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Progress Report on the NuTeV Decay Channel

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This is a final report describing the research supported by my Outstanding Junior Investigator Award granted in 1996 for "Construction of a Decay Channel for the NuTeV Experiment." The decay channel has been a rich source of physics for NuTeV. At this point, this analysis has resulted in two published papers,<sup>1,2</sup> with two further papers nearly ready to submit (one of which is already available on the web<sup>3</sup>). One Columbia thesis student, Artur Vaitaitis, has already graduated using the data taken in the decay channel. A second student, Joe Formaggio, is writing his thesis and will graduate in early summer. A phenomenology paper has also been published.<sup>4</sup>

This grant supported the construction and analysis of the NuTeV Decay Channel. This light mass detector allows the direct search for decays of beyond-the-standard-model particles which may accompany the neutrinos in the beam. These particles must be massive, neutral, relatively long-lived, and weakly interacting. Beyond these requirements, this search is essentially model-free. Examples of what might be observed include "neutral heavy leptons" (NHL's), predicted by various Grand-Unified-Theory-inspired extensions to the Standard Model.<sup>5</sup> These would be produced in the decay of the secondary mesons (pions, kaons and charm mesons) in the beamline. There is also an unexplored window for light-mass, long-lived neutralinos which are produced in pairs from the proton interactions with the BeO target.<sup>6</sup> The neutral particle will be referred to as the  $N^0$  below.

The detector built for the 1996 running period.<sup>1</sup> It was located in front of the Lab E detector. It consisted of a veto wall, followed by a helium-filled decay region, with total volume of  $3\text{m} \times 3\text{m} \times 40\text{m}$ . Two stations of  $3\text{m} \times 3\text{m}$  drift chambers, identical to those in the Lab E toroid, were interspersed within the decay region. A third station of drift chambers was located just downstream of the decay region and immediately in front of the calorimeter. The purpose of this detector was to look for decays of new particles which accompany the neutrino beam. The drift chamber stations provided tracking and the Lab E detector provided particle identification. Data taking began in September, 1996, and continued through autumn, 1997.

NuTeV is sensitive to decays of the  $N^0$  to two charged particles and possibly also a neutrino. Search modes include  $\mu\mu\nu$ ,  $\mu e\nu$ ,  $\mu\pi$ ,  $ee\nu$  and  $e\pi$ . At this point, searches from 0.02 to 2 GeV have been completed. These are the possible mass ranges for  $N^0$ 's produced by decays of secondary mesons. The initial search from 0.2 to 2 GeV resulted in no candidate

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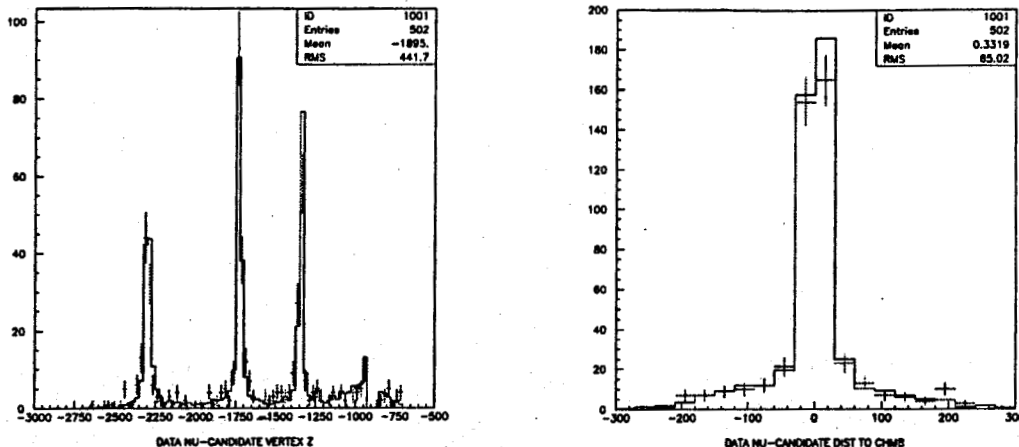


Figure 1: DIS event reconstruction in the decay channel, data are points, Monte Carlo is the histogram. Left: Shown as a function of longitudinal position in inches. Peaks indicate material in the decay channel (see text). Right: Shown as a function of distance from nearest chambers.

events and allowed NuTeV to set limits on NHL's which extend almost an order of magnitude beyond the past experiments.<sup>1</sup> The second search extended into the range of the Karmen Timing Anomaly (33.9 MeV).<sup>2</sup>

The reconstruction code for these searches was tuned using Monte Carlo and then tested using Deep Inelastic Events. Fig. 1 (left) shows reconstructed Deep Inelastic Events as a function of the longitudinal vertex position in inches. The data indicated by the points and the Monte Carlo by the histogram are in good agreement. The peaks are, from left to right, neutrino interactions in a testbeam chamber, the most upstream channel chamber, the middle channel chamber and the most downstream set of channel chambers. The region between is populated by events in the helium as well as misreconstructed events in the chambers. In general, misreconstructed events which appear in the helium are due to hit-confusion in events with many tracks. Fig. 1 (right) shows the position of the vertices with respect to the nearest chamber.

