# Neutrino Oscillations at NuTeV

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The NuTeV experiment at Fermilab has a novel opportunity to search for neutrino oscillations in separate neutrino and antineutrino beams. The analysis presented here probes neutrinos with energies between 20 GeV and 350 GeV and flight lengths between 0.9 km and 1.4 km. Results are presented for the search for $\nu_\mu \rightarrow \nu_{e,\tau}$ and their CP conjugates. In this analysis sensitivity to neutrino oscillations comes from the fact that $\nu_\mu$ charged current events produce a final state muon which traverses a large distance in the neutrino target, while $\nu_e$ and most $\nu_\tau$ charged current events do not and therefore would produce an excess of neutral-current-like events. No oscillations were found and we present the first limits on $\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$, as well as limits on $\nu_\mu \rightarrow \nu_{e,\tau}$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$.

## I. INTRODUCTION

High energy physicists and cosmologists have been intrigued by hints of neutrino oscillations for over a decade, yet we are still in the infancy of understanding them. If neutrino mixing is to tell us anything about the fundamental nature of particle mixing, we must first be able to measure the elements of the mixing matrix as well as possible. Given the three sets of experimental evidence for oscillations (solar [1] and atmospheric [2] neutrino anomalies, and LSND [3]) the form of the mixing matrix is far from clear. One puzzle is that at present we know of only three neutrino types, resulting in two mass differences, yet there are three distinct mass differences indicated by the experiments listed above. Still another uncertainty about these signals is whether or not oscillations occur for both neutrinos and antineutrinos. LSND has published signals in both $\nu_\mu$ and $\overline{\nu}_\mu$ separately, but the solar neutrino results address only $\nu_e$'s, and the atmospheric neutrino spectrum is an unmeasured combination of both neutrinos and antineutrinos.

Several neutrino mixing matrices have already been proposed [4] [5]. Although there are at present large uncertainties in these matrices they promise to look very different from the CKM matrix which governs quark mixing. Given the huge efforts required to measure the quark mixing matrix elements it is clear that doing the same for neutrinos will also prove very challenging.

One exciting possibility, if there are three (or more) generations of neutrinos contributing to mixing, is that CP violation could occur in the neutrino sector. Ideally one would like to measure the difference in rates between neutrino and antineutrino oscillations. This would then imply a CP-violating phase in the neutrino mixing matrix. In this analysis we search for a difference in rates by assuming that oscillations occur in one mode and that there are none in the CP-conjugate mode. We present the first limits on neutrino oscillations for $\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$ assuming no corresponding $\nu_\mu \rightarrow \nu_\tau$ by looking at the NuTeV data. Limits for $\nu_\mu \rightarrow \nu_e$ and its CP conjugate are also presented.

## II. MEASUREMENT TECHNIQUE

NuTeV is a precision deep inelastic scattering experiment optimized to measure the Weinberg angle by measuring the neutral current to charged current cross section ratios for both a $\nu_\mu$ beam and a $\overline{\nu}_\mu$ beam. Details of this measurement can be found in Ref. [6]. The $\sin^2\theta_W$ measurement itself is a large improvement over previous neutrino measurements of this quantity because of the separate $\nu$ and $\overline{\nu}$ beams. This allows NuTeV to use the Paschos-Wolfenstein relation, as follows:

$$R^- \equiv \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}} = \frac{R^{\nu} - rR^{\overline{\nu}}}{1-r} = \frac{1}{2} - \sin^2\theta_W \tag{1}$$

where $R^{\nu}(R^{\overline{\nu}})$ is the ratio of neutral to charged current cross sections in a $\nu$ ($\overline{\nu}$) beam, and $r$ is the ratio of charged current cross sections for antineutrinos to neutrinos. The quantity $R^-$ is much less sensitive to cross section uncertainties than $R^{\nu}$, which is what was used in the past. In particular, charged current charm production from the strange sea is responsible for the largest systematic error in previous neutrino measurements of $\sin^2\theta_W$ [7]. If the neutrino-quark cross section equals the antineutrino-antiquark cross section, and the strange sea is quark-antiquark symmetric, then these cross sections cancel in $R^-$.

