Measuring Active-Sterile Neutrino Oscillations with a Stopped Pion Neutrino Source

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Abstract

Should the MiniBooNE experiment at FermiLab confirm the LSND oscillation signal, then further measurements are required to identify the mechanism responsible for these oscillations. Possibilities include sterile neutrinos, CP or CPT violation, variable mass neutrinos, and Lorentz violation. In this paper, we consider an experiment at a stopped pion neutrino source to determine if active-sterile neutrino oscillations with Δm^2 greater than 0.1 eV^2 can account for the signal. By exploiting stopped π^+ decay to produce a monoenergetic ν_μ source, and searching for variations in the rate of the neutral current reaction $\nu_x\ {}^{12}C \rightarrow \nu_x\ {}^{12}C^*(15.11)$, we show that a convincing active-sterile neutrino oscillation measurement can be performed.

1 Introduction

Our view of neutrino oscillations has undergone a revolution over the last ten years. Neutrino mass, via oscillations, is now experimentally established [1]. The Standard Model must now accommodate right handed neutrinos, ν_R, that are sterile with respect to the weak interaction. The issue that must be addressed is where are these sterile neutrinos? Although theorists postulate that ν_R are heavy via the 'see-saw' mechanism [2], there is no experimental evidence for the mass spectrum of sterile neutrinos, or for the number of generations [3]. In fact, light sterile neutrinos have been invoked to explain many puzzles seen in nature, such as the LSND anomaly [4], solar neutrino energy spectrum anomaly [5], R-process in type II supernova [6], pulsar kicks [7], dark matter [8], and the perplexing dark energy [9]. Thus, much experimental and theoretical justification exists to motivate a search for light sterile neutrinos above the mass of 0.1 eV^2.

The LSND anomaly points to active-sterile neutrino oscillations in the Δm^2 range of 0.1 to 1 eV^2 [10]. A recent analysis of a (3 + 2) model indicates the possibility of a second sterile neutrino solution around 20 eV^2 [4]. In addition, supernovae R-process analysis favors a $3 < \Delta m^2 < 70$ eV^2 sterile neutrino [6]. We propose an experiment that is capable of the direct detection of active-sterile neutrino oscillations in this mass region of interest. One interpretation of the LSND result is an intermediate sterile state, i.e. $\bar{\nu}_\mu \to \bar{\nu}_s \to \bar{\nu}_e$, where the observed LSND oscillation probability is $P(\bar{\nu}_\mu \to \bar{\nu}_e) = 0.264 \pm 0.081\%$ [10]. Coupling this with short baseline reactor experiment limits on ν_e disappearance of $P(\bar{\nu}_e \to \bar{\nu}_s) < 10\%$ [11], we can then predict the ν_μ disappearance to sterile neutrinos to be $P(\bar{\nu}_\mu \to \bar{\nu}_s) > 10\%$. The above arguments sets the scale for the Δm^2 and $sin^2(2\theta)$ sensitivity that needs to be achieved.

2 Beyond the Standard Model

Given the prospect of a new intense stopped pion neutrino source, together with a positive signal from MiniBooNE [12], a next generation short baseline neutrino experiment needs to be carefully considered. An oscillation detector at the Spallation Neutron Source (SNS) has already been outlined [17] which demonstrates how an improved measurement in the LSND/MiniBooNE region can be made. Improving the Δm^2 and $sin^2(2\theta)$ measurement of any positive signal from MiniBooNE would be important. However, the nagging question would still remain as to the new physics behind the three distinct Δm^2 regions that have been measured with solar, reactor, atmospheric, and short baseline detectors. Several possibilities at present exist, such as sterile neutrinos [4], CP or CPT violation [13], mass varying neutrinos [9], and Lorentz violation [14].