The initial search concentrated on NHL's from 0.2 to 2 GeV in mass decaying to  $\mu\mu\nu$ ,  $\mu\nu\nu$ , and  $\mu\pi$  via coupling with a light neutrino. The sensitivity of the experiment depends upon the mass of the NHL and the coupling,  $|U|^2$ . The lower mass limit of this search was set at the threshold for 2 muon production. The upper mass sensitivity is limited by the production mechanism, which is via decays of mesons in the beamline. The long distance from production to detector (1 km) makes NuTeV most sensitive to long-lived NHL's. Hence,

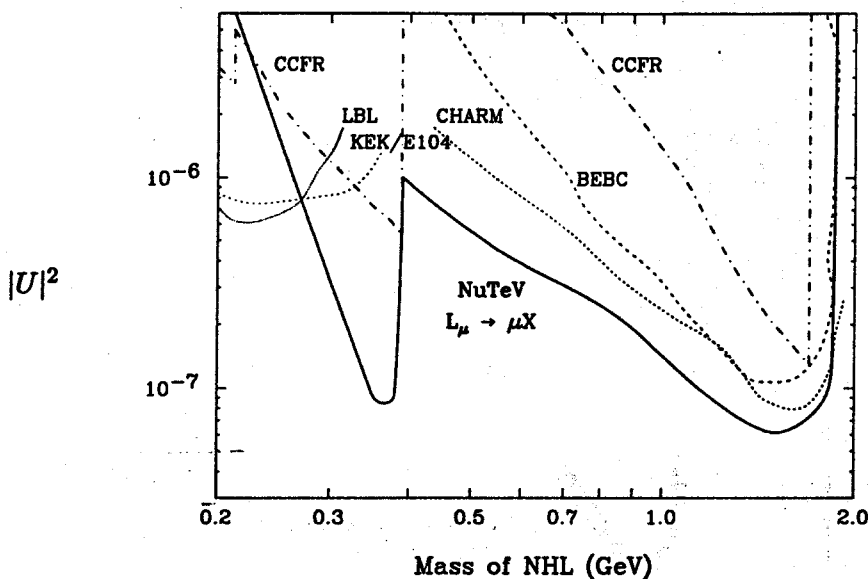


Figure 2: NuTeV limits (above solid line) on neutral heavy lepton production as a function of mass and coupling,  $|U|^2$ , compared to limits from previous experiments.

within the mass range of 0.2 to 2 GeV, this implies very small couplings.

This is a blind analysis in the sense that the cuts were selected based strictly on the Monte Carlo. Events were required to have two well-reconstructed tracks and a high-quality vertex within the decay channel fiducial region. The vertex was required to be 1 m or  $3\sigma$ , whichever was larger, from the position of the chambers within the decay channel. In order to assure good particle identification,  $\mu$ 's were required to have 2.2 GeV, and  $e$  and  $\pi$  showers to have 10 GeV. In order to reduce the background from Deep Inelastic Scatters (the main source), we made kinematic cuts to isolate a region where the DIS rate will be low. Typically, for large invariant mass ( $W$ ) DIS events, the fractional momentum carried by the struck quark ( $x_{bj}$ ) will be large. Therefore, to remove DIS events while maintaining the NHL signal, we required  $x_{bj} < 0.1$  and  $W > 2$  GeV. After all cuts, the total background was estimated to be  $0.57 \pm 0.15$  events.

No events were observed in this analysis. Therefore NuTeV has set a limit on neutral heavy leptons in the .2 to 2 geV mass region, as shown in Fig. 2. Compared to past experiments,<sup>7</sup> we have excluded a substantial new portion of parameter space, for the case of decays to at least 1 muon.

