Search for Neutral Heavy Leptons in the NuTeV Experiment at Fermilab

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Preliminary results are presented from a search for neutral heavy leptons in the NuTeV experiment at Fermilab. The upgraded NuTeV neutrino detector for the 1996-1997 run included an instrumented decay region for the NHL search which, combined with the NuTeV calorimeter, allows detection in several decay modes ($\mu\mu\nu$, $\mu e\nu$, $\mu\pi$, $e\pi$, and $ee\nu$). We see no evidence for neutral heavy leptons in our current search in the mass range from 0.3 GeV to 2.0 GeV decaying into final states containing a muon.

1 Introduction

Many extensions to the Standard Model incorporating non-zero neutrino mass predict the existence of neutral heavy leptons (NHL). See Refs. [1] and [2] for discussions and references concerning massive neutrinos. The model considered in this paper is that of Ref. [1] in which the NHL is an iso-singlet particle that mixes with the Standard Model neutrino. Figure 1 shows the Feynman diagrams for the production and decay of such an NHL.

The upgraded NuTeV detector includes a Decay Channel designed specifically to search for NHL's and provides a significant increase in sensitivity over previous searches.

2 The Experiment

The NuTeV calorimeter is described elsewhere [3]; only the features essential to this analysis are described here. The calorimeter consists of 84 layers of 10 cm steel plates and scintillating oil counters. A multi-wire gas drift chamber is positioned at every 20 cm of iron for particle tracking and shower location.

The decay channel is an instrumented decay space upstream of the calorimeter. The channel is 30 m long and filled with helium using 4.6 m diameter plastic bags. The helium was used to reduce the number of neutrino interactions in the channel. Drift chambers are positioned at three stations in the decay channel to track the NHL decay products. Figure 2 shows a schematic diagram of the decay channel. A 7 m $\times$ 7 m scintillating plastic "veto wall" was constructed upstream of the decay channel in order to veto on any charged particles entering the experiment.

3 Event Selection

Figure 2 also shows an example of the event signature for which we are searching. The characteristics of an NHL event are a neutral particle entering the channel and decaying in the helium region to two charged (and possibly an additional neutral) particles. The charged particles must project to the calorimeter and at least one must be identified as a muon.

To select events for this analysis we triggered on energy deposits of at least 2.0 GeV in the calorimeter and required no veto wall signal. We then require that there be two well-reconstructed tracks in the decay channel that form a vertex in the helium well away from the edges of the channel and the tracking chambers. The event vertex was required to be at least 3σ away from the fiducial volume edges, where σ is the resolution of the vertex position measurement. By requiring two tracks and separation from the tracking chambers we greatly reduce the number of background events from neutrinos interacting in the decay channel materials. For all the cuts a vertex constrained fit is used in which the two tracks are required to come from a single point in space. The