In a beam of pure muon neutrinos, and in the absence of neutrino oscillations, the neutral to charged current cross section ratios is measured by comparing the number of neutrino interactions with and without a muon in the final state. Assuming the electroweak Standard Model is correct, however, one can predict $R^-$ using non-neutrino measurements of $\sin^2\theta_W$, and compare that with the $R^-$ measured in the neutrino data. The presence of electron or tau neutrinos would change the measured ratios of cross sections, as well as the measured hadronic energy dependence of $R^-$ compared to prediction. For a perfect detector in a pure muon neutrino beam, $R^-$ would be independent of hadronic energy.

## III. THE NUTEV EXPERIMENT

In fact the NuTeV neutrino and antineutrino beams are not purely $\nu_\mu$ or $\overline{\nu}_\mu$, but contain a small ($10^{-2}$) contamination of $\nu_e$ or $\overline{\nu}_e$ and a much smaller ($10^{-3}$) contamination of $\overline{\nu}_\mu$ or $\nu_\mu$. The neutrino beam is formed in the Sign Selected Quadrupole Triplet beamline. Immediately downstream of the primary proton target a large dipole bends mesons of one charge which are then focused with quadrupole magnets to the decay region. Mesons of the opposite charge hit a dump, while both neutral particles and protons which did not interact hit another dump. Table I lists the sources and relative fractions of the neutrinos in each beam, as predicted by a detailed beamline simulation.

Figure 1 shows the energy distributions of neutrinos interacting in the NuTeV detector, for both neutrino and antineutrino running. The vast majority of the electron neutrinos in the beam are from the $K^\pm \to \pi^0 e^\pm \nu_e$ decays, whose rates and spectra are inferred from the fully reconstructed $\nu_\mu$ and $\overline{\nu}_\mu$ charged current spectra.

The neutrino target at NuTeV is a $3\ m \times 3\ m \times 18\ m$ 690 ton steel-scintillator sampling calorimeter interspersed with drift chambers. There are 84 2.5 cm scintillator planes spaced every 10.3 cm of steel, such that a muon must have 15 GeV to traverse all 84 planes. The calibration of the calorimeter is described in detail in Ref. [8]. The energy resolution for hadronic showers is $.87/\sqrt{E(GeV)}$. The number of photoelectrons for a minimum ionizing particle in one counter is on average 30, making the single-muon efficiency of each counter very high. A toroidal muon spectrometer was located immediately downstream of the neutrino target, but was not used directly in this analysis.

TABLE I. Table of different $\nu$ sources to the NuTeV beams

| Sources of Neutrinos and Event Fractions | | |
|---|---|---|
| Source | $\nu$ Mode | $\overline{\nu}$ Mode |
| $\pi^\pm \to \mu^\pm \nu_\mu$ | 0.79 | 0.86 |
| $K^\pm \to \mu^\pm \nu_\mu, \mu^\pm, \pi^0 \nu_\mu$ | 0.20 | 0.13 |
| $K^\pm \to e^\pm \pi^0 \nu_e$ | 0.01 | 0.008 |
| $K_L \to e^\pm \pi^\mp \nu_e$ | 0.0005 | 0.0015 |
| $\mu \to e \nu_\mu \overline{\nu}_e$ | 0.0002 | 0.001 |
| Charm Meson$\to \nu_e + X$ | 0.0002 | 0.0007 |
| $\Lambda_c \to \nu_e + X$ | 0.00007 | 0.0002 |

