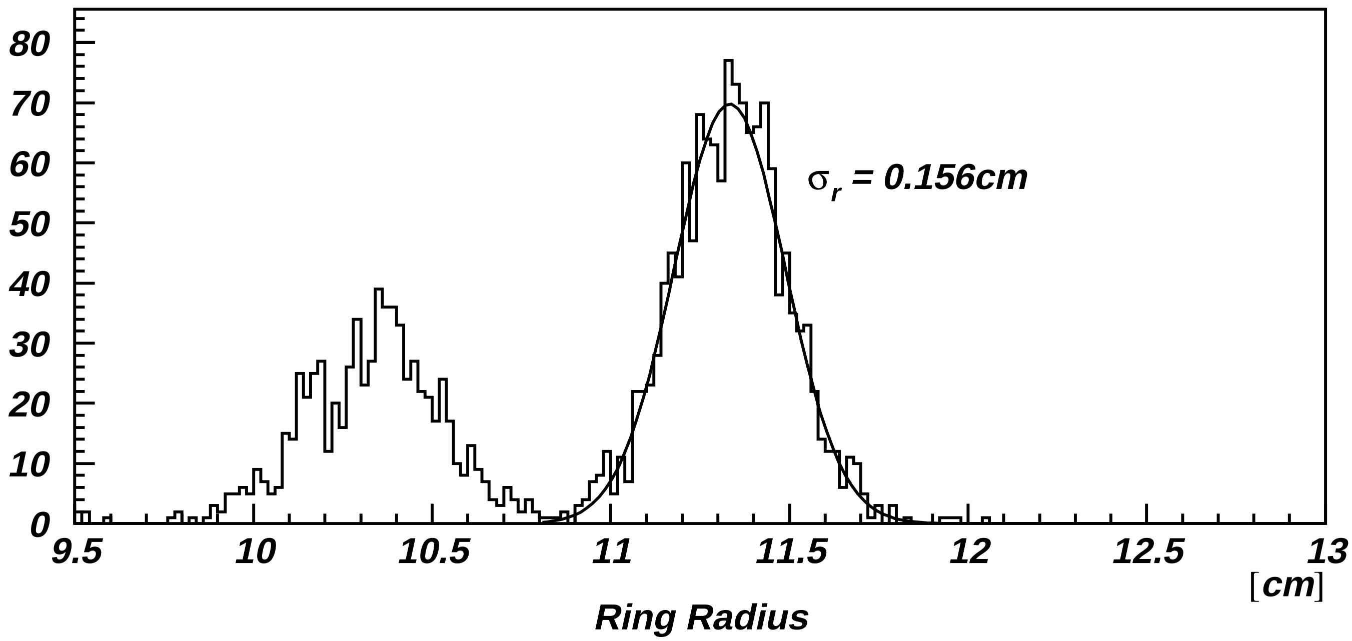

Figure 1: Ring radius distributions for interaction data for tracks with 95 – 105 GeV/c momentum. Very well separated peaks corresponding to pions (right) and kaons (left) can be seen.

4. Given these uncertainties, how precisely will you be able to predict for the MINOS experiment

a) the distributions of neutrino energy and position at the near detector? at the far detector?

b) the ratio of neutrino fluxes between the near and far detectors as a function of energy?

The ratio of the far/near energy spectra is generally somewhat less sensitive to various inputs than the individual spectra. As an example, varying the longitudinal momentum distribution of produced pions gives a nearly identical variation in the far neutrino energy spectrum (where the neutrino energy is scaled down by a factor of 2.5 because of the pion decay kinematics). The ratio of the energy spectrum in the near to the energy spectrum in the far detector is about a factor of four less sensitive to this variation. For several of the alignment parameters, however, the Near/Far ratio is only moderately less sensitive to variations than the spectrum in an individual detector. Detailed examples of various sensitivities can be found in *NuMI Wide Band Beam Alignment Requirements*, NUMI-L-221, which is available on the NuMI Beam Design web page.

