NuMI-L-780

Outline of a Shallow Underwater Main Injector Neutrino Oscillation Experiment (SUMO)

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1 Introduction

Interpretion of the Super-Kamiokande atmospheric neutrino data [4] as "standalone" evidence for neutrino oscillations within a 3 generation neutrino model [8] leads us to the following conclusions: 1) ν_μ oscillates to ν_τ with $1.6 \cdot 10^{-3} eV^2 < |\Delta m^2|_{23} < 3.6 \cdot 10^{-3} eV^2$ at a level of $sin^2(2\theta_{23}) > 0.9$, and 2) ν_μ can oscillate to ν_e at a level of $|U_{e3}|^2 < 0.06$ or less at the $|\Delta m^2|_{23}$ region. In addition, if we interpret the CHOOZ results [6] within the same theoretical framework, we obtain 3) $|U_{e3}|^2 < 0.027$ for $|\Delta m^2|_{23} = 0.003 eV^2$ (see figure 9). The generation of experiments including K2K [14], MINOS [5], OPERA [10], and KamLAND [7] are likely to obtain the following new results: 1) $|\Delta m^2|_{23}$ measured at the 10% level (with probably little or no improvement on $sin^2(2\theta_{23})$), and 2) $|U_{e3}|^2 < 0.008$ for $|\Delta m^2|_{23} = 0.003 eV^2$ (from MINOS; see figure 9).

Further improvement can be achieved with a new neutrino beam powered by the JHF and pointed at the Super-Kamiokande detector [9]. The predicted improvement with a 5 year off-axis beam run would be $|U_{e3}|^2 < 0.0015$ for $|\Delta m^2|_{23} = 0.003 eV^2$ (see figure 9). Also, measurements of $|\Delta m^2|_{23}$ and $sin^2(2\theta_{23})$ would improve significantly over MINOS.

A detector with sufficiently large mass located off-axis of the NuMI beam line can in principle be comparable to the JHF-SuperK neutrino oscillation proposal. The NuMI beamline crosses through Lake Superior near Two Harbors, Minnesota. The neutrino baseline to this point is approximately 630km. We consider in this note a 20kt ring imaging water cherenkov detector which could be deployed in the vicinity of Two Harbors (see figure 1). A comparison of NuMI on-axis and off-axis beams are shown in figure 2.

The first $\nu_\mu \rightarrow \nu_e$ oscillation appearance peak should occur for the condition:

$$1.27 \frac{L}{E} |\Delta m^2|_{23} = \frac{\pi}{2}$$

where L is the neutrino flight distance in km and E is the neutrino energy in GeV. For $|\Delta m^2|_{23} = 0.003 eV^2$ we find that the peak $\nu_\mu \rightarrow \nu_e$ neutrino energy is 1.5GeV. The off-axis angle (Θ) is approximately related to the neutrino energy by:

$$E = \frac{30 MeV}{\Theta}$$

where 30MeV is the neutrino momentum in the rest frame of the pion, assuming zero neutrino mass. Thus we find that the off-axis angle corresponding to the appearance peak (for $|\Delta m^2|_{23} = 0.003eV^2$) is 20mr. This in turn corresponds to a transverse distance of 12.4 km off of the neutrino beam axis (8 miles from Two Harbors). A comparison of NuMI on-axis and off-axis beams for 20mr are shown in figure 3. The off-axis beam event rates are summarized in the following table:

Off-axis ν_μ CC event rates for isoscalar exposure regular hierarchy, $\Delta m^2_{23} = 0.003eV^2$, L=631km				
	9.2mr	fraction $> 4GeV$	20mr	fraction $> 4GeV$
PH2 low	318 / kt-yr	43%	85 / kt-yr	28%
PH2 medium	365 / kt-yr	31%	65 / kt-yr	36%
PH2 high	243 / kt-yr	49%	38 / kt-yr	56%

The optimum case for reducing systematic error due to neutral current background occurs for the smallest tail (ie. fraction of events $> 4GeV$). On the other hand, one wants to maximize the number of signal events to reduce statistical error. For the purposes of this note we consider the case of PH2 low and 9.2mr; this appears to be a reasonable choice for the central Super-K $|\Delta m^2|_{23}$ value. Note that the tail can be further reduced by a factor of 3 with a beam plug [12].