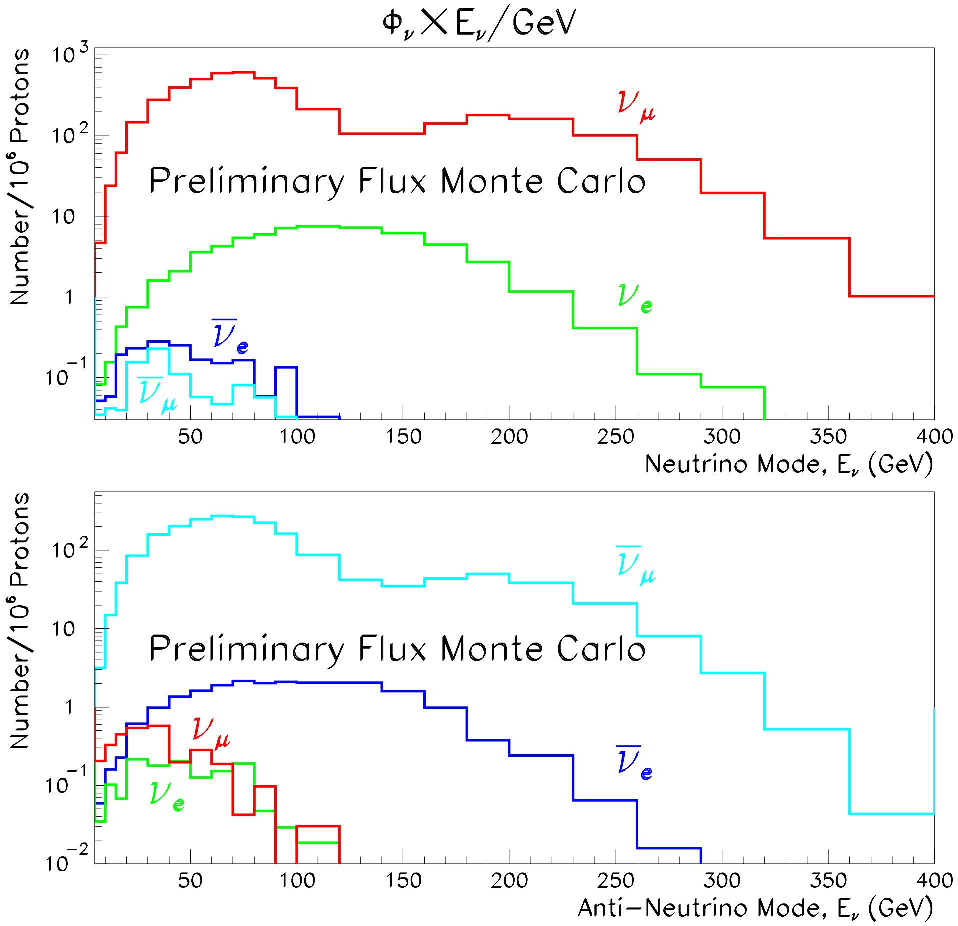

FIG. 1. Energy distribution of neutrinos interacting in the NuTeV detector, for both neutrino running and antineutrino running

## IV. ANALYSIS

Very few cuts are applied to the data for this analysis. The event is required to have a reconstructed hadron energy above 20 GeV in order to ensure efficient vertex finding and to reduce contamination from cosmic rays. The event must pass fiducial volume cuts on both the transverse and longitudinal vertex position to ensure that it was induced by a neutrino interaction and not something else entering from the side or front of the detector. Finally, the event must not start too close to the downstream edge of the calorimeter to ensure accurate detection of a possible final state muon. The small remaining background from cosmic rays (primarily at low hadron energy) is subtracted.

Once an event has passed these cuts, it is then classified as being either a neutral or charged current candidate depending on its length. The length of an event is defined as the difference between the counter where the neutrino first interacted and the last consecutive counter with energy above a low threshold. Events that are longer than 20 scintillation counters (approximately 2 meters of steel equivalent) are charged current candidates (long events), and the remainder are neutral current candidates (short events). There is approximately a 20%(10%) background from charged current events in the short $\nu(\overline{\nu})$ event sample, caused by muons exiting the side of the detector or ranging out before 20 counters. The small electron neutrino contamination in the beam (see table I) also contributes a charged current background to the short events, in particular at high reconstructed hadronic energy. Rather than extract $R^-$ by subtracting all the backgrounds, we consider the variable $R^-_{data} \equiv R^\nu_{data} - xR^{\overline{\nu}}_{data}$, where $R^\nu_{data}$ and $R^{\overline{\nu}}_{data}$ are simply the ratios of short to long events in the neutrino and the antineutrino beams. The coefficient $x$ is picked by the Monte Carlo as that fraction which minimizes the systematic error arising from charm quark production. The number chosen is close to 1/2, the ratio of antineutrino to neutrino charged current cross sections, as predicted by equation 1.