The CP or CPT violation possibility could be readily tested with a MiniBooNE/LSND style detector coupled with a short duty-factor stopped pion beam (discussed in the next section) which allows, via timing cuts, a separation of ν_μ and $\bar{\nu}_\mu$ events. Thus, a direct comparison of oscillation probabilities from these two simultaneous data sets will allow a test of CPT and CP violation models. Mass varying neutrinos can be tested by changing the density of material between the source and detector. The Lorentz violation model can be tested by looking for sidereal variations in the neutrino flux. These three tests will be discussed in more detail in a future paper.

This paper discusses the first possibility that of sterile neutrinos. To directly demonstrate active-sterile neutrino oscillations, and achieve the best sensitivity, requires a two detector setup and a stopped pion neutrino source. The following sections describes how this can be done.

3 Intense Stopped Pion Neutrino Sources

To detect sterile neutrino effects in the mass range of LSND and above, requires an intense source of well characterized neutrinos. Neutrinos from stopped pion decay is such a source, having well defined flux, well defined energy spectrum, and low backgrounds. Fortunately, accelerators that can provide such a source are either being built or are being proposed. The first such prospect is the 1.4 MW, 1.3 GeV, short duty-factor Spallation Neutron Source (SNS) at ORNL [15], which is currently being built and will be fully commissioned by 2008. The second is a proposal for a 2 MW, 8 GeV, Proton Driver (PD) at FNAL [16].

The dominate decay scheme that produces neutrinos from a stopped pion source is

$$\pi^+ \rightarrow \mu^+ \nu_\mu, \quad \tau = 26\, nsec \tag{1}$$

followed by

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e, \quad \tau = 2.2\, \mu sec. \tag{2}$$

The neutrinos from stopped π^-'s are highly suppressed because the negative pions are completely absorbed in the surrounding material. Thus, neutrinos from the π^- decay chain are significantly depleted and can be estimated from the measured ν_μ, $\bar{\nu}_\mu$, and ν_e flux. Figure 1 shows the neutrino spectra and timing plots from a stopped pion source. As shown in the right hand plot, the ν_μ energy is monoenergetic ($E_{\nu_\mu} = 29.8$ MeV), while the $\bar{\nu}_\mu$ and ν_e have known Michel decay distributions, with an end point energy of 52.8 MeV. Furthermore, the left hand plot shows the SNS beam timing and the time distributions for the three neutrino species. One of the advantages of the SNS relative to the LAMPF accelerator is the three orders of magnitude shorter beam time of 695 nsec (the FNAL PD will have a similar beam time). With a simple beam-on timing cut, one can achieve a fairly pure ν_μ sample, with only a 14% contamination of $\bar{\nu}_\mu$ and ν_e each. This remaining background is easily measured and subtracted.

Table 1 shows the expected proton rates for both SNS and FNAL beamlines, normalized to a full year of running, i.e. 3.15×10^7 seconds. The FNAL Proton Driver proposal is broken down into a 8 GeV, 2 MW and a 5 GeV, 1.25 MW beamline. The FNAL 8 GeV option will

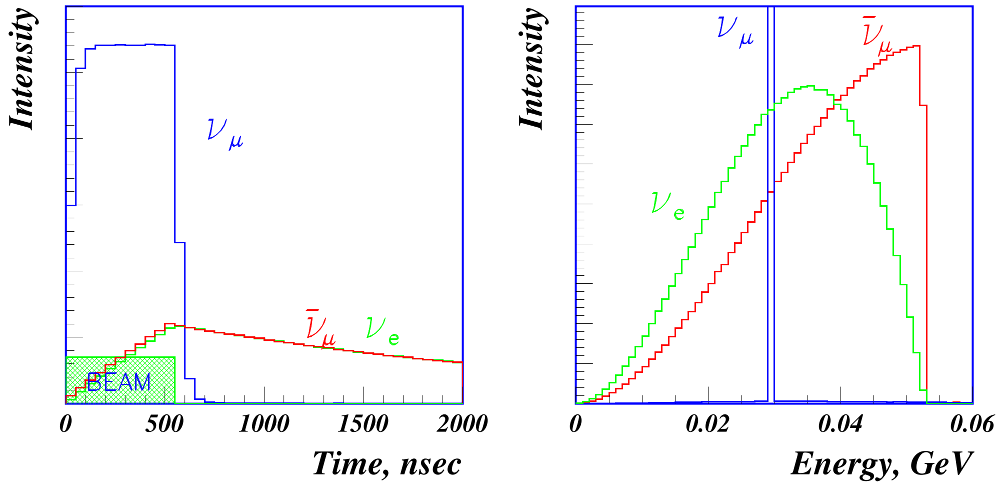

Figure 1: The neutrino time and energy spectra of the different neutrino species produced isotropically from a stopped pion source [15].