The ν_μ CC spectrum with and without oscillations is shown in figure 4. Ratios of oscillated/unoscillated ν_μ CC spectra for different values of $|\Delta m^2|_{23}$ are shown in figure 5. The NuMI-SUMO measurement errors for Δm^2_{23} and $sin^2 2\Theta$ are shown in figure 6 along with the corresponding errors for JHF-SuperK. At first glance, it appears that NuMI-SUMO is significantly better than JHF-SuperK in the measurement of Δm^2_{23} (especially below $3 \cdot 10^{-3}$). At least part of this is because we do not yet include the full complement of reconstruction effects and systematic errors. In particular, the JHF-SuperK analysis assumes a 4% energy scale uncertainty, which will degrade the Δm^2_{23} sensitivity, especially at low values. A full NuMI-SUMO analysis will likely produce sensitivities that are similar to JHF-SuperK. We tabulate the inputs to the three sensitivity calculations (NuMI-MINOS, JHF-SuperK and NuMI-SUMO) here:

experiment	PID	Bkgd	σ_{stat}	norm	bin-to-bin	PID-error	E_{calib}
NuMI-MINOS	MC	NC	Y	2%	2%	2%	
JHF-SuperK	MC	Non-QE	Y	10%	10% ?	20%	4%
NuMI-SUMO	perfect		Y	2%	2%		

Key:
PID - particle ID: MC=Monte Carlo
Bkgd - simulated backgrounds
σ_{stat} - statistical error
norm - systematic error in overall rate
bin-to-bin - correlated bin-to-bin systematic error
PID-error - error in background efficiency(MINOS)/subtraction(JHF)
E_{calib} - energy calibration error

Note that K2K claims a systematic error less than 1% in $sin^2 2\Theta$ and less than $1 \cdot 10^{-4}$ for Δm^2_{23} (corresponds to 4% for SK best-fit value).

We show in figure 7 the $\nu_\mu \to \nu_e$ appearance oscillation probability for various mass hierarchy/CP-phase combinations. The ν_e CC spectrum including signal and background is shown in figure 8. Note that if beam related ν_e CC is the dominant background, then in the signal region ($E_\nu < 3GeV$) these will be due mainly to muon decays (not kaon decays). An estimate of the NuMI-SUMO sensitivity to $|U_{e3}|^2$, assuming a 30% efficiency and ν_e CC events ($E_\nu < 3GeV$) as the dominant background, is shown in figure 9 along with the corresponding sensitivities for NuMI-MINOS and JHF-SuperK. Of course, the beam energy can be "tuned" to $|\Delta m^2|_{23}$ by changing the off-axis location of the detector; the resulting sensitivity curve would shift accordingly.

2 Detector considerations

At sea level the hard component of the cosmic ray flux through a unit spherical surface is 170Hz per square meter. A spherical detector volume with diameter of 36.8m (20kt for 2m from-the-wall fiducial volume cut) would have a 723kHz cosmic ray event rate. If we consider detected photons which undergo up to one reflection in the detector, then the maximum "afterglow" time per cosmic ray muon would be 245ns for a deadtime of 18%. If we consider a 32mwe overburden [1], then the cosmic muon rate is reduced by a factor of 6 for a deadtime of 3%.

Thus to obtain a deadtime at the level of 3% we must keep the detected cherenkov photons from cosmic muons down to at most one reflection and place the detector at a depth of 69m (37m diameter of detector plus 32m overburden). This depth can be achieved 0.5km to 1km offshore.

Because of the shallow depth of the detector, a light-tight barrier would have to envelope the entire detector; this corresponds to 4000 square meters of opaque material (Tyvek, for example). If we want to match the pattern recognition capability of SuperK, then the number of PMTs can be estimated as follows. Since the fiducial volume of SUMO is the same as that of SuperK, the number of PMTs should also be the same if we want to have 4π coverage. But since we only care about neutrinos coming from the NuMI beamline, we can reduce the number of PMTs by a factor of 2. Thus we would need about 6000 PMTs covering 50% of the full angular phase space. The size of the PMTs regulates the energy resolution; given the shape of the neutrino appearance peak, 20cm diameter PMTs appear to be adequate.

