NuTeV DET019

NHL Limits: Production and Background Studies

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Overview:

The purpose of this writeup is to document information and address issues concerning the NHL decay channel proposal which were raised by the collaboration at and after the Oregon Meeting. The decay channel is to be installed in Lab F and will consist of an upstream veto wall, a helium-filled decay region, and drift chambers for tracking. The Lab E detector is used for particle identification. The organization of this write-up is:

- Introduction
- NHL sensitivity as determined from a set of production Monte Carlos,
- Cuts applied to the data,
- Backgrounds from Lund and Geant based studies
- Conclusions

For those who want to skim, a summary of each section is provided in italics at the top.

INTRODUCTION

The following document presents additional information on the proposal to build a decay channel in Lab F to search for decays of Neutral Heavy Leptons. The search for neutral heavy leptons which undergo weak mixings with the standard model neutrinos has a long history.[1] Such relatively heavy leptons are not forbidden by the Standard Model and result from various plausible extensions to the theory.[1] In these extensions, the neutral heavy leptons are isosinglets, but mix with the Standard Model neutrinos in such a way that the observed neutrinos have a small admixture of the heavy state. Simple models for the mixing have been developed and lifetimes and branching ratios for decays have been estimated.[1] A high statistics neutrino experiment with a multipurpose detector, such as NuTeV, is an ideal place to search for signs of the existence of these particles. One possible source of neutral heavy leptons which could be observed by NuTeV is from particle production in the beam line. Mesons produced in the beam line target and proton dumps can decay to a neutral heavy lepton plus a charged lepton. Because the beam line is $\sim 1.3\ km$, these neutral heavy leptons must have a relatively long lifetime and hence relatively low mass. These heavy leptons can then decay into a neutrino and two charged leptons.

The sensitivity which NuTeV can expect, based on the studies presented here, for 3×10^{18} protons on target (our minimum) and 6×10^{18} protons on target (our expectation), are shown in figure 1. Equal running in neutrino and antineutrino mode was assumed. In the following text, NHL will be used to denote neutral heavy lepton.

Design of the Decay Channel

The channel detectors are an upstream veto wall and four downstream drift chambers. The decay space is filled with a helium bag. The design of the channel has not changed since the Oregon Meeting.

The purpose of the proposed Lab F decay channel is to observe decays of neutral heavy leptons to $\mu\mu\nu$ and $\mu e\nu$. Therefore, the channel must have detectors to veto incoming charged particles, to track particles from decays, and to identify the particles as electrons, muons or hadrons. The proposed design is a veto wall followed by a helium bag which extends the length of the channel, followed by four drift chambers placed directly in front of the Lab E detector. A schematic of the channel is shown in figure 2.

The veto wall would consist of two planes of scintillator with two inches of steel shielding upstream. It would be located approximately 5 m from the upstream wall of Lab F. The wall would be $15' \times 15'$. As a result, a hole in the wall is necessary to allow the test beam to pass through. The hole will be located on the east edge of the wall. The wall will be assembled from scintillator from Bicron Corporation. This is the same scintillator used in our Lab E veto wall, so all of the preliminary studies have been performed. The efficiency of these counters, according to Unki's tests, is 99.96%.