	FNAL (8 GeV)	FNAL (5 GeV)	SNS
P/yr	1.6×10^{22}	1.6×10^{22}	6.7×10^{22}
DAR $\nu(\nu/P)$	1.5	0.9	0.13
DAR $\nu(\nu/yr)$	7.3×10^{22}	4.4×10^{22}	2.9×10^{22}

Table 1: Proton intensity at FNAL and SNS. The numbers are taken from [16], assuming 3.16×10^7 s/yr operation.

provide about 2.5 times more protons per year than the SNS. However, the FNAL PD is only a proposal, while the SNS is under construction and will be operational by 2008, which makes it more timely. Furthermore, the SNS is planning an upgrade for 2014, which will deliver 3MW to two sources, which makes for the interesting situation of multiple baselines with a single detector.

A key component of the sterile neutrino measurement is the physical size of the stopped pion source, which adds an uncertainty to the neutrino path length. For the SNS, the compact liquid mercury target will contribute approximately 25 cm (FWHM) to the neutrino path length uncertainty.

4 Active-Sterile Neutrino Oscillation Measurements

The direct observations of active-sterile neutrino oscillations with $\Delta m^2 > 0.1\ eV^2$ can be achieved because of two key features of a short duty-factor stopped pion neutrino source. First, all active neutrino species are measured using the neutral current reaction $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$, which is identified by the emitted 15.11 MeV gamma ray. A deficit of the neutral current rate from expectation can only be from oscillations to sterile neutrinos. Second, using timing cuts relative to the beam spill, we can extract a fairly pure sample of 29.8 MeV monoenergetic ν_μ events. Thus, the oscillation probability can be expressed as,

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - sin^2(2\theta)\sin^2(1.27\ \Delta m^2 \frac{L}{29.8MeV}) \tag{3}$$

Given these two features, we can observe sterile neutrino oscillations by measuring changes in the $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ rate as a function of L (in meters). Figure 2 shows the oscillation length as a function of Δm^2. Thus, a two detector configuration of the appropriate size and distances can achieve the desired sensitivity. A near detector greater than three meters in length and about 10-20 meters from the source will be sensitive to $\Delta m^2 > 20eV^2$. A second large detector (required to increase statistics because of decreasing $1/r^2$ neutrino flux) at 50-100 meters will be sensitive to $\Delta m^2 > 0.1eV^2$. Figure 3 shows a simple schematic of a detector setup that would allow sensitivity to sterile neutrino oscillations using the $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ channel.

A possible detector configuration at the SNS would be a 25 ton fiducial volume (3.5 m a side) liquid scintillator near detector at 18 m distance from the neutrino source. This is the homogeneous detector proposed by the ν-SNS collaboration to measure neutrino carbon cross sections [15]. The limited fiducial volume size of the near detector might be improved with future developments in flat PMT technology. Next would be a 500 ton fiducial volume liquid scintillator (6 m radius) far detector at 60 m distance from the neutrnio source. Both designs would be similar to a LSND style detector, i.e. a mineral oil detector doped with butyl PBD scintillator to increase light output, instrumented with 25%, or more, photocathode coverage. As well, both detector masses are quoted in fiducial volume, which is the useful volume available for reliable event reconstruction. To estimate NC neutrino rates in the near and far detector, we scale to the detection rate calculations in [17], which have assumed a $\nu_\mu\ ^{12}C \rightarrow \nu_\mu\ ^{12}C^*$ cross section of $2.7 \times 10^{-42}\ cm^2$ [18]. The Karmen colalboration has measured this cross section with limited statistics, getting a value of $(3.2 \pm 0.5_{stat} \pm 0.4_{syst}) \times 10^{-42}\ cm^2$ [19], which agrees well with theory.