3 Summary

We have shown that a shallow underwater water cherenkov detector located off-axis of the NuMI beamline in the vicinity of Two Harbors, Minnesota, can match the physics capability of the recent JHF-SuperK proposal [9]. The detector could be deployed from the existing infrastructure in the harbor, but would have to be located outside of the harbor to obtain the required depth. 30m of water overburden is needed, and another 40m for the height of the detector. The detector would consist of approximately 6000 20cm diameter PMTs enclosed in a 4000 square meter light-tight envelope.

References

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[4] Evidence for oscillation of atmospheric neutrinos. Super-Kamiokande Collaboration. Phys.Rev.Lett.81, pp.1562-1567 (1998); J.Kameda, proc. of 27th ICRC, Hamburg (2001).

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[9] Letter of Intent: A long baseline neutrino oscillation experiment using the JHF 50 GeV proton-synchrotron and the Super-Kamiokande detector. Y.Itow et.al. (Feb.2000).

[10] An appearance experiment to search for $\nu_\mu \to \nu_\tau$ oscillations in the CNGS beam. OPERA collaboration. CERN/SPSC 2000-028 (July 2000)

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[12] A study of $\nu_\mu \to \nu_e$ sensitivity in MINOS. M.Diwan et.al. NuMI-L-714. (Feb.2001)

[13] Oscillation Measurements with Upgraded Conventional Neutrino Beams. V.Barger et.al. FERMILAB-FN-703, hep-ex/0103052 (Mar.2001)

[14] Detection of accelerator produced neutrinos at a distance of 250-km. K2K Collaboration. hep-ex/0103001 (Feb.2001)

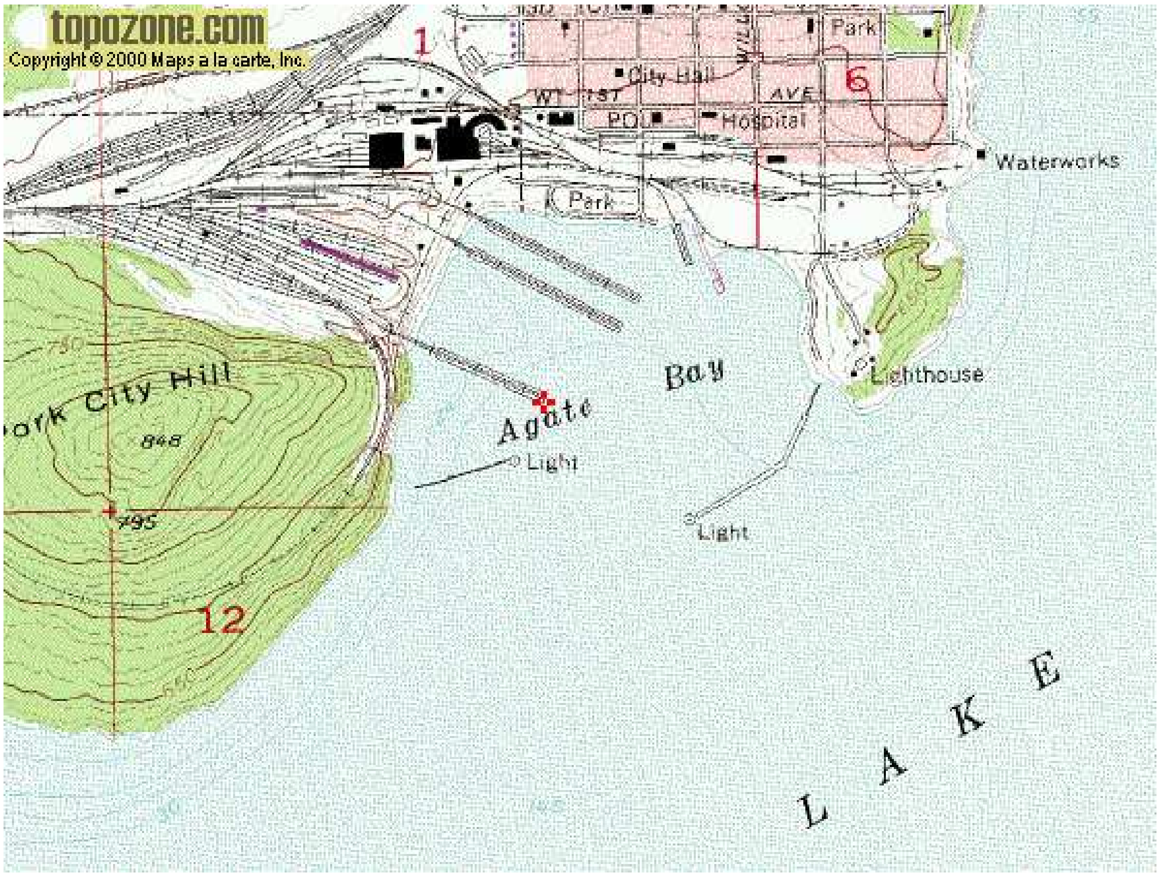

Figure 1: Possible SUMO site. The off-shore deployment could be based at the end of the 3rd pier in Two Harbors (marked with a red cross). The depth at the end of the pier is 12 meters. A depth of 70m can be reached outside of the harbor.