A second search extended to lower mass regions. This was motivated largely by the Kar-

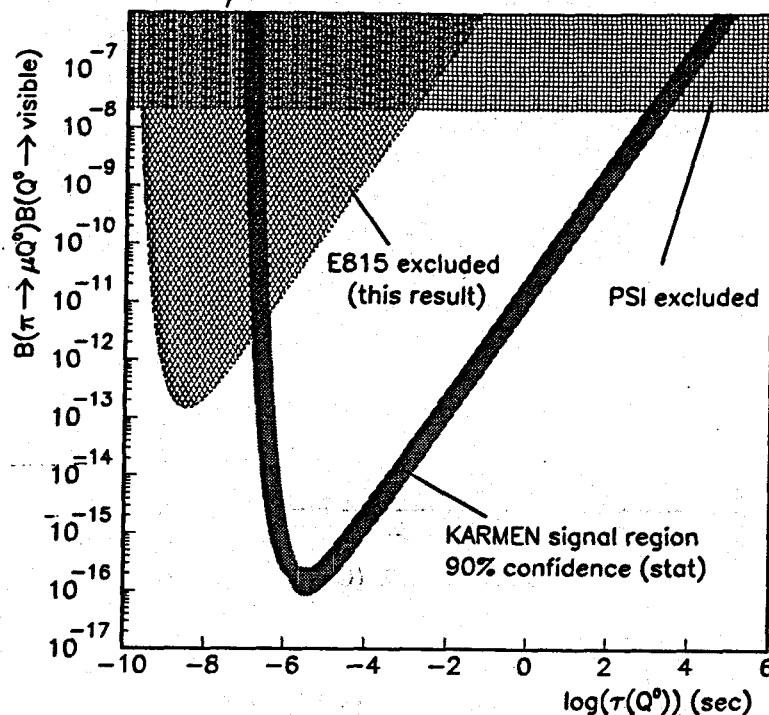


Figure 3: The allowed region for the Karmen Timing Anomaly as a function of branching ratio and lifetime (narrow band). NuTeV excludes four orders of magnitude of the short lifetime solution (shaded region at left). The PSI direct search excludes branching ratios larger than  $2 \times 10^{-8}$  (shaded region at top).

men Timing Anomaly<sup>8</sup> which could be interpreted as a 33.9 MeV neutral particle produced in  $\pi$  decay which subsequently decays to  $ee\nu$ . This signal is observed in Karmen beam dump experiment, in which the particles would be produced nearly at rest. The allowed region is a band which covers a wide range of lifetimes *vs.* branching ratio.

If this particle were produced in the NuTeV beam, it would be highly boosted. As a result, NuTeV has access to only the short-lifetime solutions for the Karmen Timing anomaly. The high boost, combined with small mass, implies that decays will have a very small opening angle. As a result, the vertex resolution is poor and it is not feasible to make a cut around the chamber region for this analysis.

Again, this was a blind analysis with cuts based on the Monte Carlo. Events were required to have good track and vertex  $\chi^2$ . The vertex was constrained to be within the upper and lower limits of the decay region. Due to the small opening angle, the showers associated with the two tracks were allowed to be merged. A likelihood function was used to determine if

the shower was electromagnetic.

Because the  $\pi$  decay which produces this hypothetical particle has such small  $Q$ -value, the direction of the particle has a deviation from the pion which is on the order of  $\mu$  radians. This represents an advantage for NuTeV because the SSQT clusters the pions so that they point at the center of the detector. On the other hand, photon conversion background to the  $ee\nu$  decay signal is populated nearly isotropically across the face of the detector.

No events were observed in a search from 0.02 to 0.2 GeV. Therefore, NuTeV has set a limit which excludes over four orders of magnitude of the short lifetime solution to the Karmen Timing Anomaly. This is presented in Fig. 3.

The third search performed in the decay channel explored the region with mass greater than 2 GeV in decay modes with at least one muon. This analysis is not complete, but preliminary results have been presented at conferences and is available on the NuTeV website.<sup>9</sup> Draft papers related to this result are in preparation.

In this analysis, event selection criteria were developed to minimize known backgrounds while maintaining efficiency for a possible  $N^0$  signal. A series of cuts isolated events with exactly two well-reconstructed tracks forming a vertex within the decay channel fiducial volume and having no charged particle identified in the upstream veto system. Both tracks were required to be well-reconstructed and have an associated calorimeter cluster, with at least one of the tracks identified as a muon. The track and vertex quality criteria were numerically the same as in the 0.2 to 2 GeV analysis. The vertex position was required to be within the detector fiducial volume; in addition, the longitudinal distance from the vertex position to any drift chamber was required to be greater than the larger of 101.6 cm and  $3\sigma_z$ , with  $\sigma_z$  the longitudinal vertex position error. A third track which formed a downstream vertex with one of the two initial tracks was permitted, to allow for  $\delta$ -ray emission. Cosmic ray tracks were removed by requiring the slope of each track relative to the beam direction be less than 100 mr. Muons, hadrons, and electrons were required to have an energy greater than 2.2 GeV, 10 GeV, and 10 GeV, respectively, with an additional total energy cut of 12 GeV applied to  $\mu\mu$  events. In order to isolate high mass events, a transverse mass cut  $m_T > 2.2 \text{ GeV}/c^2$  was applied, with  $m_T \equiv |P_T| + \sqrt{P_T^2 + m_V^2}$ ,  $P_T$  the component of the total reconstructed momentum perpendicular to the beam direction, and  $m_V$  the invariant mass of the visible particles.