For a proposed experiment at FNAL, we would not have space restrictions, allowing for

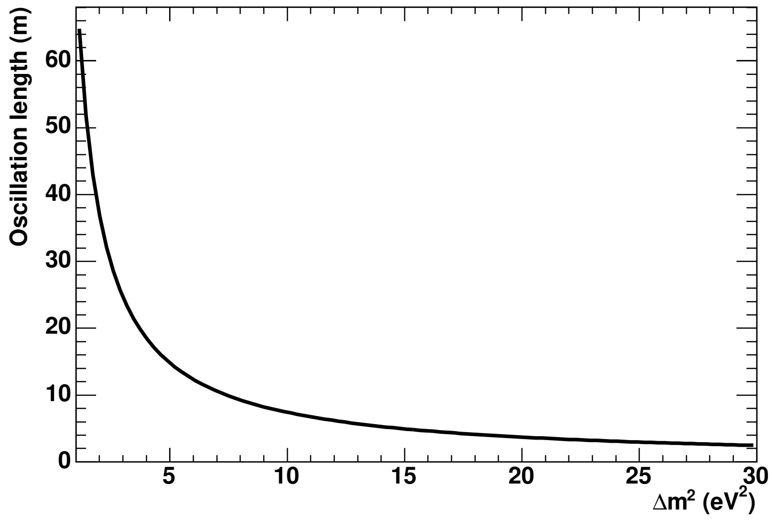

Figure 2: Oscillation length as a function Δm^2 for the NC reaction $\nu_\mu\ ^{12}C \rightarrow \nu_\mu\ ^{12}C^*$ where $E_{\nu_\mu} = 29.8$ MeV.

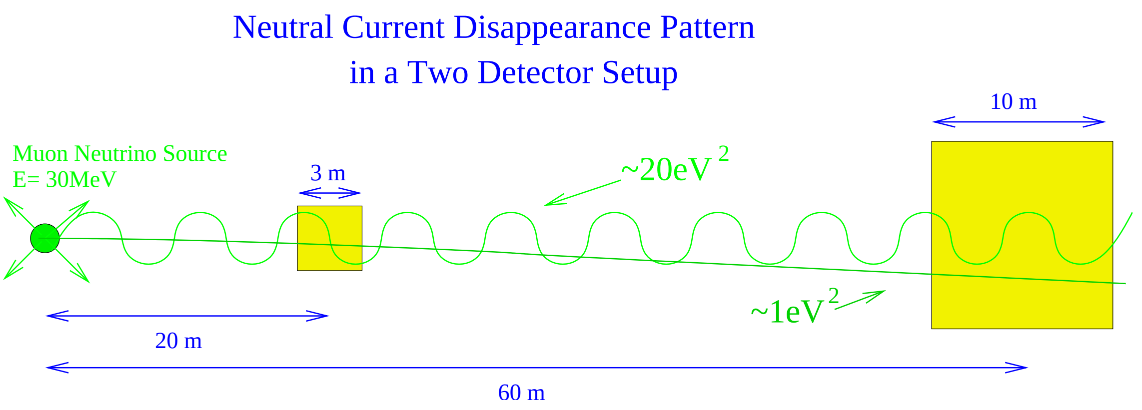

Figure 3: Neutral Current $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ disappearance patterns for a two detector setup.

Detector	Source Dist. (m)	FD Size (tons)	FD Length (m)	$\nu_\mu\ ^{12}C \rightarrow \nu_\mu\ ^{12}C^*$ events/yr
SNS Near	18	25	3	2056
SNS Far	60	500	10	3701
FNAL Near	10	116	5	77806
FNAL Far	100	1300	12	8720

Table 2: Estimated $\nu_\mu\ ^{12}C \rightarrow \nu_\mu\ ^{12}C^*$ events per year at the SNS and FNAL (2MW) source, assuming 100% event reconstruction efficiency.

larger near and far detectors. We assume a longer baseline, out to 100 m, and a detector size of 2 ktons (8 m radius), which would be required to keep roughly the same statistics. This would give a fiducial volume of 1.3 ktons (7 m radius).