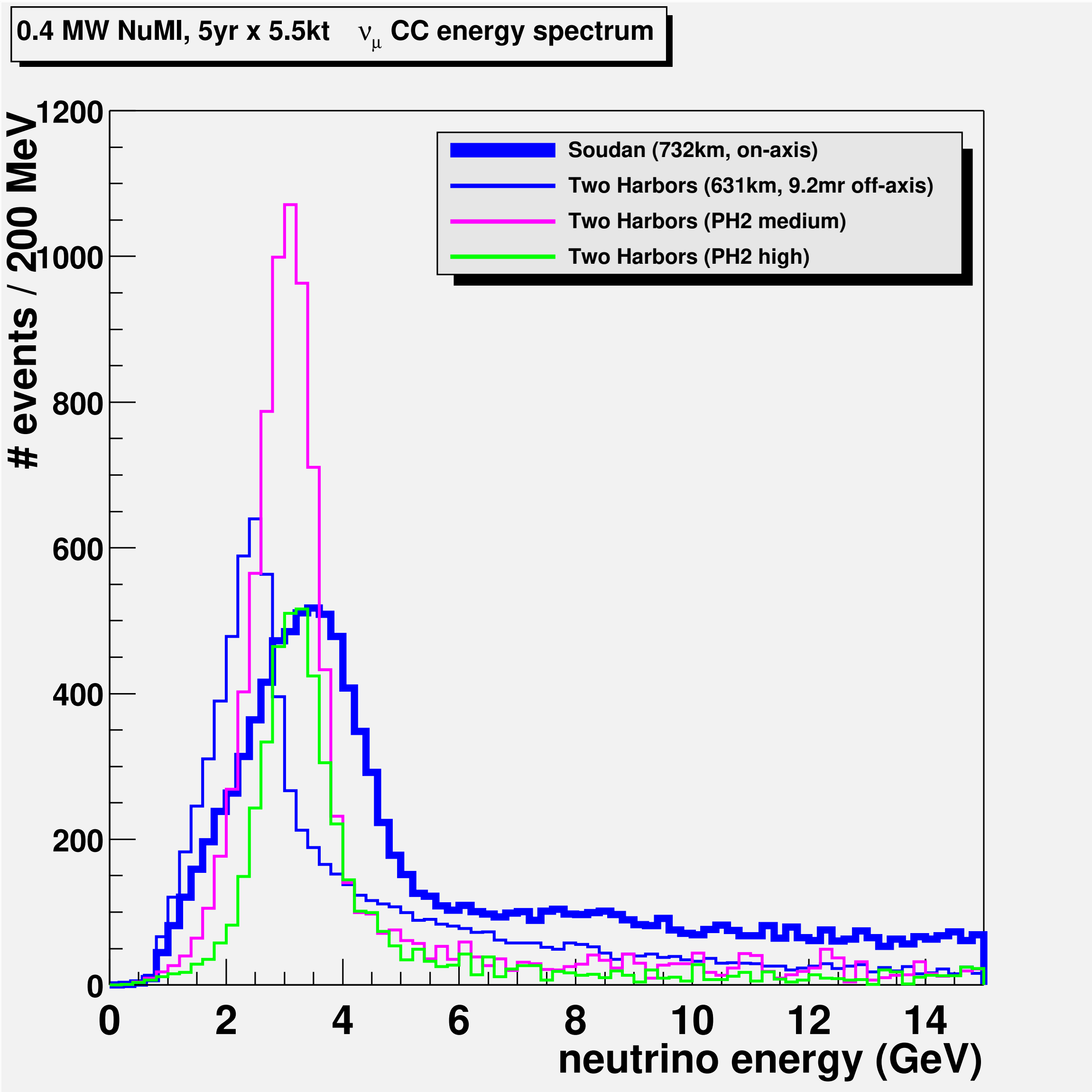

Figure 2: Comparison of on- and 9.2mr off-axis number of muon neutrino charged current events for an isoscalar target.