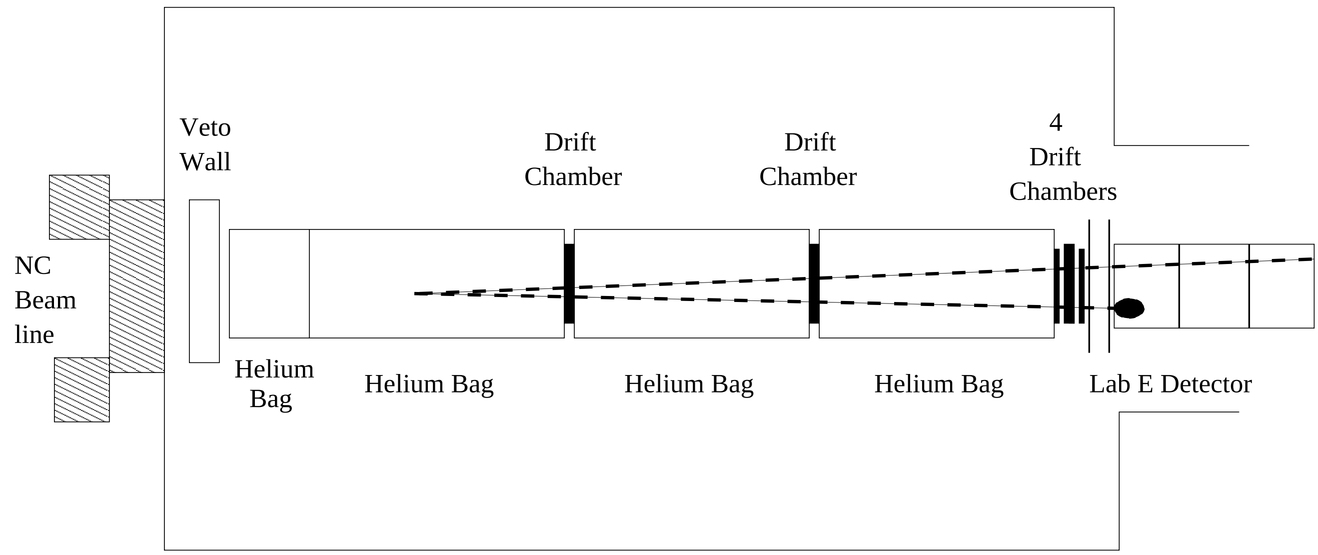

Figure 2: A schematic diagram of the NuTeV decay channel. The beam enters from the left, and at the far right is the NuTeV neutrino target. An example of an NHL decay to $\mu\pi$ is also shown. The event appears as two tracks in the decay channel, a long muon track in the calorimeter and a hadronic shower.

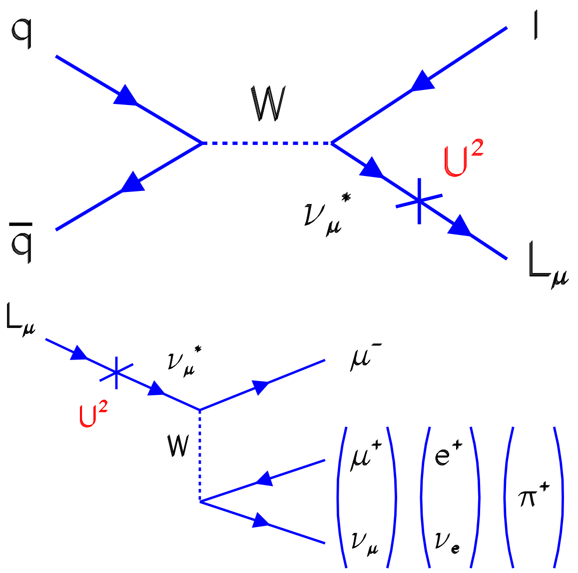

Figure 1: Feynman diagrams showing the production (from meson decay) and decay of neutral heavy leptons (L_μ). Decay via the Z^0 boson is also allowed, but not shown.

vertex resolution depends on the opening angle of the tracks, but it is typically 25 cm along on the beam axis and 2.5 cm transverse.

The two decay tracks are required to project to the calorimeter and to match (in position) with particles identified in the calorimeter. At least one of the two particles must be identified as a muon, because for this analysis we only consider decay modes with at least one muon. In order to insure good particle identification and energy measurement, we require all muons in the event to have energy greater than 2.0 GeV and all electrons or hadrons to have energy greater than 10.0 GeV. These energy cuts also reduce backgrounds from cosmic rays and neutrino interactions.

To further reduce acceptance for background events, additional kinematic cuts are applied. NHL decays are expected to have a small opening angle; therefore, the decay particles are required to have slopes p_x/p_z and p_y/p_z less than 0.1 (p_z is the momentum component along the direction of the incoming beam, p_x and p_y are the transverse components). We are only considering NHL's produced by kaon and charmed meson decays in this analysis; therefore, NHL's with mass above 2.0 GeV are not considered. We require the transverse mass[a] of the event to be less than 5.0 GeV in order to restrict ourselves to this lower mass region. Finally, in order to reduce neutrino-induced events even further we form the quantities $x_{\rm eff}$ and $W_{\rm eff}$ by assuming that: i) the event is a neutrino charged current interaction ($\nu N \to \mu N' X$), ii) that the highest energy muon comes from the neutrino-W vertex, and iii) the missing transverse momentum in the event is carried by the final state nucleon. We require $x_{\rm eff} < 0.1$ and $W_{\rm eff} > 2.0$ GeV.

[a]The transverse mass is $p_T + \sqrt{p_T^2 + m_V^2}$, where p_T is the component of the total momentum of the two charged tracks perpendicular to the beam direction (i.e. the "missing transverse momentum"), and m_V is the invariant mass of the two charged tracks.