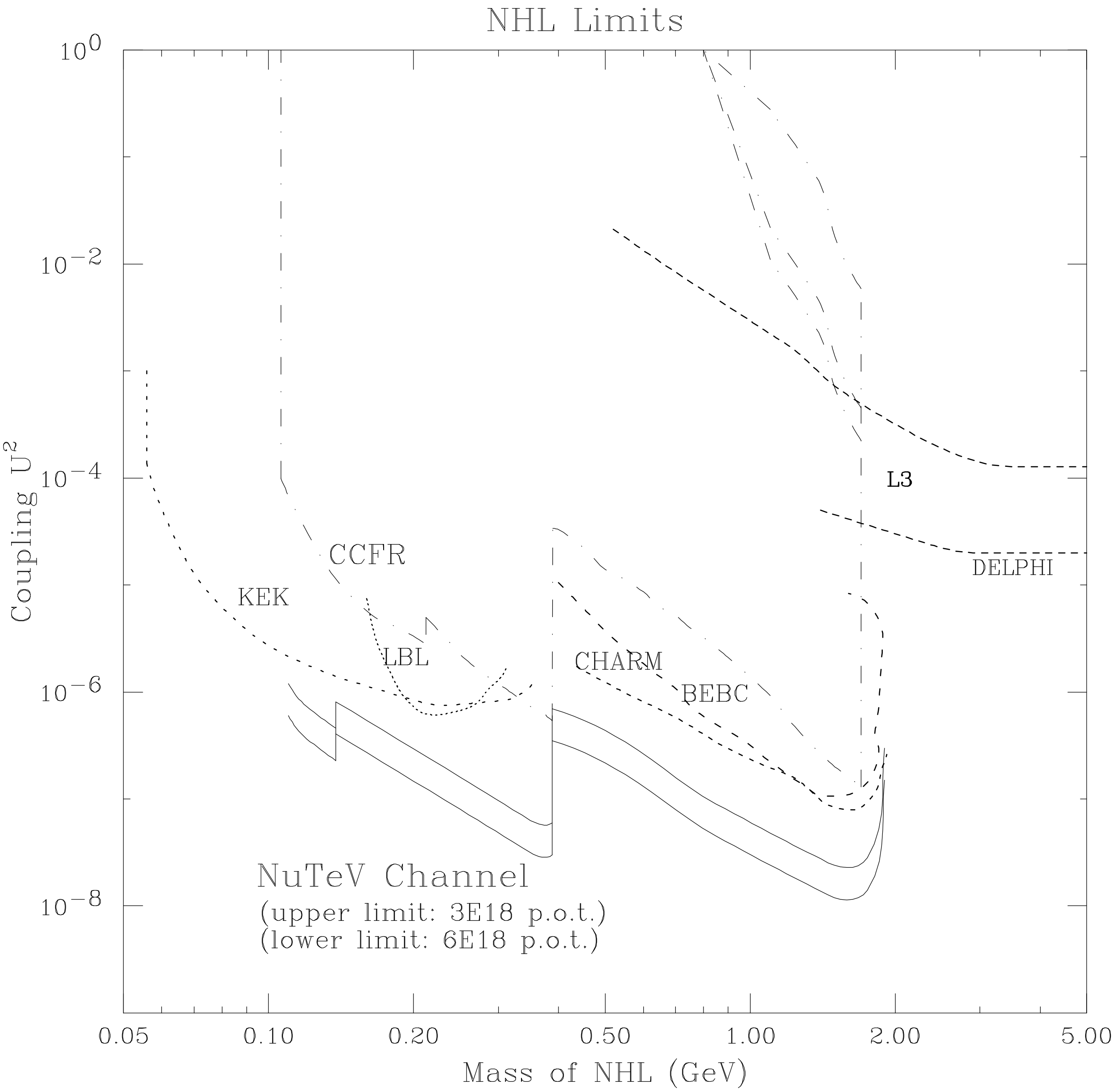

Figure 1: Sensitivity of NuTeV with the Lab F decay channel

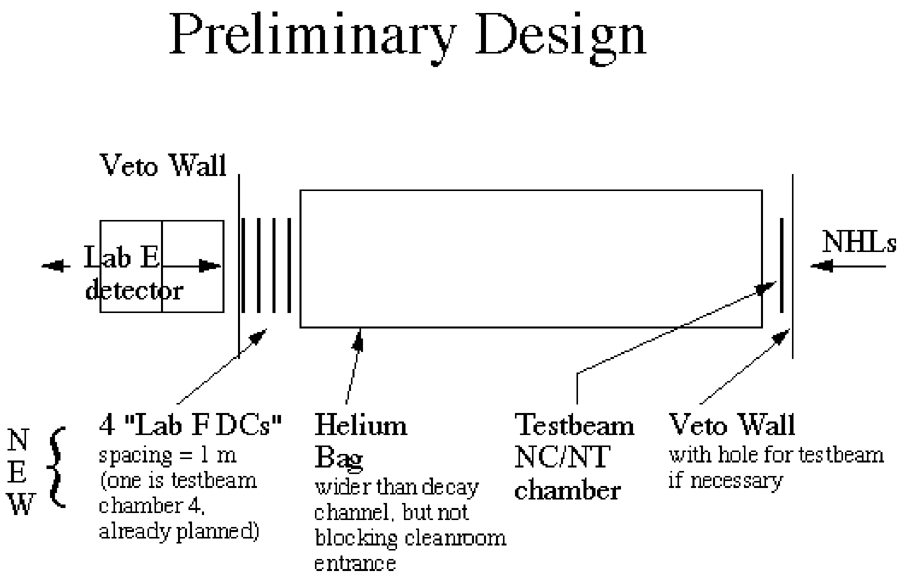

Figure 2: Layout of the proposed decay channel

The helium bag will be $15' \times 15' \times 40\ m$. It will be suspended by a unistrut frame.

The redundant drift chambers from the toroid region will be moved to the region in front of the detector to provide tracking. As was presented at the Oregon meeting, removing these chambers does not hamper our ability to reconstruct high energy muons from neutrino events. One of these chambers is assumed to be the spectrometer chamber for the NuTeV test beam. The chambers will be placed 1 m apart. They will be supported by unistrut stands, which are standard Fermilab design. Nevis will supply the stands.

The Lab E detector provides particle identification. The specifics of the identification is discussed below in the section on Cuts. However, in general, muons are required to traverse approximately 2 m of steel, while electrons are required to have showers which are classified as electromagnetic based on the shower profile.

EXTRACTION OF SENSITIVITY

The sensitivity which can be expected are presented in Figure 1. They are approximately the same as what was presented at Oregon. They have been calculated from Monte Carlo simulations.

This section describes the Monte Carlos which were used to obtain the neutral heavy lepton sensitivity, presented in figure 1. The sensitivities shown are calculated for 3×10^{18} protons on target (our minimum) and 6×10^{18} protons on target (our expectation). Equal running in neutrino and antineutrino mode of the SSQT was assumed. These limits are calculated from meson production production and decay simulations described below.

The method for calculating the sensitivity for NHL lepton production follows the method described by Gronau, Leung and Rosner (GLR).[1] Limits are expressed in terms of the mass of the NHL, m_N, and the coupling $|U|^2$. First the production of the heavy meson and its subsequent two and three body decays must be simulated. The branching of the heavy meson to the NHL must be calculated. The number of NHLs which survive to the start of the NuTeV decay channel, approximately 1300 m, must be found. The sensitivity is then based on the number of NHLs which decay within the channel. The NuTeV detector will be sensitive to decays to $\mu\mu\nu$ and $\mu e\nu$. The acceptance of the channel to these modes, based on the cuts described later, has been folded into the sensitivities presented here.

π and K Meson Production

π and K production is obtained from the E815 Monte Carlo

The pion and kaon production was simulated using the turtle-based[2] E815 Monte Carlo which is available through CVS. This code is located in jconrad/nhl/beammc. No changes from the E815 standard were made. Only charged pions contribute to the pion limits. For the kaon limits, charged and neutral kaons were considered, however it was found that the charged kaons were the dominant source of NHLs. Charged pions and kaons were produced at the target and transported up to the meson decay pipe, where the weight and momentum vector were recored for input into the decay program. Neutral kaon momentum vectors were recorded at the target. The decay programs, jconrad/nhl/production/kdecays/kprod.F and /pidecay/piprod.F, transported each meson to the point of decay. The programs then allowed two and, in the case of the kaon, three body decays, for a range of possible NHL masses. The resulting NHLs were projected to the NuTeV decay channel. Those within the acceptance were recorded in a file for input into the program which finds the sensitivity.

D Meson Production

A Monte Carlo was written to simulate the production of D and D_s mesons in the beam line target and dumps. Production is based on parameterizations of experimental measurements.

Production of D mesons is not simulated in the E815 standard monte carlo. So a new program for D production was written based parameterizations by Frixone, *et al.*[3] of heavy flavor production data. Data from two 800 GeV fixed target experiments, E653 and E743, as well as data from lower energy experiments were considered in the parameterizations. In the simulation, D mesons were produced according to $(1-x_f)^{8.36}$. The p_T^2 distribution was taken as a falling exponential, $e^{-0.635 p_T^2}$, for low p_T^2. For high p_T^2, the distribution which fits the data is $(1/(Am_C^2 + p_T^2))^{\beta}$, where $A = 1.966$, $m_C = 1.5$ GeV, and $\beta = 5.540$. The cross section for D meson production was taken to be 27μb, based on an average of the E653 and E743 experiments. The production was normalized to the total cross section for 800 GeV fixed target proton-nucleus scattering. The total cross section has an $A^{.67}$ dependence, while D meson production has A-dependence of $A^{1.0}$.[3,4] The p-p scattering cross section was taken to be 43 mb.[6] Production from D_S mesons was taken to be 0.54 of the D meson rate.[5] The D mesons were then allowed to decay via 2 and 3 body decays. The resulting NHLs were projected to the NuTeV channel, and those which were found to be within the acceptance were recorded in a file.

D meson production by 800 GeV protons on the BeO target and the proton dumps provided the main contribution to the NHL sensitivity. In calculating this limit, the angle at which the protons hit the target and proton dumps in the two running modes was taken into account. Equal time was assumed for running the sign selected quad train in positive and negative bending mode. The code for 800 GeV proton production of D mesons can be found in jconrad/nhl/production/d-major/dprod.F. Other contributions for production of D mesons were investigated and found to be small. This includes reinteractions of secondaries in the target and proton dumps and secondaries striking objects within the beam line. The input protons and pions for these studies were obtained from the standard E815 turtle Monte Carlo discussed above. The code for the production from these secondary sources can be found in the directory jconrad/nhl/production/d-minor.

B Meson Production

A B production Monte Carlo was written. However, the rates of production and decay are such that NuTeV cannot set interesting limits from B mesons. So the following is just informative.

Because of the low production rate and the distance from the target to the decay channel, NuTeV will be unable to set interesting limits from B production. However, in case there is interest in how this conclusion was reached, the production code is located in jconrad/nhl/production/bdecays. Information for production of B mesons in fixed target experiments is relatively sparse. Theoretical estimates for the cross section for B meson production by 800 GeV protons on a fixed target vary from 39 nb down to 4 nb.[7] Experiment 772 measured[8] the total cross section to be 5.7 ± 1.9 nb. As this is one of the few direct experimental results, 5.7 nb was used in the simulation. Parameterizations of the x_f and p_T^2 distributions from Mangano, *et al.*,[7] were used for the simulation. The x_F parameterization was the same as for the D mesons, above. The p_T^2 parameterization was of the form $(1/(m_b^2 + p_T^2))^\beta$, where $m_b = 5.0$ GeV, in agreement with the E772 result cited above, and $\beta = 5.540$. Three body decays of the B mesons were simulated, the resulting NHLs were projected to the NuTeV channel, and those within the acceptance were written to a file. Again, the acceptance for the two SSQT modes was included in the simulation, with equal running time assumed.

Branching Ratios for Heavy Mesons

Branching Ratios are based on calculations by Gronau, Leung and Rosner.