A detailed extrapolation of the P907 systematic errors through the neutrino beam Monte Carlo has not been done, and should be done in the future. But from studies of the sensitivity of the ratio of MINOS Far/Near detectors to the hadronic production model, we know that measurements of the pion production spectrum to several percent is what is needed for NuMI to get below the 2% criterion for the medium energy beam. A measurement of the transverse and longitudinal momentum spectrum of pion production from the NuMI target at the 2% level would allow an absolute prediction of the neutrino spectrum in the near detector, which would serve as a powerful cross-check of the prediction of the spectrum in the far detector. A less stringent measurement, of the order of 5% in pion production, would constrain the far/near neutrino ratios to the required 2%.

5. Compare the impact of the hadron-spectrum measurement on establishing the far detector to near detector neutrino-flux ratios for the three neutrino beams being planned for MINOS. The Committee notes that p. 32 (Conclusions) of the presentation to the PAC states that knowledge of the hadron spectrum is even more important for the low beam energy configuration.

Figure 2 indicates the sensitivity of the high energy beam configurations to the hadronic production uncertainty, Figure 3 shows the same for the medium energy (baseline) configuration, and Figure 4 shows the low energy configuration.

In each figure, the top graph shows the energy spectrum. The solid histogram is the spectrum at the far detector, with the error bars showing the Monte Carlo statistical error. The dashed histogram represents the spectrum at the near detector, scaled by the factor 0.863×10^{-6} for the high and medium energy beams, and scaled by the factor 1.25×10^{-6} for the low energy configuration.

The middle graph shows the relative spectral changes that would be induced by oscillations with $sin^2(2\theta) = 0.1$ and with different values of δm^2. For the high energy configuration, $\delta m^2 = 0.010\ eV^2$ is shown. For the medium energy configuration, $\delta m^2 = 0.010\ eV^2$ (dashed line) and $0.005\ eV^2$ (dotted line) are shown. For the low energy configuration, $\delta m^2 = 0.005\ eV^2$ (dashed line) and $0.002\ eV^2$ (dotted line) are shown. Statistical error bars per GeV from a two year run (10 kilo-tonne years) are also shown. The values of δm^2 are in the region indicated by the SuperKamiokande experiment, but the mixing parameter has been chosen so that the detected oscillation is of a size similar to the systematics discussed below. Increase of the mixing parameter would to first order linearly increase the size of the effect, with the dips at the same locations.

For each configuration, the bottom graph shows relative spectral distortions from a couple variations in the hadronic production model. The solid curve is derived by comparing the model in the GEANT/FLUKA Monte Carlo to the same model but with the mean P_t of pion production modified to approximately that found in the NUADA and PBEAM Monte Carlos. The dashed curve shows the result of a more arbitrary 20% variation in the P_l spectrum of pion production in the GEANT/FLUKA Monte Carlo.

In general one sees that the Near/Far ratio is less sensitive to hadronic production variations at low energy. Furthermore, the statistical power of the event sample for the low energy configuration is not as good. Hence the improvement to the MINOS experiment given by the hadronic production measurement would be less in the case of the low energy beam. However, one sees that for both the medium and high energy cases the P907 measurement would substantially improve the ability to measure the neutrino oscillation spectrum, and hence make a precision measurement of the oscillation parameters.

P-907 Comments on remark on page 32 of PAC presentation- It can be seen from Figure 4 that the low energy spectrum *is* subjected to distortions from particle production uncertainties. Further, low energy particles have enhanced contribution from secondary interactions in the target which will thus have cumulative error contributions from Geant/Fluka cross section and multiplicity assumptions. This contribution is not estimated by changing the p_T spectrum of the pions, as in the current analysis. It turns out however that the distortions are in a region of neutrino energy that MINOS is insensitive to for the low energy run.