Table 2 shows the number of events expected per year for the $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ reaction for the two possible configurations, one at SNS with 1.4 MW, the other at FNAL with 2 MW. The event reconstruction efficiency was assumed to be 100%, as the 15.11 MeV gamma ray is relatively easy to detect.

A simple Monte Carlo calculation was performed to estimate the $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ oscillation sensitivity, which includes smearing of 25 cm (FWHM) from the neutrino source uncertainty, and 30 cm (FWHM) from the reconstructed position for the 15.11 MeV gamma ray, which is dominated by Compton scattering. Also included is background subtraction of 1033 neutral current events (per year) from $\bar{\nu}_\mu$ and ν_e in the beam window [17]. Because we can isolate a clean sample of these backgrounds in the time window after the beam, we will have an excellent estimation of their number and character. This effectively increases the statistical error on the measured $\nu_\mu\ ^{12}C \rightarrow \nu_\mu\ ^{12}C^*$ rate by 40%.

Figures 4 and 5 show the active-sterile neutrino oscillation sensitivity for a three year run at the SNS and FNAL proton driver. At the 3σ level, both setups achieve a $\nu_\mu \rightarrow \nu_s$ oscillation sensitivity of $\Delta m^2 > 0.4\ eV^2$ and $sin^2(2\theta) > 0.05$, which is desired if the LSND signal is due to active-sterile neutrino oscillations. If we allow a realistic 5% systematic error on the ν_μ flux times neutral current cross section ($\phi_{\nu_\mu} \times \sigma_{NC}$), then Figures 6 and 7 show the resulting sensitivity. As expected, we lose some sensitivity, with the SNS oscillation amplitude becoming $sin^2(2\theta) > 0.07$ at 3σ. However, with a two detector setup for $\phi_{\nu_\mu} \times \sigma_{NC}$ normalization, many interaction channels for cross checks, and the simplicity of the SNS neutrino beam, we might expect to get the $\phi_{\nu_\mu} \times \sigma_{NC}$ errors down to 1%, which is much closer to the no systematic error plots.

If we consider just a single detector setup at the SNS, either near or far, Figures 8 and 9 show what might be expected for 5% $\phi_{\nu_\mu} \times \sigma_{NC}$ errors. There is a good chance that the ν-SNS near detector will be built by 2008 for cross section measurements. Figure 8 shows that even this one detector has sensitivity to active-sterile oscillation parameters of $\Delta m^2 > 1\ eV^2$ and $sin^2(2\theta) > 0.10$. This interesting measurement can be performed in parallel to the neutrino carbon cross section measurement.

In Figures 4 thru 9, two black stars are plotted that corresponds to the (3+2) model sterile neutrino solutions $\Delta m^2_{41} = 0.9\ eV^2$, $sin^2(2\theta_{41}) = 0.15$, and $\Delta m^2_{51} = 22\ eV^2$, $sin^2(2\theta_{51}) = 0.19$ [20]. The first solution is the LSND region, while the second larger mass solution is indicated by the other short baseline experiments. This (3+2) model gives significantly better fits that (3+1) models [4]. As can be seen, there is good coverage at the 3σ to 5σ level for all beam/detector combinations. If we solve explicitly for the (3+2) model, then Figures 10 and 11 shows the solution ellipses for the SNS and FNAL with two detectors. Again, the sensitivity is excellent, with two clear solution islands near the expected (3+2) predictions.