The fully-leptonic and semileptonic branching ratios for heavy meson decays to NHLs have been calculated by GLR. This study follows their prescriptions. NHLs which couple to the electron family (N_e) and the muon family (N_μ) were considered.

In general, the fully-leptonic decay branching ratios to a neutrino and a charged lepton are modified by the coupling to obtain the NHL branching ratio. However, in the fully-leptonic modes where the branching is suppressed by helicity, such as in the case of the D and D$_S$ decays, the branching ratios to neutral heavy leptons are explicitly calculated by GLR, in equations 3.14 and 3.15. It is interesting to note that the D$_S$ branching fraction exceeds the D branching fraction by almost the same factor as the D$_S$ production is suppressed with respect to the D. The branching ratios from this study (divided by the coupling) are shown in table 1 for comparison. As a result of this effect, the D and D$_S$ contribute approximately equally.

The semileptonic branching ratios of heavy mesons to NHLs are related to the semileptonic branching ratios to neutrinos by the form:

$$Br(A \to BN\ell) = Br(A \to B\nu\ell) I(m_A, m_B, m_N, m_\ell)|U|^2$$

where A is the heavy quark, B is the next lighter quark, N is the NHL, ν is a neutrino and ℓ is a charged lepton. The function I, which depends on the masses of the quarks and leptons, is given by GLR, in equation 3.39 and 2.40. The function highly suppresses semileptonic decays for NHL masses approaching the mass of the decaying particle. So near the boundary of the limit set by each meson decay, it is the fully-leptonic decays that mainly contribute. An example of this is is shown in table 1, which compares the semileptonic to the leptonic branching ratios for D mesons. The B meson effectively has no fully-leptonic decays because V_{ub} is very small. Because the semileptonic branching is highly suppressed at large masses, very few high mass NHLs are produced. This is one of the reasons we cannot set interesting limits through B decays in NuTeV.

m_N	$D^+ \to Ne^+$	$D_S^+ \to Ne^+$	$D^+ \to meson + Ne^+$
0.25	1.2E-3	1.1E-2	7.5E-2
0.55	5.0E-3	4.8E-2	4.8E-2
0.85	9.0E-3	9.0E-2	2.2E-2
1.15	1.0E-2	1.1E-1	6.0E-3
1.45	6.8E-3	8.1E-2	7.5E-4
1.75	9.5E-4	2.6E-2	6.3E-6

Table 1: Branching Ratio divided by Coupling for D meson decays. This table is comparable to figure 7 in GLR.

Decays of NHLs

Lifetimes and Branching Ratios are based on calculations and tables from the paper by Gronau, Leung and Rosner.

The lifetime of the NHLs, as calculated by GLR in equations 2.47 and 2.48, depend on the mass of the NHL and inversely on the coupling. With this, the number of NHLs which survive to the NuTeV decay channel can be calculated. The two observable decay modes for NuTeV will be $\mu\mu\nu$ and $\mu e\nu$. The branching ratio for these decay modes is based on a parameterization of table 1 in the paper by GLR. NHLs from pion decays must be above $\sim$ 110 MeV in order to decay to $\mu e\nu$. It will be interesting to consider whether limits can be set in $ee\nu$ decays in the channel because that would extend our sensitivity into an unexplored region. However, this will be difficult and has been left for consideration in the future. Below the threshold for production of two muons, several NHL decays are absent. The remaining branching ratios were scaled to total 100%. By coincidence, the scaled $\mu e\nu$ branching ratio below threshold results in total decays almost equal to the ratio above threshold for decays to $\mu\mu\nu$ and $\mu e\nu$ combined. So the threshold is shown as a smooth curve on the plot.

Incorporating acceptance into the Limits

The acceptance is determined as a function of NHL mass, position of the decay in the channel and the decay mode. The acceptance has been folded into the limits presented here.

The sensitivity shown in figure 1 have acceptance of the channel and Lab E detector included. The details of the cuts on the decays is discussed in a later section. This section describes the way in which the acceptance was incorporated into the limit determination.

The acceptance for decays from these NHLs was determined at 5 m intervals in z in the decay channel. In a change from the algorithm used to find the acceptance in the first draft of this note, the z position was chosen from a random flat distribution within the 5 m interval (before, the z position was always at the center of the interval). At each z-interval, the acceptance was determined in a transverse 10×10 grid, where each region of the grid was 30 cm^2. In order to determine the acceptance at each point in the grid, NHLs which were tracked to that region in the channel were allowed to decay many times. The tracks from the decay were projected to the detector and the cuts on the decays were applied. The acceptance was calculated separately for $\mu\mu\nu$ and $\mu e\nu$ decays. The acceptance was calculated for each generated NHL mass. The code for calculating the acceptances can be found in jconrad/nhl/production/limits/accept.

As an example, the acceptances for decays occurring at the most upstream 30-25m of the decay channel are shown in figure 3 for six NHL masses, and for the two decay modes. The acceptances are shown in percent. It can be seen that the acceptance drops steeply near the edges. The acceptance also drops as the NHL mass increases because the decaying particles have higher P_T. The acceptance for $\mu e\nu$ decays is worse than for $\mu\mu\nu$ decays because of the energy cuts imposed for particle identification, which are discussed later.

The tables of calculated acceptance are used to adjust the NHL weight for the fractional acceptance. The final limit is determined by calculating the number of NHL decays that are expected to occur in each 5 m section of the decay channel by summing the NHL weights. So multiplying the NHL weights by the fractional acceptance for the correct mass, z section, x, y position, and decay mode folds the acceptance into the sensitivity determination.

Calculation of Sensitivity

Sensitivity is for 90% confidence level.

After all of the above is taken into consideration, the observable number of NHL decays depends on three free parameters: the number of protons on target producing the heavy mesons, the mass and the coupling. For the limits presented here, we will assume the minimum and expected intensities expected for NuTeV: 3×10^{18} protons on target and 6×10^{18} protons on target, respectively. As discussed later in the section backgrounds, no events are expected in the channel. If no events are observed, the upper limit on the number of events which could be produced, at 90% confidence