Neutrino oscillations would cause a discrepancy in the neutrino data from the Standard Model prediction in both the level of $R^-$ and its shape as a function of reconstructed hadronic energy. This is because $\nu_e$ and most $\nu_\tau$ charged current interactions do not produce a final state muon, and do produce final state particles that deposit all their energy in the hadronic shower region. (The 17% branching ratio of $\tau \to \mu\nu_\tau\overline{\nu}_\mu$ is included in this analysis). By looking for deviations from the Standard Model prediction of $R^-_{data}$ in both the level and the shape, we are sensitive to neutrino oscillations. In fact the $R^-$ variable is relatively insensitive to CP-conserving neutrino oscillations; the results quoted here are for oscillations which occur entirely in neutrinos or entirely in antineutrinos.

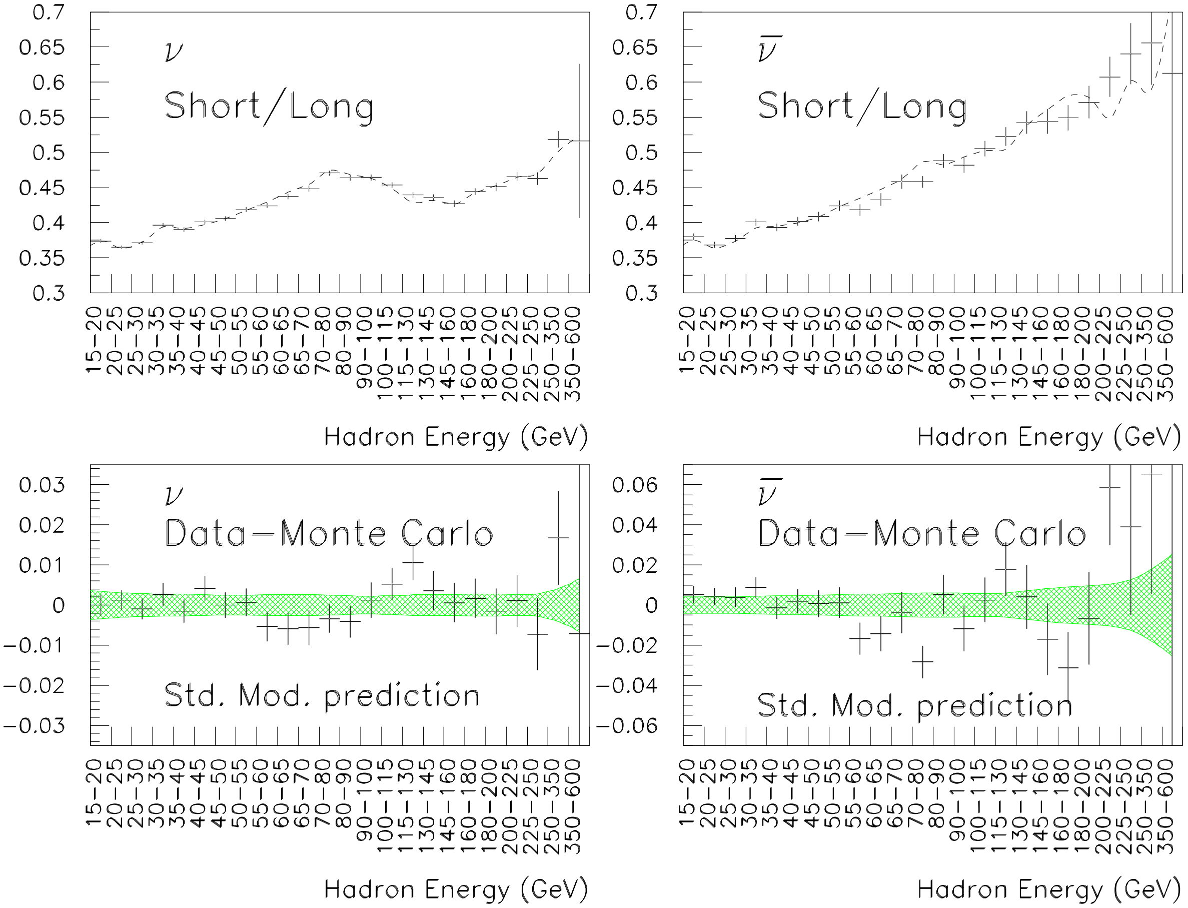

FIG. 2. The ratio of short to long events in both neutrino (left) and antineutrino (right) running. The top plots show the ratio in the data, and the bottom plots show the difference between the data and the Monte Carlo prediction with a Standard Model prediction of $\sin^2\theta_W = 0.2241$. The systematic error on the ratio is shown in a band, but there are significant correlations between those errors in neutrino and antineutrino data.