5 Conclusion

In the coming year, new physics beyond the Standard Model will be implied if MiniBooNE confirms the LSND oscillation anomaly. To understand whether active-sterile neutrino oscillations are responsible for this new physics will require a new class of oscillation experiments. A stopped pion source such as the SNS, coupled with two well positioned large liquid scintillator detectors, can achieve the desired sensitivity. This is made possible by the fortuitous combination of a monoenergetic ν_μ flux and the easily reconstructed neutral current interaction $\nu_x\ {}^{12}C \rightarrow \nu_x\ {}^{12}C^*(15.11)$. With perfect knowledge of $\phi_{\nu_\mu} \times \sigma_{NC}$, the $\nu_\mu \rightarrow \nu_s$ oscillation region $\Delta m^2 > 0.4\ eV^2$ and $sin^2(2\theta) > 0.05$ can be explored at the 3σ level. This would cover the $\nu_\mu \rightarrow \nu_s$ oscillaiton solutions indicated by LSND, and the (3+2) model. Such a measurement would be the first clear indication of the existence of light sterile neutrinos, and would hearld a new era in neutrino physics.

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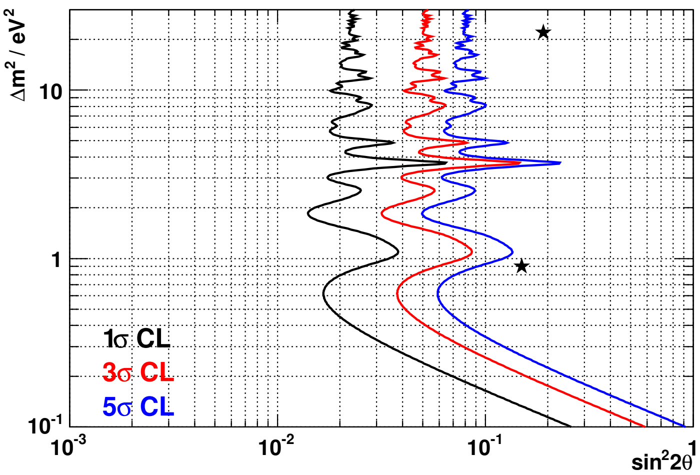

Figure 4: Active-Sterile neutrino oscillation sensitivity with NC reaction $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ for SNS with two detectors, no $\phi_{\nu_\mu} \times \sigma_{NC}$ systematic errors, and three years of running. The two black stars corresponds to the (3+2) solutions (see text).

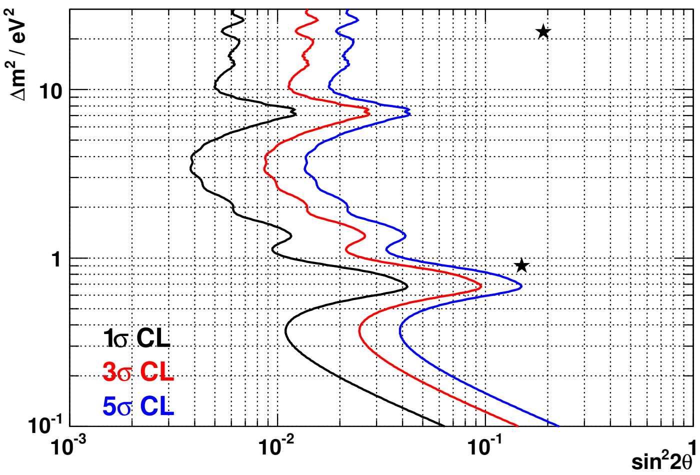

Figure 5: Active-Sterile neutrino oscillation sensitivity with NC reaction $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ for FNAL proton driver with two detectors, no $\phi_{\nu_\mu} \times \sigma_{NC}$ systematic errors, and three years of running. The two black stars corresponds to the (3+2) solutions (see text).