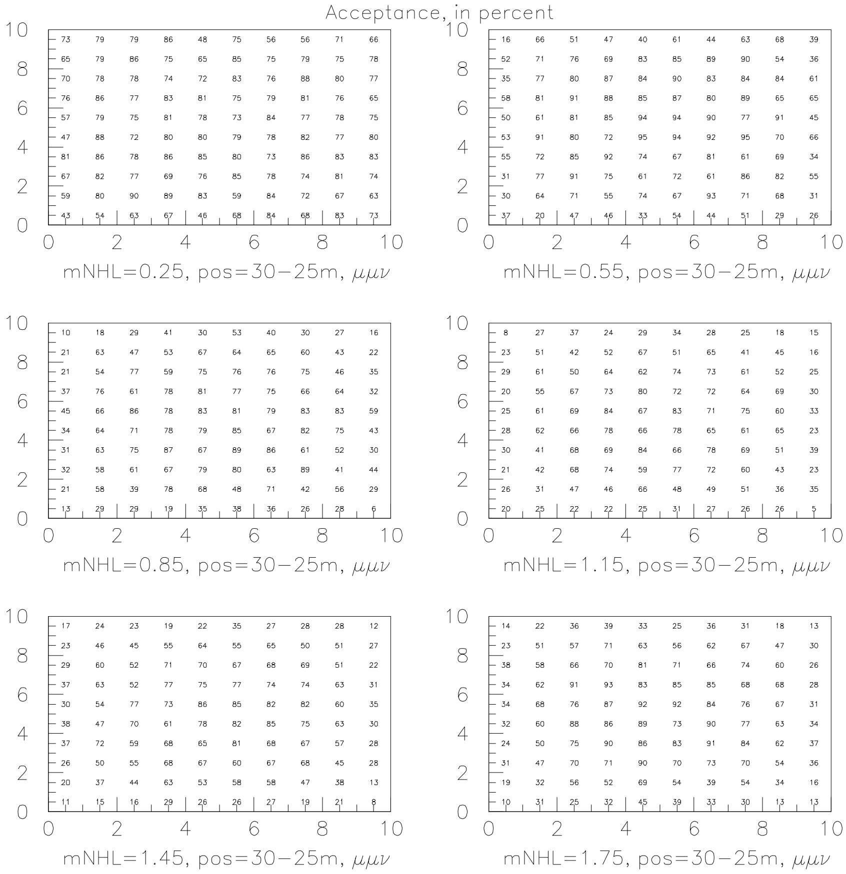

Figure 3: A) Example of acceptances for six NHL masses, $\mu\mu\nu$ decays

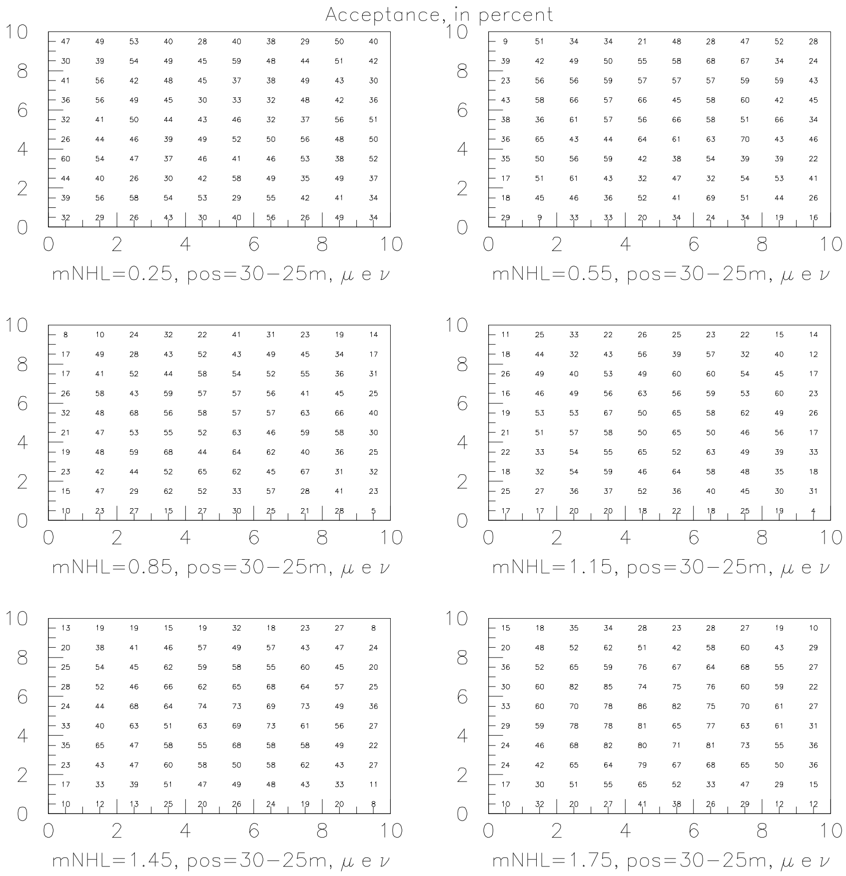

Figure 3: B) Example of acceptances for $\mu e \nu$ decays, in percent

level, is 2.3. So the limit in mass and coupling space is the choice of those parameters which yields 2.3 events in the channel. The resulting sensitivity is shown in figure 1. The limits exceed the previous experimental limits over a large region, and by more than an order of magnitude in some regions. The code to obtain the limits presented here is in jconrad/nhl/production/limit.

CUTS APPLIED TO THE DATA

The goal of the cuts on the data described below is to isolate NHL decays in the $\mu\mu\nu$ and $\mu e\nu$ modes from backgrounds which can simulate these decays. In general these cuts are designed to identify an unaccompanied neutral which decays in the channel fiducial volume into only two charged particles which can be identified in the Lab E detector as either two muons or a muon and an electron.

General Cuts

General cuts are: no veto, two tracks and a vertex in the channel

In the case of all candidate events, the requirements were: no hit in the proposed Lab F veto wall, only two tracks reconstructed in the proposed Lab F drift chambers, and a vertex which reconstructs within the decay channel volume. Each of these cuts is considered separately below.

The veto is expected to be 99.96% efficient based on tests of the Bicron counters obtained for the Lab E detector veto. However, for the sake of argument, a 1% inefficiency in the veto wall is assumed. For the limits obtained above, it was assumed that there were no spurious vetoes.

In order to understand the efficiency for finding exactly two tracks in a relatively noisy environment, hits in the drift chambers of the muon spectrometer located behind the calorimeter (the blue cart) were studied. This is a much noisier environment than the channel is expected to be, because the calorimeter is much closer to the chambers than the berm will be to the chambers in the proposed channel. 100 events were visually scanned. In neutral current events, approximately 42% of the events had hits in the chambers, but these hits did not form tracks. For charged current events, 28% of the events had clean muon tracks, while the remaining had excess hits. In most cases, the hits clustered around the region of the muon track. The excess hits formed a second track in only one event. The extra track extended partly into the toroid calorimetry. It may, in fact, have been a real, backward-going cosmic-ray. The conclusion of this study is that the environment should be sufficiently clean to impose this cut without affecting the efficiency for finding NHL decays. In the limits shown above, two tracks within the Lab F drift chamber acceptance were required.

The resolution on the position of the vertex depends on the length of projection, a maximum of 30 m; the wire spacing of the chambers, 250 μm; the chamber spacing, 1 m separation; the material in the chambers, 13% of a radiation length; and the energy and angle of the incoming particles. For the decays of NHLs produced from D decays, in the mass region of 0.4 to 1.8 GeV, the average opening angle of the charged leptons in the NHL decay was 0.002 rad. The average energy was 56 GeV. From this, one can calculate that the resolution on the z position of the vertex is 7%. So for a decay which occurs at the upstream end of the channel, the vertex resolution is 2.1 m. Because of the poor resolution, the channel is defined to begin 6 m downstream from the helium bag. The channel is defined as a $3m \times 3m$ region within the $4.5m \times 4.5m$ helium bag.

Reconstruction of a vertex was required within the $3m \times 3m \times 30m$ region of the channel with a separation at closest approach of less than 10 cm. The code for this is contained within the acceptance calculation code in jconrad/nhl/production/limit/accept. For each NHL decay, the tracks were projected to the Lab F DCs. Smearing of the hits for each track included multiple scattering and the resolution of the chamber. The tracks were reconstructed using a least-squares fit to the points. The tracks were then projected back into the channel to locate the vertex. The z position of closest approach and separation of the tracks at this point were identified. The separation at closest approach requirement cut no NHL decays but eliminated some background, as discussed in the following section. As a test, 10,000 events with 50 GeV tracks and 0.002 rad opening angles were generated. The RMS of the distribution of the difference between the reconstructed and true vertex was 2.29 m, which is in somewhat higher, but in relatively good agreement with, the calculated expectation of 2.1 m.