Figure 2 shows the ratio of short to long events in the NuTeV data for both neutrino and antineutrino running, for events passing all the cuts described above. The lower two plots show the difference between the measured and predicted ratios, assuming the Standard Model value of $\sin^2\theta_W$ of $0.2241 \pm 0.0006$. This value comes from the 1998 average of LEP1/SLD for the W boson mass of $80.32 \pm 0.037\ GeV$ given by the LEP Electroweak Working Group, Ref. [9], and the prediction that $\sin^2\theta_W$ measured in neutrino scattering is equal to $1 - \frac{M_W^2}{M_Z^2}$. The uncertainty in the oscillation sensitivity due to the uncertainty on $\sin^2\theta_W$ is about a third of the statistical uncertainty.

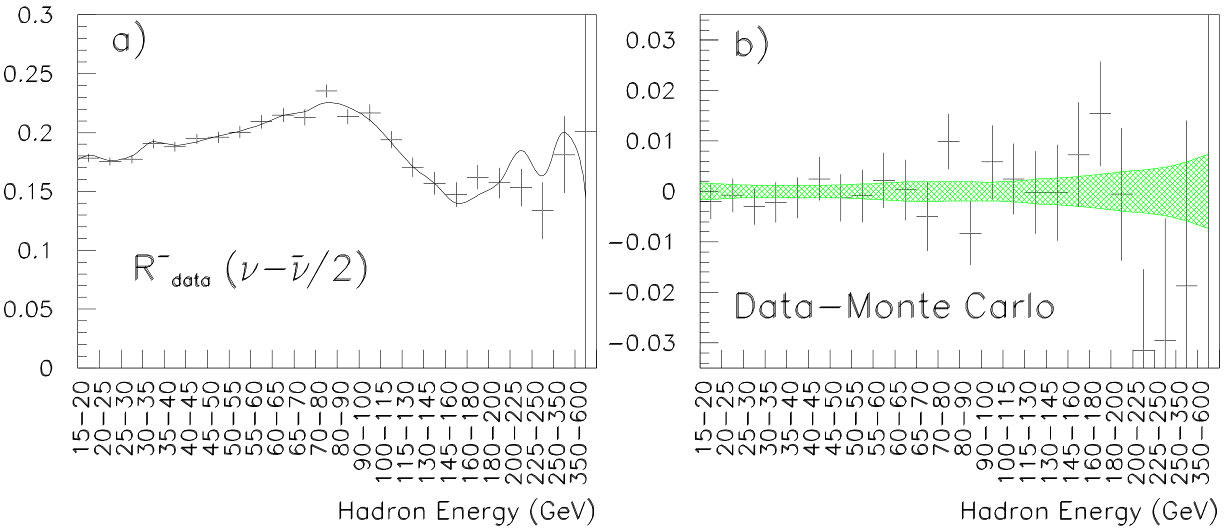

FIG. 3. $R^-_{data}$ in the data for both data and the Standard Model prediction without any neutrino oscillations, where the error bars are statistical only: the band shows the systematic errors. Note that the systematic error band on $R^-_{data}$ is significantly smaller than that of either $R^{\nu}_{data}$ or $R^{\overline{\nu}}_{data}$.

Figure 4 shows what the discrepancy between the data and the Standard Model prediction would be if there were neutrino oscillations of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ or $\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$, assuming no corresponding oscillations in $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$. Oscillations in these regions in the neutrino sector have already been ruled out by CHORUS and NOMAD [10]. Note that the shape of the discrepancy is sharper in the case where there is an electron in the shower rather than a tau. This is because the electron deposits all its energy in the shower whereas the tau will decay into several particles including one or two neutrinos. The tau decays are generated by the TAUOLA program [11].