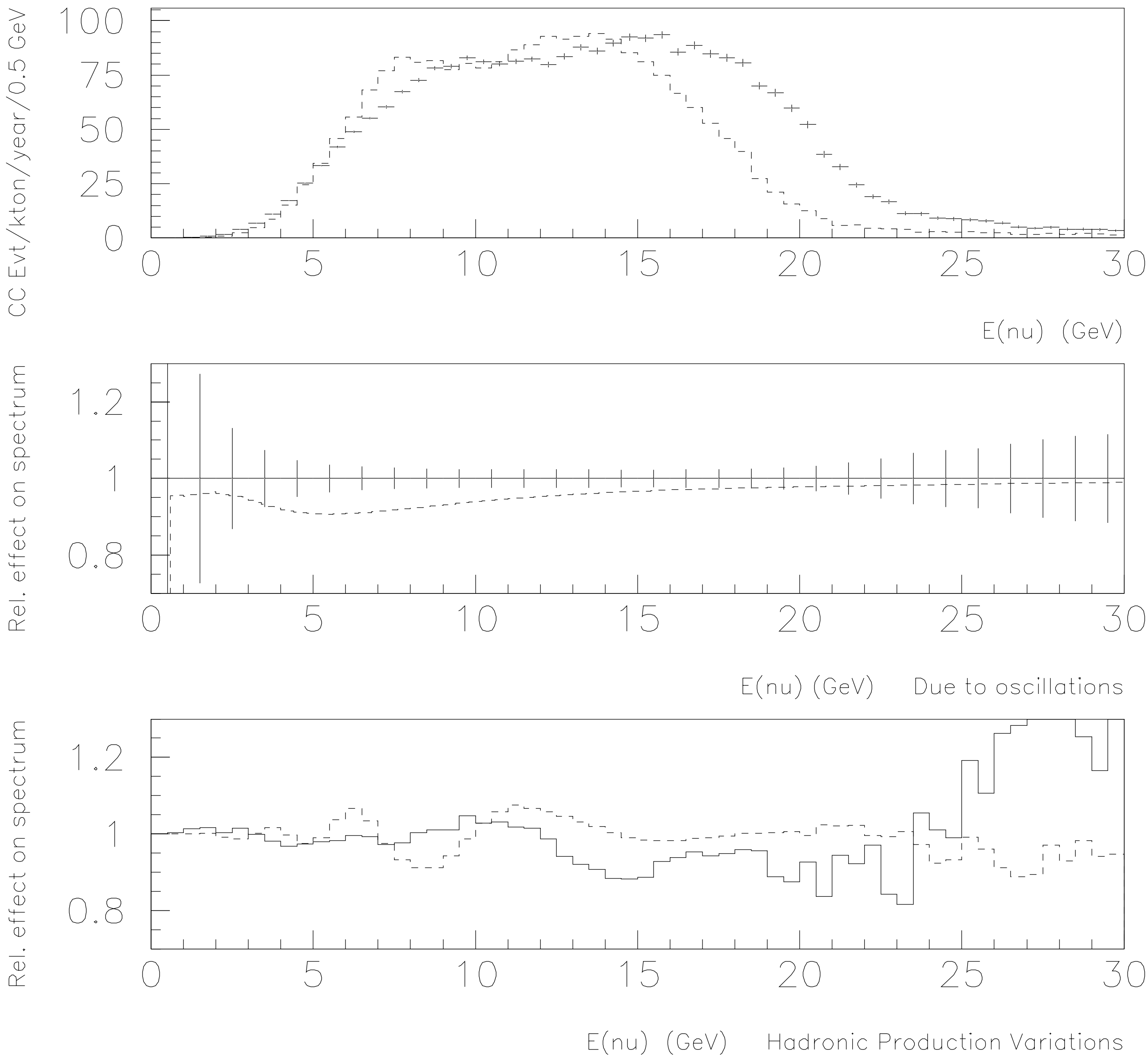

Figure 2: NuMI High Energy Beam Configuration

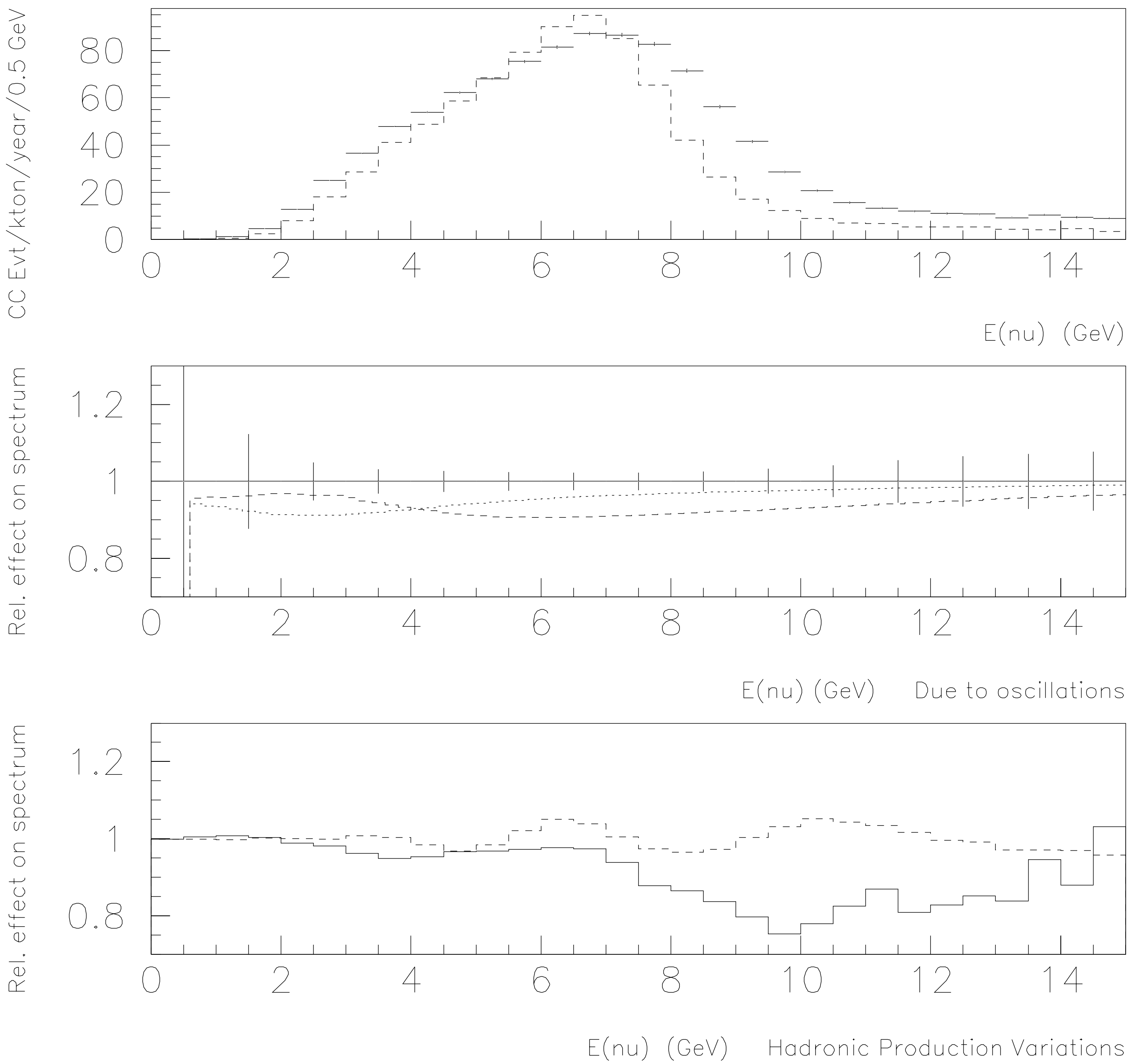

Figure 3: NuMI Medium Energy Beam Configuration

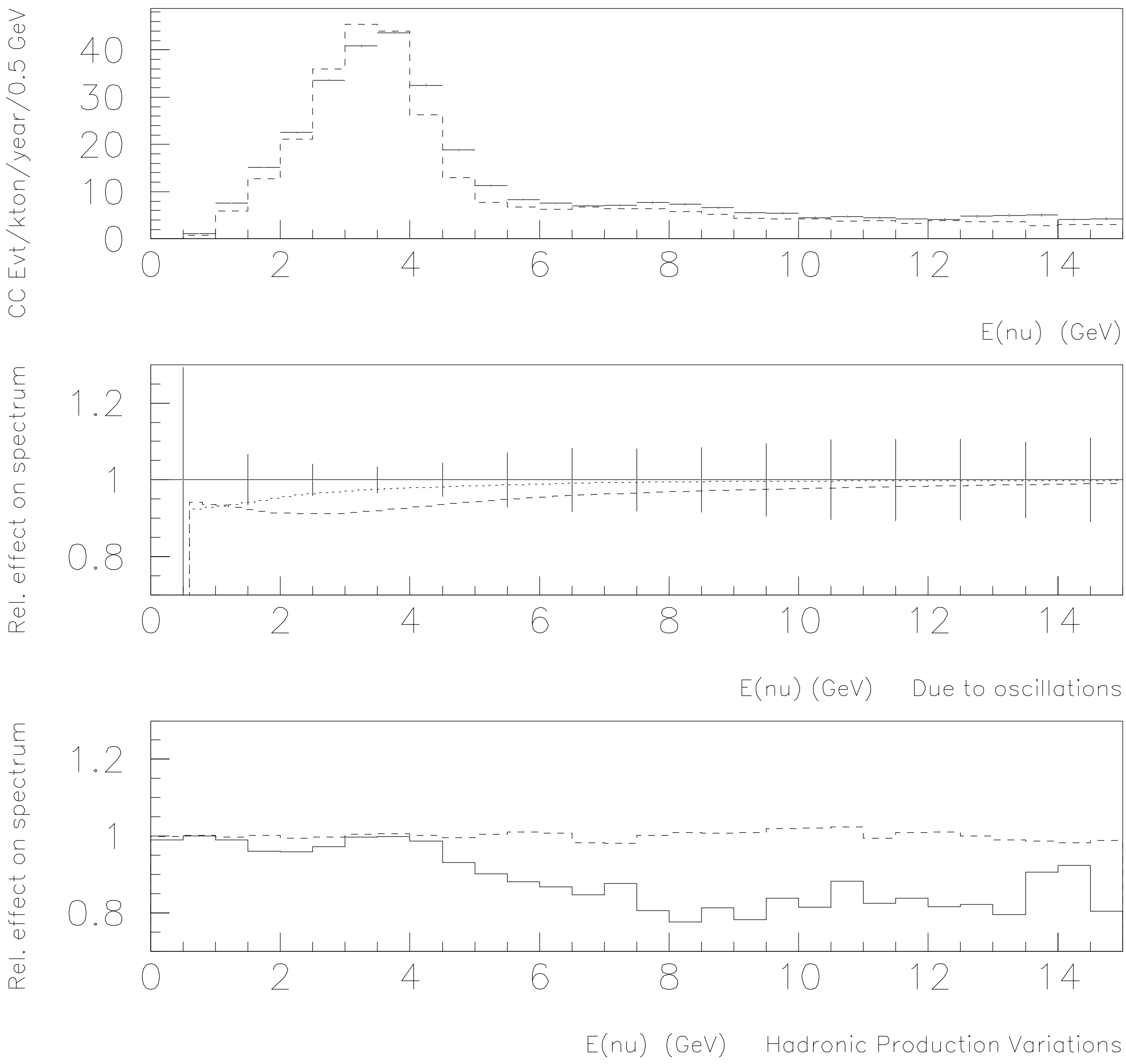

Figure 4: NuMI Low Energy Beam Configuration

MINOS Question 2. What are the major uncertainties in neutrino flux due to beam environment not addressed in question # 1, (e.g. targeting angle, beam dispersion, horn alignment, etc.)?

The NuMI Facility Technical Design Report, Oct. 1998, has a table on page 3.6-12 which addresses this question. In particular, the uncertainty in calculating the far detector spectrum from the near detector spectrum is listed as 0.015% due to the angle of beam on target, 0.6% due to horn 1 transverse offset, 0.4% due to horn 1 rotation, etc. Our criterion has been to work hard enough on alignment that we expect less than 2% uncertainty from these factors. The major item not addressed in that table is the horn magnetic field, which must be known to somewhat better than 1%. We plan to measure the field of the horn on a test bench, and the current will be monitored to 0.4%. The errors due to dispersion and beam spot size uncertainties has not been explicitly calculated for the current design, however in a previous similar design the spot size RMS had to change by 34% to cause a 2% uncertainty in the extrapolation from near to far detector (*Conceptual Design for the Technical Components of the Neutrino Beam for the Main Injector*, Sept. 1997, page 62). Considering the insensitivity to spot size and targeting angle, uncertainty in the dispersion is not thought to be a problem.