Figure 4 shows the distribution of reconstructed vertices ("zclap") for decays which pass all other cuts described in this document, for 3 NHL masses, 0.15, 0.25, and 1.75 GeV. Decays to $\mu\mu\nu$ and $\mu e\nu$ have been combined on these plots. For this figure, decays were generated flat along the z-direction of the channel and according to the transverse distribution of the NHLs in x and y. The x-axis gives the distance from the downstream end of the decay channel, hence 30 m is the farthest point in the channel from the detectors. The most upstream Lab F detector was taken to be at $z = -1$ m. The slope of the distributions is a reflection of the loss of acceptance for vertices farther from the detectors. A cut was made on events with z of closest approach greater than 30 m or less than 0 m, as indicated by the dashed lines on the plots. Figure 4 also shows the separation of the tracks at closest approach, "clap". Note that the x axis is the log_{10} of clap.

$\mu e\nu$ Mode Cuts

The 20 counter requirement isolates muons. An η cut isolates electrons

The purpose of these cuts is to isolate events with only one muon and one electron.

Muons tracks in the detector are required to extend beyond 20 counters (2 m of steel) in the Lab E detector. Geant studies of the particles produced in in background events indicated that no hadrons will fake a muon track with this requirement. This represents an effective lower energy cut of ~ 3 GeV on the muons, as below this, the muons will range-out in the iron.

Electron tracks are required to be within the acceptance of the proposed Lab F drift chambers located upstream of the Lab E detector.

Energy distributions in the calorimeter are required to pass cuts on η, where $\eta = (1 - (E_{84} +$

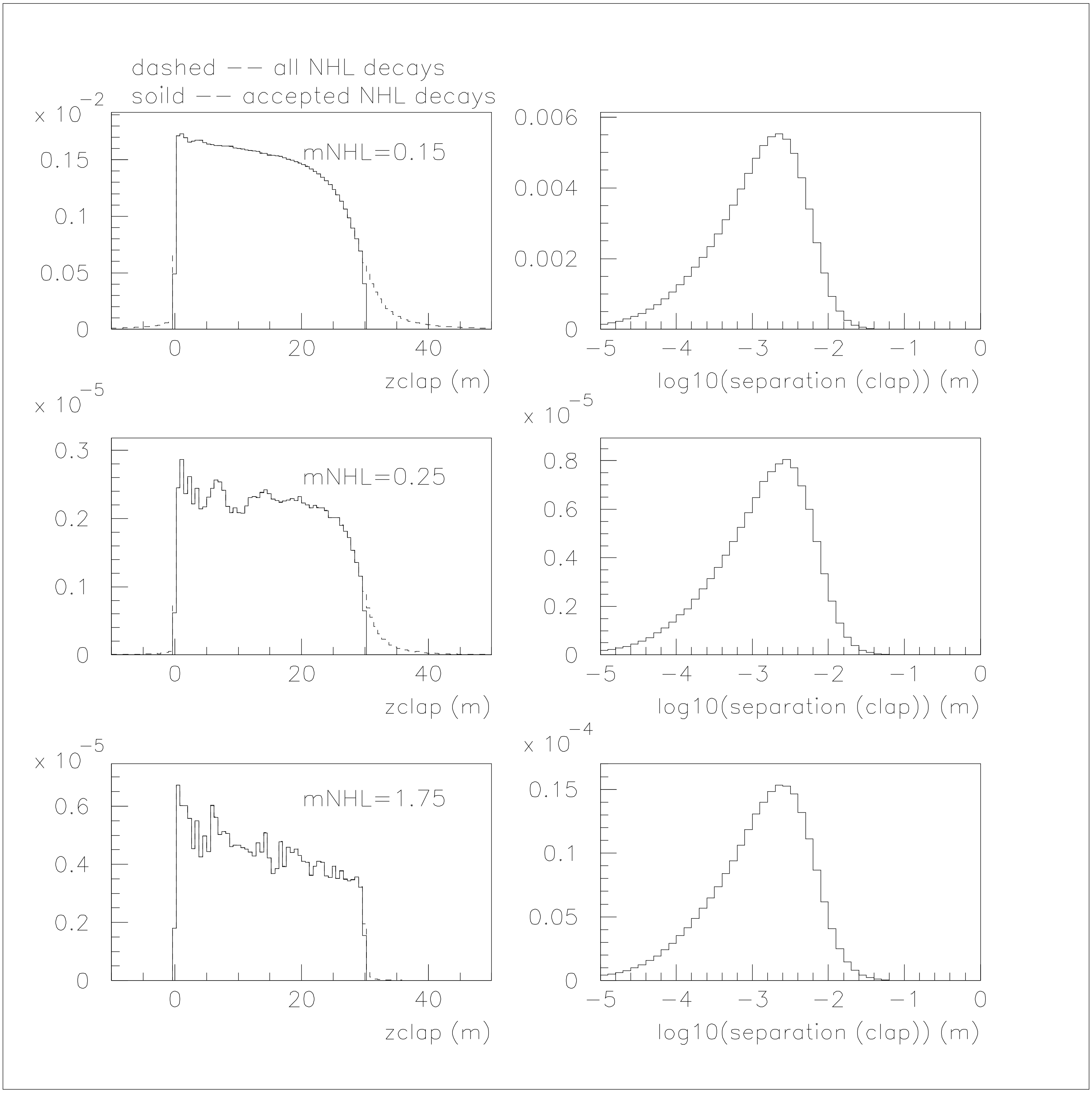

Figure 4: Distribution of reconstructed vertices for NHLs of masses 0.15, 0.25 and 1.75 GeV. Dashed shows all decays, solid indicates decays which pass cuts.

$E_{83})/E_{tot}$). Here, E_{84} and E_{83} are the energy deposited in the most upstream two counters of the Lab E detector and E_{tot} is the total energy in the calorimeter. Electromagnetic showers begin early and are relatively short. Hence this cut can differentiate between electromagnetic and hadronic showers. A low cut on η isolates electromagnetic showers. Three cuts were used, depending on the total energy in the calorimeter: $\eta < 0.2$ for $10 < E_{tot} < 20$ GeV, $\eta < 0.3$ for $20 < E_{tot} < 60$ GeV, and $\eta < 0.5$ for $E_{tot} > 60$ GeV. Scaling the cut with energy maintains efficiency for finding electrons, while continuing to eliminate pion showers. These cuts maintain the pion rejection level at 3% or less, depending on the energy, while keeping the electron acceptance at 95% or better.

The above rejection levels were obtained from the Geant simulation of the detector. It will be important to tune this cut using the test beam data taken during the run. There are two reasons the cut applied to this analysis is to expected to be substantially more efficient than for electron identification in Alex Romosan's ν_e studies. First, there is no smearing due to vertex position. Second, there is a single shower rather than a mixture of hadronic and electromagnetic showers.

For obtaining the limits presented here, the electrons and muons were required to pass the above energy and acceptance requirements. In order to reflect the effect of the η cut, the overall acceptance for NHLs in this mode was reduced by 5%. So the above cuts are reflected in the sensitivity presented.

$\mu\mu\nu$ Mode Cuts

The 20 counter requirement isolates muons. The calorimeter energy requirement eliminates neutrals in $\mu\mu$ events

The purpose of these cuts is to isolate events with only two muons.

Muons tracks in the detector are required to extend beyond 20 counters (2 m of steel) in the Lab E detector.

For isolating events with only muons and no neutrals, a cut on calorimeter energy in the most upstream 10 counters is applied. The calorimeter energy cut was $E < 10$ GeV=50 mips. Geant studies indicated that there was no significant loss of events for this lower cut. Based on a study of 2000 Trigger 6 data (muon straight-through events), the probability that 70 to 110 GeV muons will deposit 10 GeV in 10 counters of the detector is 1.18%. The probability that 110 to 150 GeV muons deposit 10 GeV, based on 1000 events, is 1.9%. Because there are two muons in this decay, the probability that an NHL will self-veto is double, or approximately 4% at 150 GeV. It should be noted that most of the muons from NHL decays are below 100 GeV, so 4% is an upper limit. To get a proper estimate for the loss, the affect at each energy should be determined and an average weighted by the NHL muon energy distribution should be obtained. This study has been left for the future. For now, it is reasonable to assume that the loss is small. At 10 GeV, this cut dramatically eliminates background to this decay mode. Therefore the cut will remain at $E < 10$ GeV for this study. Once again note that this can be very well studied during the next run using test beam and trigger 6 data. The cut can be tuned at that time.