4 NHL Monte Carlo

Figure 3 shows a schematic of the NuTeV beamline. The experiment took 2.5×10^{18} 800 GeV protons from the Fermilab Tevatron on a BeO target. Secondaries produced from the target are focused in the decay pipe with a central momentum of 250 GeV. The decay pipe is 0.5 km long, and the center of the decay pipe is 1.5 km from the center of the decay channel. Non-interacting protons, wrong-sign and neutral secondaries are dumped into beam dumps just beyond the BeO target. NHL's would be produced in decays of kaons and pions in the decay pipe, as well as from charmed hadron decays in the primary proton beam dumps. Pion decays do not contribute significantly to this analysis, as they cannot produce NHL's in the mass range of our search.

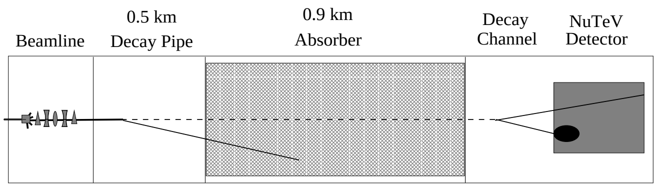

Figure 3: A schematic diagram of the NuTeV beamline. The 800 GeV proton beam from the Fermilab Tevatron enters from the left. NHL's are produced from the decays of kaons and pions in the decay pipe and from the decays of charm hadrons in the beam dumps.

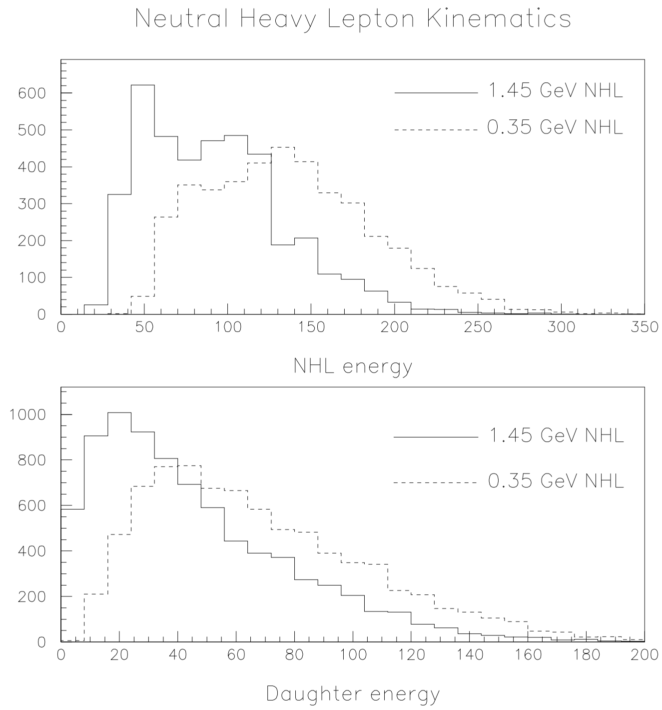

Figure 4: The upper plot shows the energy distributions for Monte Carlo NHL's with mass 1.45 GeV and 0.35 GeV. The lower plot shows the energy of the decay products of the NHL.

The production of kaons is simulated using the Decay Turtle [4] program. The simulation of kaon decays to NHL's includes the effects of mass both in decay phase space and in helicity suppression. The production of charmed hadrons in the beam dump are simulated using a Monte Carlo based on the production cross sections reported in Ref. [5]. For this analysis we only generate muon flavored NHL's. Figure 4 shows examples of the momentum distribution of NHL's produced by the NuTeV beamline. For a 1.45 GeV mass NHL, the average momentum is ~140 GeV. For a 0.35 GeV mass NHL the average momentum is ~100 GeV.

The simulation of NHL decays uses the model of Ref. [6]. The polarization of the NHL is also included in the decay matrix element [7]. The decay products of the NHL are run through a full Geant detector simulation to produce simulated raw data which is then run through our analysis software.

5 Results

We observe no events which pass our event selection cuts. The number of expected background events are approximately 0.5. The largest background is 0.4 events expected from neutrino interactions in the decay channel helium. This estimate was made using the Lund Monte Carlo [8] to simulate neutrino–nucleon interactions. In order to present a conservative limit, we assume an expected background of zero events (this is only a small change in the resulting limits).

In order to demonstrate the acceptance and reconstruction efficiency of the experiment, we loosened several cuts in order to examine the neutrino interactions in the decay channel material. We removed the cuts on the event vertex position (allowing events at the positions of the chambers), and allow events with more than 2 tracks. No calorimeter cuts (matching to particles, or energy cuts) were applied, and no x_{eff} or W_{eff} cuts were applied. Figure 5 shows the distribution of the event vertex along the beam axis. The peaks correspond to the positions of the tracking chambers. The plot also shows the neutrino interactions in the helium gas between the chambers. The number of events seen is consistent with expectations. This study demonstrates that the channel and our tracking reconstruction are working well.