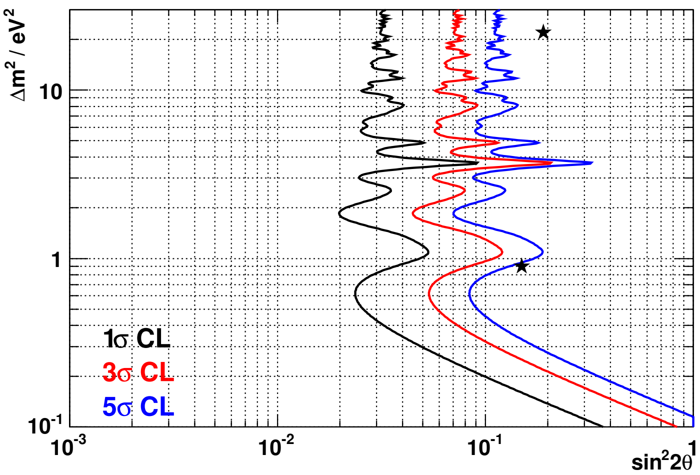

Figure 6: Active-Sterile neutrino oscillation sensitivity with NC reaction $\nu_x\ ^{12}C \to \nu_x\ ^{12}C^*(15.11)$ for SNS with two detectors, 5% $\phi_{\nu_\mu} \times \sigma_{NC}$ systematic errors, and three years of running. The two black stars corresponds to the (3+2) solutions (see text).

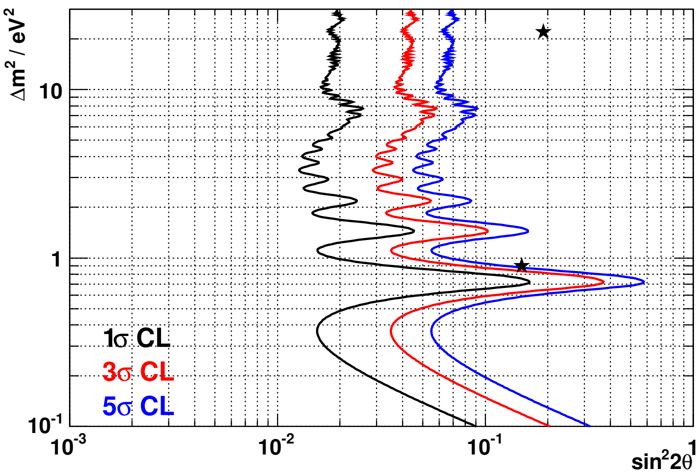

Figure 7: Active-Sterile neutrino oscillation sensitivity with NC reaction $\nu_x\ ^{12}C \to \nu_x\ ^{12}C^*(15.11)$ for FNAL proton driver with two detectors, 5% $\phi_{\nu_\mu} \times \sigma_{NC}$ systematic errors, and three years of running. The two black stars corresponds to the (3+2) solutions (see text).

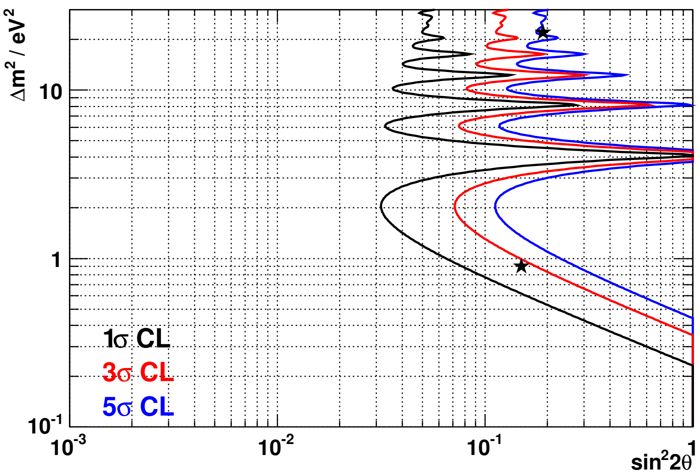

Figure 8: Active-Sterile neutrino oscillation sensitivity with NC reaction $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ for SNS with a near detector, 5% $\phi_{\nu_\mu} \times \sigma_{NC}$ systematic errors, and three years of running. The two black stars corresponds to the (3+2) solutions (see text).