For obtaining the sensitivity presented here, the muons were required to pass the energy and acceptance requirements. The effect of the calorimeter energy requirement was not included.

Cuts dropped since the Oregon Meeting

The invariant mass cut and the conversion cut were not used in this analysis.

Several cuts which were proposed at the Oregon Meeting have not been applied because they requires detailed study and because I have reached acceptable background levels without these cuts. However, I still believe that these cuts may be useful and in the future they should be considered carefully.

First, an invariant mass cut has not been applied. The reconstructed invariant mass of the NHLs may have poor resolution for small opening angles. However, if the background had a significantly different invariant mass distribution this cut could be useful. The reconstruction for small opening angles will be improved if the chambers are distributed throughout the channel. However, the impact of placing chambers throughout the test beam must be thoroughly investigated before this option can be considered. This is in progress. Once a decision is made concerning distribution of chambers, this cut will be investigated.

Second, the cut on conversions in the proposed Lab F drift chambers which line up with a shower in the calorimeter is not applied in this study. There are a number of concerns with this cut. First, in order for an electromagnetic shower to have a high probability of reaching the first drift chamber in the calorimeter, it must have energy $\sim$ 10 GeV. Second, isolating hits in the calorimeter and assigning them to the hits in the Lab F drift chambers may require a tricky algorithm. Third, noisy channels in the drift chambers and spurious hits from delta rays may cause mistakes in identifying photon conversions. Fourth, taking the I-beams into account, the drift chambers are only 93% efficient. These are all valid issues. To understand the effectiveness of this cut, I need to write a more detailed Geant monte carlo of the chambers and Lab E detector.

BACKGROUNDS

A detailed investigation of the backgrounds, based on Monte Carlo simulations, yields a background level well below 1 event. The purpose of this section is to outline this investigation. Sources of background, neutrino interactions in beam line berm, in the material surrounding the bag, and in the helium. This section also discusses backgrounds from the straight-through muons which will traverse the channel. Also included is a study of backgrounds from events in the veto wall which have a reconstructed vertex in the decay channel.

Measuring Backgrounds from the Data

Although this study must rely on Monte Carlos, the actual analysis can rely on data to measure the backgrounds directly.

When the data is analyzed, the background estimations will be based largely on actual measurements of events in the decay channel rather than on Monte Carlo studies. Also, the test beam will permit studies with which we will be able to actually measure our misidentification rate.

As an example, consider the background to the μe mode from neutrino interactions in the helium of the bag which produce one charged pion and any number of neutral pions. There will be many of these events which are *not* misidentified as μe events. So the rate of two prong production can be measured. The events can be studied as functions of energy in the calorimeter. The effect of varying the η cut on the estimated background can be directly measured.

The discussion below relies heavily on Monte Carlo because we do not have data from which to make these studies. Where possible, the simulations have been connected to actual measurements

Monte Carlos for Background Simulations

The Lund Monte Carlo was used to simulate neutrino interactions. The Geant Monte Carlo was used to simulate showers in the berm and detector.

The code used to investigate neutrino interactions is located in jconrad/nhl/nu/lund. Neutrino events were generated using the Lund Monte Carlo.[9] The beam which was used as input to Lund was a simple two Gaussian parameterization.[10] After initial decays at the vertex (for example, π^0s, ρs, etc.), the resulting particles in each event were stored in a library.

The code used to investigate showering of particles is located in jconrad/nhl/nu/geant-ph and jconrad/eta. Showers were generated using the GEANT Monte Carlo[11] Instead of interfacing Lund to Geant, which results in extremely slow running time, a library of showers to be used as a look-up table was created.[12] Five showers were generated for every unit in GeV from 1 to 200 GeV. The materials used were cement and a simulation of the detector (iron). The pulse heights of the showers were sampled every four inches. Libraries were made for electrons, protons, pions, charged kaons, and neutral kaons. After comparisons, electron showers were used to simulate photon showers and proton showers were used to simulate neutron showers. The purpose of this was to save CPU time, since creating these libraries is time-consuming.

Simulating Neutrino Interactions in the Berm

Simulations of berm interactions provide the rate of unaccompanied neutral kaons into the channel.

First, consider neutrino interactions in the berm. These interactions may produce neutral particles which punch through the absorber and enter the channel before decaying. If these particles are unaccompanied by charged partners they will not be vetoed. If they decay in a topology which fakes an NHL decay, then they would pose a serious background. The two neutrals which are produced at a relatively high rate and decay to topologies that have two muons or have a muon and an apparent electron are the K_s^0 and K_L^0. The code to simulate these events is located in jconrad/nhl/nu/study/decays.

This code used the design for the decay channel described previously. The berm is split in half, with the upper half ending 30 m before the proposed Lab F veto wall and lower half ending 5 m before the proposed veto wall. The most downstream ten interaction lengths of berm are considered. The veto wall is considered to be 4.57 $m \times 4.57$ m. In order to accommodate the test beam, a hole at the east edge of the veto wall may be necessary. For the purposes of these studies, a 0.3 $m \times 0.6$ m section of the wall, centered in y and at the east edge was considered to be inactive. The wall was assumed to have 5 cm of steel upstream. Tim Bolton and Bob Bernstein have raised the question of the efficiency of the veto wall. It will be a double wall of scintillator. Unki has measured this scintillator from Bicron to be 99.96% efficient.[14] However, to be assured that there will be no issue, a 1% inefficiency has been introduced in the code. For particles with showers reaching the veto wall, including muons, 1% of the particles are rejected. It should be noted that this is extremely conservative because in reality a shower consists of many particles and a small percentage of those will fail to veto, while the above algorithm eliminates the entire shower 1% of the time. The channel is located 6 m downstream of the veto wall.

The vertex of the event was chosen according to the E815 Monte Carlo methods. The z-position of the vertex was chosen randomly within 10 interaction lengths of berm. The x and y position of the event was chosen according to the E815 standard turtle-based flux-file generator.[13] The x and y positions were selected within a 5 m radius, which extends well beyond the edges of the veto wall. Hence neutral particles can enter the channel from the side.

Each neutral kaon produced by the Lund program was assigned a weight which was the probability of survival from the point of interaction to the end of the berm multiplied by the probability of survival in the 5 cm of steel and by the probability of decay before entering the channel. Neutral kaons can also be produced in the showering process. In order to simulate these "secondary kaons", the fraction of kaons produced and their energy spectrum were parameterized for pions at 50, 100, 200 and 300 GeV. Only kaons produced with energy greater than 6 GeV were considered, because at minimum two 3 GeV muons will be required from the decays to fake an NHL event. For each of the above energies, the fraction of pions producing secondary kaons was 0.018, 0.031, 0.044 and 0.060, respectively.The energy spectrum of these kaons falls off rapidly. For example, the kaons produced in 50 GeV pion showers falls as $5.25e^{-0.09}$, where the χ^2/DOF of the fit was 1.18. Using the parameterizations, every particle above 50 GeV had some probability of producing a neutral kaon by showering.