Further "clean event" cuts were applied to reduce the level of the dominant deep-inelastic neutrino scattering (DIS) backgrounds. DIS events typically had large track multiplicities, many drift chamber hits, and extra unassociated clusters in the calorimeter. Clean cuts required: (1) three or fewer tracks in any one DC view, (2) three or fewer DC hits in any

view of the first chamber downstream of the vertex, (3) at least one DC view with fewer than eight hits total in the first two chambers downstream of the vertex, (4) no energy clusters in the calorimeter not associated with tracks, and (5) no tracks identified as electrons with missing hits in either view of the first two chambers downstream of the vertex. The final cut removed events where a photon from the primary vertex converted to  $e^+e^-$  and was reconstructed as an electron.

Detailed MC simulations of both physics processes and detector effects were used to estimate possible backgrounds to the  $N^0$  signal. Two major classes of physics processes considered included DIS, resonance production, and diffractive scattering by neutrinos; and decays and interactions of hadrons and photons produced in neutrino interactions. Particular attention was given to known sources of dimuon or dimuon-like production: DIS, resonance, and diffractive production of charm; neutrino trident production;  $\mu^+\mu^-$  vector meson decays; electromagnetic muon pair production; low multiplicity  $\nu_\mu$  DIS accompanied by a secondary pion or kaon decay; and decays of  $K_L^0$  mesons produced by neutrino interactions in the decay channel or surrounding material. Neutrino interactions as in the data were simulated in the decay channel volume; in addition, a large sample of DIS events were generated in the material surrounding the decay channel.

Background calculations were normalized to data using charged-current DIS interactions in the decay channel DC. Events in this sample were required to pass the following five normalization cuts: a vertex within the transverse fiducial volume ; a  $z$  vertex within 76.2 cm of a DC; no upstream veto;  $\geq 1$  GeV energy deposit in the front of the calorimeter; and one toroid-analyzed muon matched to a decay channel track. The MC was normalized to match the total number of data events with two or more tracks; the error on this normalization is 9%.

MC events were also compared to another data control sample as a check on the quality of the simulation. For this sample, the vertex was required to be within the decay channel transverse fiducial volume but the  $z$  position was allowed to be either in the chambers or the helium. Tight track angle cuts were imposed, and there was a strict requirement on veto system activity. The majority of these events were from interactions in the chamber material or from interactions in the laboratory floor. Of 502 events in the data, 169 had vertices reconstructed in the helium at least 101.6 cm from the nearest DC. This can be compared to the MC, which predicted  $(525 \pm 84)$  total events and  $(159 \pm 25)$  events reconstructed in the helium. Because loose vertex quality requirements allowed mis-reconstructed interactions in the chambers and floor to enter this sample, only 15% of the vertices reconstructed in the helium were actually due to  $\nu$ -He interactions.

The experiment is still in the process of increasing Monte Carlo statistics, and so we present a preliminary value for the background estimate. The present estimate is  $0.040 \pm 0.009$  events in the dimuon mode.

Before looking at the data in the signal region, we performed a series of analyses on other fiducial and kinematic ranges. These included using: (1) identical analysis cuts applied to events within 15.2 cm of a DC (the "chamber region"); (2) the chamber region with loosened cuts to increase  $\mu\pi$  acceptance; (3) the "intermediate region" between 15.2 and 101.6 cm from the chambers, with otherwise standard analysis cuts; and (4) events with well-reconstructed two-track vertices where the tracks were both identified as pions. Measurements agreed with MC predictions within  $1.5\sigma$  in all cases. For example in the "chamber region" sample (1), three two track events were observed in the data with 2.6 predicted by the MC.