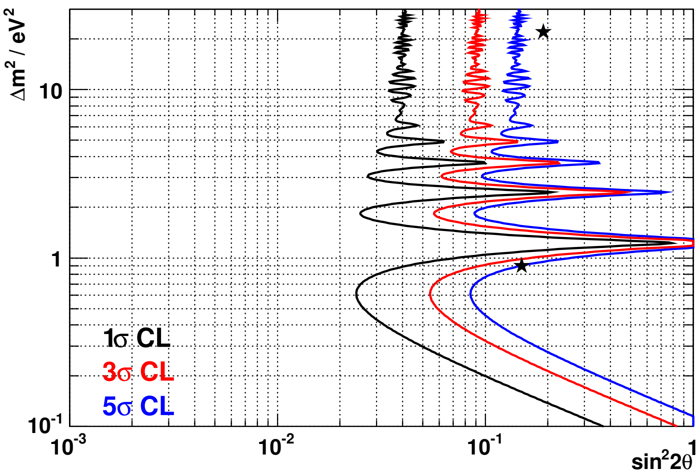

Figure 9: Active-Sterile neutrino oscillation sensitivity with NC reaction $\nu_x\ ^{12}C \rightarrow \nu_x\ ^{12}C^*(15.11)$ for SNS with a far detector, 5% $\phi_{\nu_\mu} \times \sigma_{NC}$ systematic errors, and three years of running. The two black stars corresponds to the (3+2) solutions (see text).

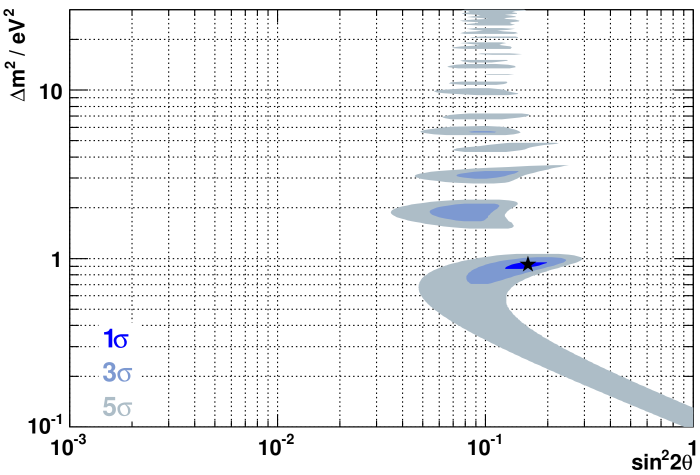

Figure 10: The (3+2) active-sterile neutrino oscillation solution contours for SNS with two detector, no $\phi_{\nu_\mu} \times \sigma_{NC}$ systematic errors, and three years of running. **Note: at present fig only showing (3+1) solution**.

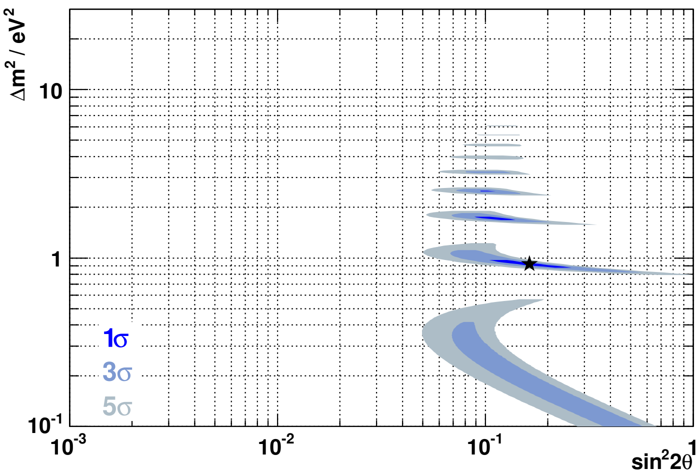

Figure 11: The (3+2) active-sterile neutrino oscillation solution contours for FNAL with two detector, no $\phi_{\nu_\mu} \times \sigma_{NC}$ systematic errors, and three years of running. **Note: at present fig only showing (3+1) solution**.