The shower tables were used to represent the interactions of the particles other than neutral kaons and muons in the event. A shower was chosen randomly from among five produced within a

1 GeV bin of the particle energy. The pulse heights of the shower were parameterized every four inches. A shower was determined to extend beyond the berm if the pulse heights extended beyond the length from interaction to berm-end. A shower was determined to be within the fiducial region of the veto wall if the original particle pointed to the defined region of the veto wall. Showers were assumed to have no transverse extent. This is actually a conservative assumption, because particles which narrowly miss the wall due to this assumption in the simulation may fire the wall in reality because of the spatial extent of the shower. Events with showers which extended beyond the berm and were within the fiducial region were considered to be vetoed.

The muon is considered separately from the other charged particles. The muon is projected to the veto wall. If it is within the fiducial volume and is of sufficient energy as to not range out in the berm material, then it is assumed to fire the veto wall in the case of a charged current event. Based on these studies, 38% of the charged current events will have a muon which fails to hit the veto wall. The large number is not surprising considering that the transverse position of the vertex was allowed to extend well beyond the edge of the veto wall.

Based on the relative fiducial volume of the berm and the detector, scaling from the number of events in the last run, including both NC events and CC events with no vetoing muon, 5×10^5 events are expected for 3×10^{18} protons on target. For the sake of being conservative, this number will be doubled to 1×10^6 events.

As a test of the algorithm, Arie Bodek has suggested that I compare my results for neutral kaon punch-through to the rates for NC-NC double vertex events. In CCFR, 14 NC-NC events were observed, out of approximately 500,000 total NC events. According to Arie, the separation cut for “long” events was based on the distance from shend to the secondary vertex and was 21 counters. Other neutral particles than kaons can cause the NC-NC interactions. Moreover, there are differences in cuts and definitions of the analysis and the above algorithm. However, the algorithm should give a rate for punch-through of 20 counters that is near $2. \times 10^{-5}$ per NC event in order to agree with the NC-NC analysis. The rate from the algorithm is 4.3×10^{-5}.

Background from Berm Neutral Punch-through

Neutral punch through from the berm results in 4.1×10^{-3} μe *background events and* 9.5×10^{-4} $\mu\mu$ *background events for* 3×10^{18} *protons on target*

Based on the above algorithm, unaccompanied K_L^0s and K_S^0s, are simulated as entering the channel and can decay in ways which fake an NHL event. Two body and three body decays of the kaons are simulated at random positions in the channel thrown according to the decay spectrum. Decays which result in muons, electrons and pions are considered: $K_S^0 \to \pi^+\pi^-$, $K_L^0 \to \pi\mu\nu$, $K_L^0 \to \pi e\nu$, $K_L^0 \to \pi^+\pi^-\pi^0$, $K_L^0 \to \pi^+\pi^-$. Pion decays to muons are simulated in the code. Cuts on the variable η, defined above, provide pion rejection level at 3% or less while keeping the electron acceptance at 95% or better. For the purposes of this study, pions were assumed to fake electron showers 3% of the time.

Only minimal requirements were placed on the decay products and the rates were found to be very low. The decay was required to occur within the channel volume. This cuts many kaons which are exiting the berm at large angles. The muons were required to have energy greater than 3 GeV. The electrons or pions-faking-electrons were required to have energy greater than 10 GeV. Without requiring other cuts, it was found that the rate of $\mu\mu$ fakes was 8.85×10^{-3} events for 3×10^{18} protons on target, veto wall, and 1.70×10^{-2} events for μe fakes. If one then applies the requirement that the two lepton candidates actually hit the Lab E detector, the rate of $\mu\mu$ fakes is 9.5×10^{-4} events μe fakes is 4.1×10^{-3} events. So one expects no background with 99.5% confidence level.

As stated above, these cuts can be studied and tuned during the run using data. Test beam data allows study of the η cut. Data can be taken on background in the channel by using a prescaled trigger without the veto wall. Also, for every event with a topology that will fake a $\mu\mu$ or μe event, there are many more which do not which can be used for studies. This analysis is not heavily dependent on models in the sense that there are many cross-checks.

The study was stopped here because this is a reasonable level for the background. However, there are other cuts which can be applied if studies during the run indicate that they are needed. These will need to be studied in further detail later.

Neutrino Interactions in the Material

"Two prong" (one muon and one charged hadron) events from neutrino interactions in the veto wall which are reconstructed in the channel could be an important background. During the run, approximately 1×10^4 neutrino events are expected to occur in the wall for 3×10^{18} protons on target. Most of these events will occur in the steel shielding of the wall. This steel shielding is upstream of the scintillation counters in the proposed design. Therefore, most of these events should veto. A very conservative assumption is that 1% of the events fail to veto. This represents much worse than a 1% inefficiency in the wall, because the events of concern will have at least two charged tracks, and in general more. Based on this assumption, 100 events may fail to veto.

In order to study this background, the 50,000 events generated by Lund were used. All events were assumed to occur $6m$ upstream of the upstream edge of the channel. In the proposed design, this is actually the upper edge of the bag, and drift chamber and veto wall are proposed to be located even further upstream, so this is a conservative estimate. Events with two charged tracks, one muon and one other charged particle, within the acceptance of the Lab F drift chambers and Lab E detector, with any number of associated neutrals, were used. As discussed in the section on cuts, above, the tracks were converted to hits in the Lab F DCs, smeared and then reconstructed. The z position of closest approach and the separation of the tracks at this point were determined. Figure 5 shows the z of closest approach without any requirement on the separation of the tracks