Upon examining the signal region, three  $\mu\mu(\nu)$  events were observed, which is considerably above the predicted background. No  $\mu e$  or  $\mu\pi$  events were observed, which is consistent with background estimates. The three  $\mu\mu$  events have some features consistent with a  $N^0$  decay hypothesis. The events pass the analysis cuts, where the background is estimated to be 0.04 events. All three occur well within the fiducial volume away from the chambers and are evenly distributed throughout the decay channel. The transverse mass, invariant mass, and missing  $P_T$  are all consistent with the decay of an  $N^0$  with a mass of about  $5 \text{ GeV}/c^2$ . Since only 1(0)  $\mu e$  and 2(0)  $\mu\pi$  events (consistent with MC expectations) were observed in the chamber (helium) data, it is unlikely that  $\mu\mu$  events are related to low multiplicity neutrino events followed by  $\pi$  and  $K$  decay.

Unlike the background, in both an NHL or neutralino model one would expect the  $\mu\pi$  rate to be highly suppressed relative to leptonic decays. However, for a  $5 \text{ GeV}/c^2$  NHL model, one would expect 1.4 times more  $\mu e \nu$  events. A neutralino model, on the other hand, can accommodate the observation of either only  $\mu\mu$  or a combination of  $\mu\mu$  and  $\mu e$  candidates by selecting appropriate couplings.

However, several aspects of the candidate events are similar to those from neutrino interaction backgrounds, and might be indicative of unaccounted-for sources or a statistical fluctuation. Globally, the events share one feature that is improbable for an  $N^0$  decay hypothesis. All three events have a muon energy asymmetry  $A > 0.85$ , where  $A \equiv (|E_1 - E_2|) / (E_1 + E_2)$ . For DIS background, the probability for three  $\mu\mu$  events which pass the signal cuts to have the observed energy asymmetry is 25 – 35%. The probability that this occurs in a weak decay hypothesis<sup>4</sup> is less than 0.5% (including acceptance). All three events occurred during the higher rate  $\nu$ -mode rather than  $\bar{\nu}$ -mode running periods. In the two events where the charge of the higher-momentum muon can be measured, it has

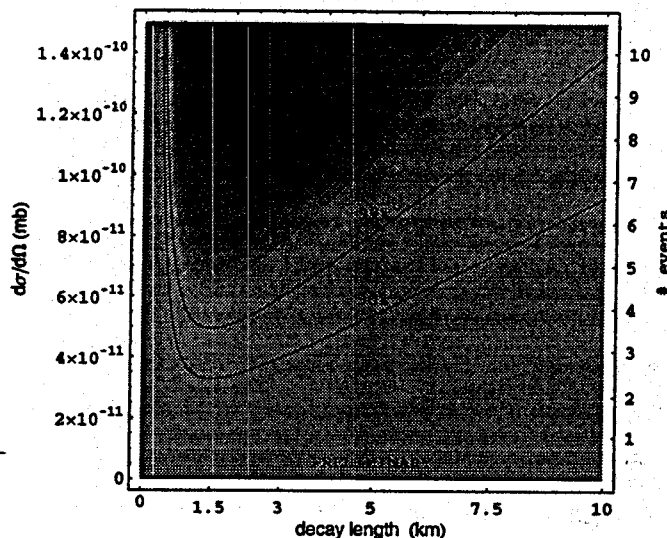


Figure 4: NuTeV limit on neutralino production. This limit is generic for an  $N^0$  produced at the target. The right axis (# of events) follows the shaded contours.

the same sign as expected for the leading muon in a charged-current neutrino interaction. Event kinematics ( $M_T$ ,  $M_{\mu\mu}$ ,  $P_T$ ) are also consistent with DIS characteristics. However, the observed number of events is inconsistent with expected neutrino interaction background.

Based on this result, an interesting limit on the production of neutralinos can be set; these limits were determined by calculating one-sided limits using a frequentist approach without background subtraction. NuTeV is the first experiment to set limits on the production of long-lived neutralinos in this mass range which decay by  $R$ -parity violation. This limit (Fig. 4), although motivated by a neutralino hypothesis, is a generic limit applicable for any model of neutral particle production at the target.<sup>6</sup>

In summary, NuTeV has performed analyses in three kinematic regions using the decay channel apparatus. Two of the searches produced null results and allowed NuTeV to rule out substantial regions associated with neutral heavy leptons and the Karmen Timing Anomaly. At high mass, NuTeV observed three  $\mu\mu$  events, zero  $\mu\pi$ , and zero  $\mu e$  events with transverse mass above  $2.2 \text{ GeV}/c^2$ . The expected backgrounds  $0.040 \pm 0.009$ ,  $0.14 \pm 0.02$ , and  $0.13 \pm 0.02$  events (*preliminary*). The rate corresponding to the observed three events is not consistent with Standard Model processes we have identified and the source of the events is not clear. This analysis is continuing and, at present, we interpret the data by setting an exclusion limit on neutralino production.

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