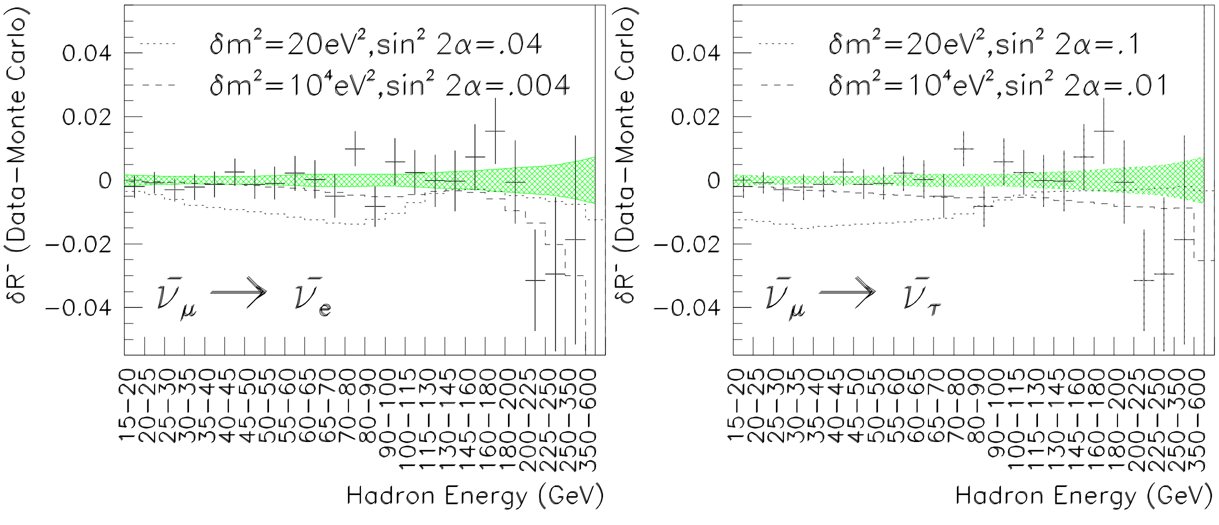

FIG. 4. These figures show the discrepancy that would arise in the data if there were neutrino oscillations where $\overline{\nu}_\mu \rightarrow \overline{\nu}_{e,\tau}$ for two different mass differences. The data subtracted from the prediction with no oscillations as well as the systematic errors are also shown.

There are a few systematic errors in this analysis which contribute significantly to a measurement of oscillation parameters, notably the fraction of electron neutrinos that do not arise from charged kaon decays. These other sources of electron neutrinos are from $K_L$ and secondary muon decays, and are not measured directly but predicted by the detailed beamline simulation. Table II lists the largest systematic errors in the $\overline{\nu}_\mu \rightarrow \overline{\nu}_{e,\tau}$ and $\nu_\mu \rightarrow \nu_{e,\tau}$ searches.

Many of the systematic errors are correlated between neutrino and antineutrino data and partially cancel, but a few, most importantly the electron neutrino contaminations in the neutrino and antineutrino beams, are not.

A best fit $\sin^2 2\alpha$ was determined for each $\delta m^2$ by fitting the the $R^{-}_{data}$ distribution as a function of hadronic energy. In this fit, systematic effects were allowed to vary around their expected values, and one unit of $\chi^2$ was added for every sigma that a systematic effect was pulled from its central value. None of the systematic effects were pulled by more than one sigma, and the fit results for $\sin^2 2\alpha$ were consistent at the one sigma level with zero. The frequentist approach was used to set a 90% confidence level upper limit for each $\delta m^2$.

## V. CONCLUSIONS

Figure 5 shows the preliminary 90% confidence limits on single-mode oscillations compared with other current limits and signals. The limits were calculated using the two-generation formalism for neutrino mixing, but if a CP-violating signal had been found a three-generation formalism would have to be adopted. NuTeV is the only experiment with direct limits on the process $\overline{\nu}_\mu \to \overline{\nu}_\tau$ and has also excluded a region in $\overline{\nu}_\mu \to \overline{\nu}_e$ phase space not previously excluded by other $\overline{\nu}$ experiments. However, the importance of this result lies in its suitability for long baseline experiments, where detectors are likely to be very similar and a short/long ratio technique is required. If all of the current indications for neutrino oscillations are true and there is indeed a fourth sterile neutrino, then CP violation may occur in the mass difference range accessible to long baseline experiments [12].