Figure 6 shows our limits on the NHL–neutrino coupling, $U^2_{2\mu}$, as a function of the mass of the NHL. The results of previous experiments [9,10,11,12,13] are shown for comparison. Our result is a significant increase in sensitivity in the range from 0.3 GeV to 2.0 GeV. These limits

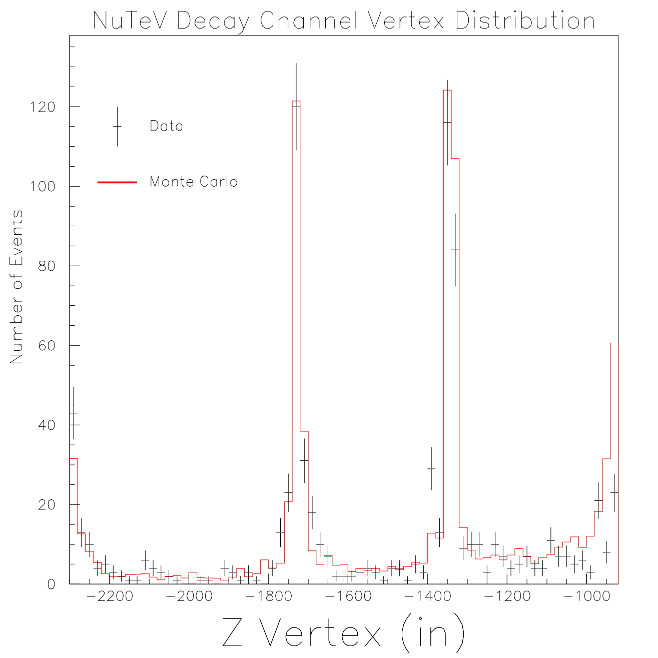

Figure 5: The Z vertex distribution for neutrino interaction events in the NuTeV decay channel. The points are data and the lines are Monte Carlo. The peaks correspond to the positions of the drift chambers.

are for muon flavored NHL's and only include their decay modes containing a muon. The limits do not yet include the effects of systematic uncertainties.

6 Conclusions

We have shown new preliminary limits from a search for muon flavored neutral heavy leptons from the NuTeV experiment at Fermilab. In the future we plan to expand our search to include masses greater than 2.0 GeV as well as masses less than 0.3 GeV (perhaps to a final range of $\sim$ 0.020 GeV to $\sim$ 10.0 GeV). We will also expand our search to include electron flavored NHL's and all NHL decay modes ($\mu\mu\nu$, $\mu e\nu$, $\mu\pi$, $e\pi$, and $ee\nu$).

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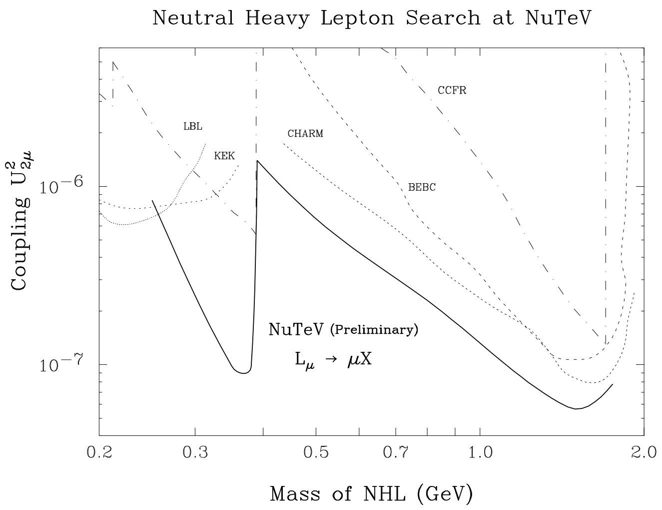

Figure 6: Preliminary limits from NuTeV on the coupling, $U^2_{2\mu}$, of neutral heavy leptons (NHL) to the Standard Model left-handed muon neutrino as a function of NHL mass. Only the μX decay modes of the NHL are included in this first search. The limits are 90% confidence and are based on zero observed events with zero expected background events. The limits do not yet include effects from systematic uncertainties

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