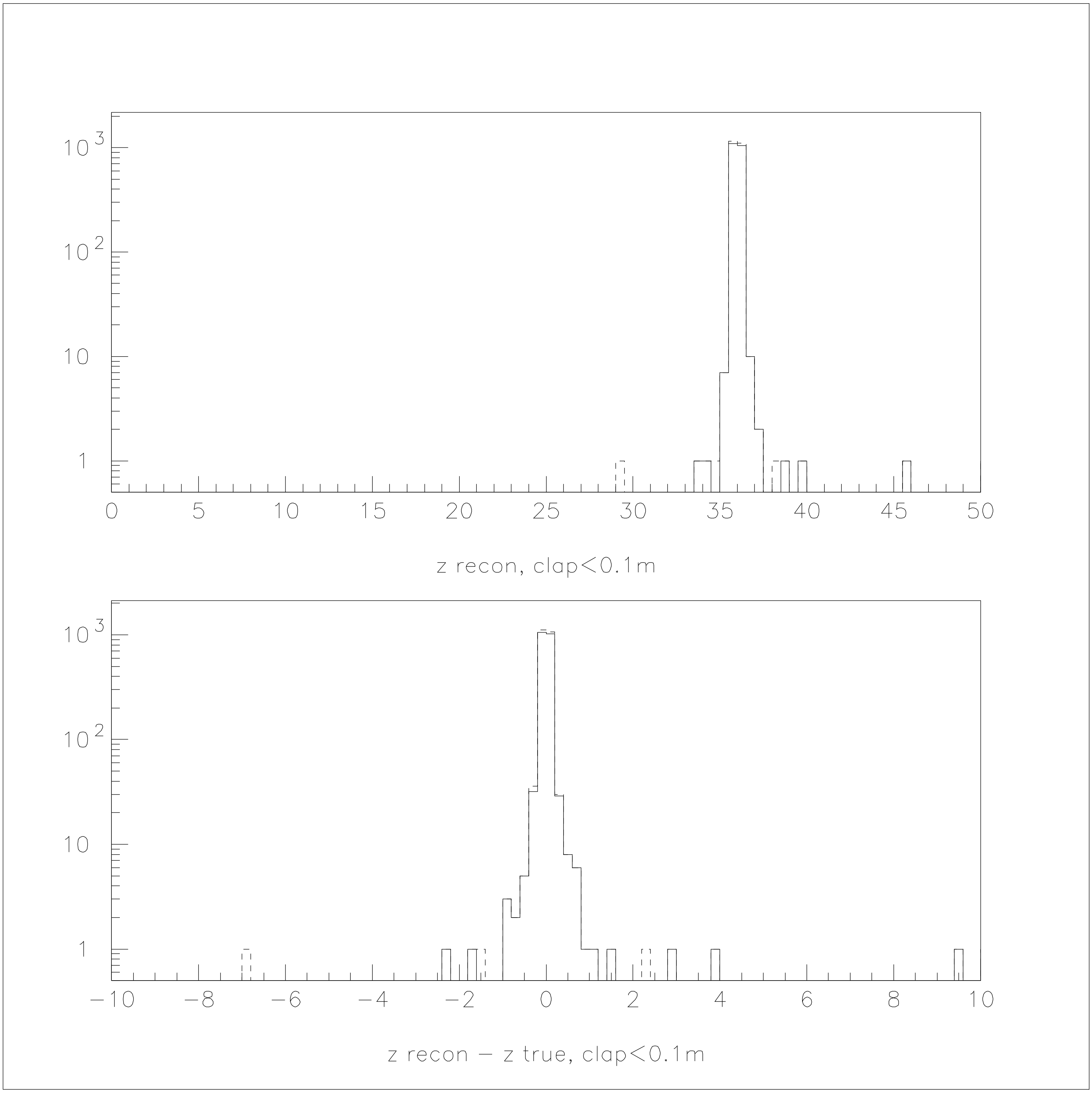

Figure 5: (a) Distribution of reconstructed vertices for neutrino events from the proposed veto wall with (solid) and without a "CLAP" cut (dashed). (b) Difference of reconstructed and true vertex position.

(dashed) and with the requirement that the tracks be within 10 cm separation (solid). Without the separation cut, one event was reconstructed in the channel. This would correspond to a background rate of 2×10^{-3} events. With the separation cut, this event is removed. More Lund events will have to be generated in order to calculate the background. The conclusion is that the background from events in material upstream of the detector is very low.

Neutrino Interactions in the Helium

Neutrino interactions in the helium will result in 100 events events for 3×10^{18} *protons on target*
Neutrino interactions in the helium result in 2×10^{-3} μe *background events and* 2×10^{-2} $\mu\mu$ *background events for* 3×10^{18} *protons on target*

For 3×10^{18} protons on target, 100 charged current events are expected in the helium of the channel. In order to simulate these events, the Lund Monte Carlo described above was used. 50,000 events were used in this study.

The code for these studies is located in jconrad/nhl/nu/helium. The vertex position was distributed randomly, flat in the z direction and according to the E815 Monte Carlo in the x and y position. Particles were projected to the face of the calorimeter.

The events of concern are "two prong events" with any number of accompanying neutral particles. It should be noted that events with more than 2 charged particles can contribute if all but two charged particles miss the Lab F drift chamber acceptance.

For the fake μe background, electron candidates were required to reach the face of the calorimeter. Muons were required to traverse the upstream 20 counters of the detector. The total energy in the the calorimeter was required to be greater than 10 GeV for μe candidates. These cuts eliminated 90.7% of the events. Requiring the η cuts described above reduces the background to 0.37%. For 100 events, this is 0.37 events, so the probability of 1 background event is 31%. This probability is high enough that another cut should also be applied.

The η cut selects events with a lot of electromagnetic energy, hence containing a large number of photons hitting the detector. In order reduce this background one can use the fact that the electromagnetic shower of the photons will shift the mean of the hits in x and y away from the position of the charged track observed in the Lab F drift chambers. As pointed out by Tim, low energy photons will not shower sufficiently to produce hits in the first drift chamber of the calorimeter. Based on Geant studies, it was found that 10 GeV photon showers will penetrate to the first drift chambers. (Note that this assumption can be tested during the run using the test beam if the tertiary target is installed.) Therefore only photons with energy greater than 10 GeV were considered as candidates for shifting the x and y mean of the hits in the event. The studies of vertex-finding in the Neutral Current analysis have shown that the error on the shower transverse position determined from a shower is ± 5 cm.[15] So in this study, the mean of the hit position will required to shifted by 3σ, or 15 cm, in x or y for the event to be cut. This cut can be tuned during running using the test beam data. It was found that all of the remaining events were cut when this requirement was applied.

Either noise or inefficiency could adversely affect this cut. Noise would cause an apparent shift in real NHL candidates and inefficiency would lead to no shift in real background events. Noisy counters will have to be identified through monitoring, and those hits will have to be eliminated. To study an inefficiency, a fraction of photons were randomly defined to fail to shift the track position. For a 50% inefficiency of this type, 0.002% of the events remained. So for 100 events, the number expected is 0.002. The probability of fluctuation to one event is 0.1%.

This cut is surprisingly effective and needs further study. One way to study this during the run will be to overlay showers from the test beam according to the energies and spatial positions of the hits predicted from the Monte Carlo. These events can then be used to determine the efficiency of this cut. Other methods of testing this cut using data should also be devised.

For the $\mu\mu$ candidates, the combination of acceptance and energy cuts leaves 0.02% of the events. The remaining 11 events had two muons in them. Because of the way that the Lund code is used, I cannot trace the parent of the second muon at this time. It could come from pion decays or charm production. In the future, this will be traced. It should be noted that more than 11 events had two muons, but the majority were eliminated by the energy cut. In the case of these 11 events, they all had some neutral energy in the calorimeter, but it summed to less than 10 GeV.

Because 100 events are expected, this represents 0.02 events. The probability that this will fluctuate to 1 events is 2%. This probability was considered sufficiently low to end the study at this time. However, in the future, if there is evidence that further cuts are needed, there are several possibilities. These include a CLAP cut and an invariant mass cut, as mentioned above.

Background from Berm Muons

There is no background from berm muons producing e^+e^- pairs because the energy of the pair fails the cuts.

At the Oregon meeting, Tim Bolton requested that I study the background from muons traversing the channel, producing e^+e^- pairs. If the veto wall were inefficient and the energy of the e^+e^- pair were sufficient, this could fake a μe event. These muons come from neutrino interactions in the berm, if the veto wall is not 100% efficient, and from horizontal cosmic rays. This is not a significant background because the energy of the electrons and positrons is very low. A spectrum of the energy of the electrons and positrons produced by Geant for 1 million 100 GeV muons traversing the helium channel showed no events with energy greater than 10 GeV. The mean of the log of the energy was -1.28 for the electrons and positrons.

LIST OF STUDIES TO DO

The following is a list of questions that I plan to investigate next:

- Consider high mass, high coupling region (probably excluded already)
- Study impact of distributed chambers on the test beam. The chambers can be used in test beam reconstruction and therefore may improve the test beam.
- Investigate ways to cut backgrounds further. In particular, the invariant mass cut and conversion cut. Also, further tune CLAP cut.
- Investigate value of instrumenting DC 41 and 42 with Flash ADCs.
- Develop a Lund-Geant interfaced Monte Carlo (rather than the library system described here). Switch to FLUKA-MICAP.

CONCLUSIONS

I am requesting approval from the collaboration to upgrade the detector with a Lab F decay channel. The studies presented here show that the decay channel has sensitivity beyond present limits on NHL masses between 0.1 and 1.8 GeV. In some regions the limits are extended by over an order of magnitude. The channel can increase the physics possibilities of NuTeV for a relatively small cost and without a large effort in manpower. The results of these detailed studies are in agreement with the expectations presented at the Oregon meeting. Although more studies will certainly refine these limits, the work here provides a solid basis for supporting the construction of the decay channel.

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