TABLE II. Table of systematic errors that contribute to an oscillation measurement

| SOURCE OF UNCERTAINTY | $\delta(\sin^2 2\alpha) \times 10^3$ | | | |
|---|---|---|---|---|
| | $\nu_\mu \to \nu_e$ | $\nu_\mu \to \nu_\tau$ | $\overline{\nu}_\mu \to \overline{\nu}_e$ | $\overline{\nu}_\mu \to \overline{\nu}_\tau$ |
| Other sources of $\nu_e$'s | 0.6 | 0.9 | 0.6 | 1.3 |
| *Energy Measurement*: | | | | |
| Calibrations (0.5%) | 0.2 | 0.6 | 0.1 | 0.8 |
| Longitudinal Vertex Determination | 0.3 | 0.3 | 0.3 | 0.5 |
| *Sea Quarks*: | | | | |
| Strange Sea | 0.3 | 0.3 | 0.3 | 0.5 |
| Charm Sea | 0.2 | 0.2 | 0.2 | 0.4 |
| Charm Mass | 0.3 | 0.2 | 0.3 | 0.4 |
| $\sin^2\theta_W$ | 0.5 | 0.8 | 0.5 | 1.2 |
| *Cross Section*: | | | | |
| $\sigma^{\overline{\nu}}/\sigma^{\nu}$ | 0.4 | 0.5 | 0.4 | 0.7 |
| Longitudinal Structure Function | 0.3 | 0.3 | 0.3 | 0.4 |
| SYSTEMATIC UNCERTAINTY | 1.1 | 1.6 | 1.1 | 2.3 |
| STATISTICS | 1.5 | 2.0 | 1.5 | 2.9 |

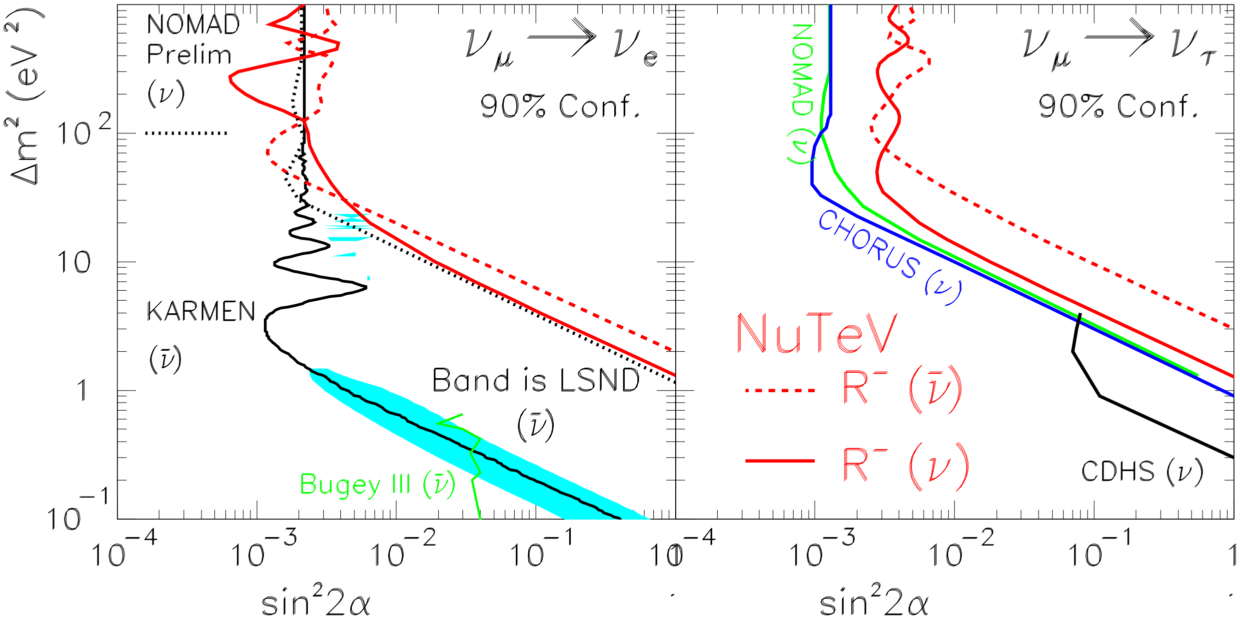

FIG. 5. This figure shows the limits that have been set with this analysis compared to the LSND signal and limits from other experiments.

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