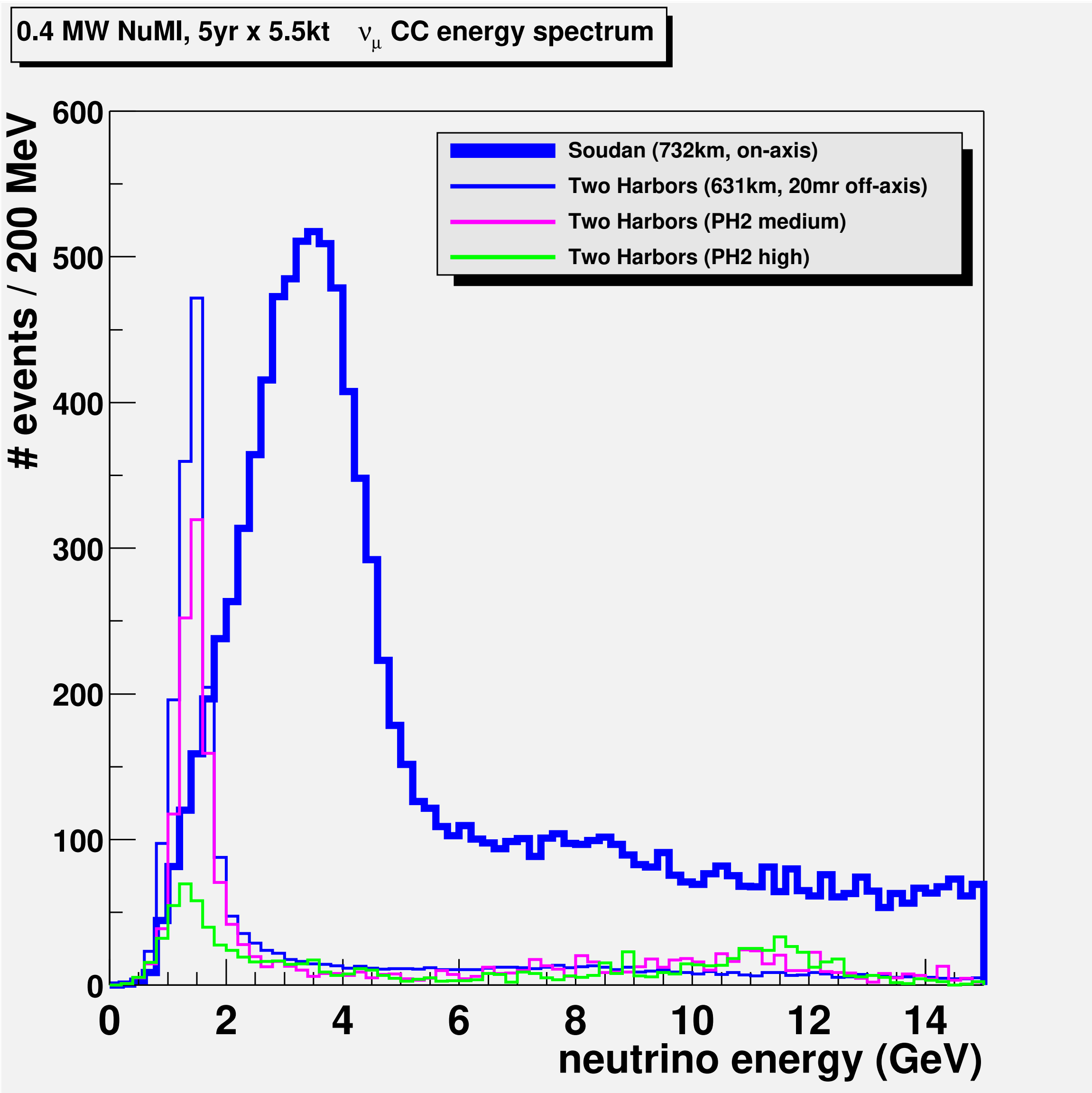

Figure 3: Comparison of on- and 20mr off-axis number of muon neutrino charged current events for an isoscalar target. Note that in this case the actual site is 12km distant from Two Harbors.

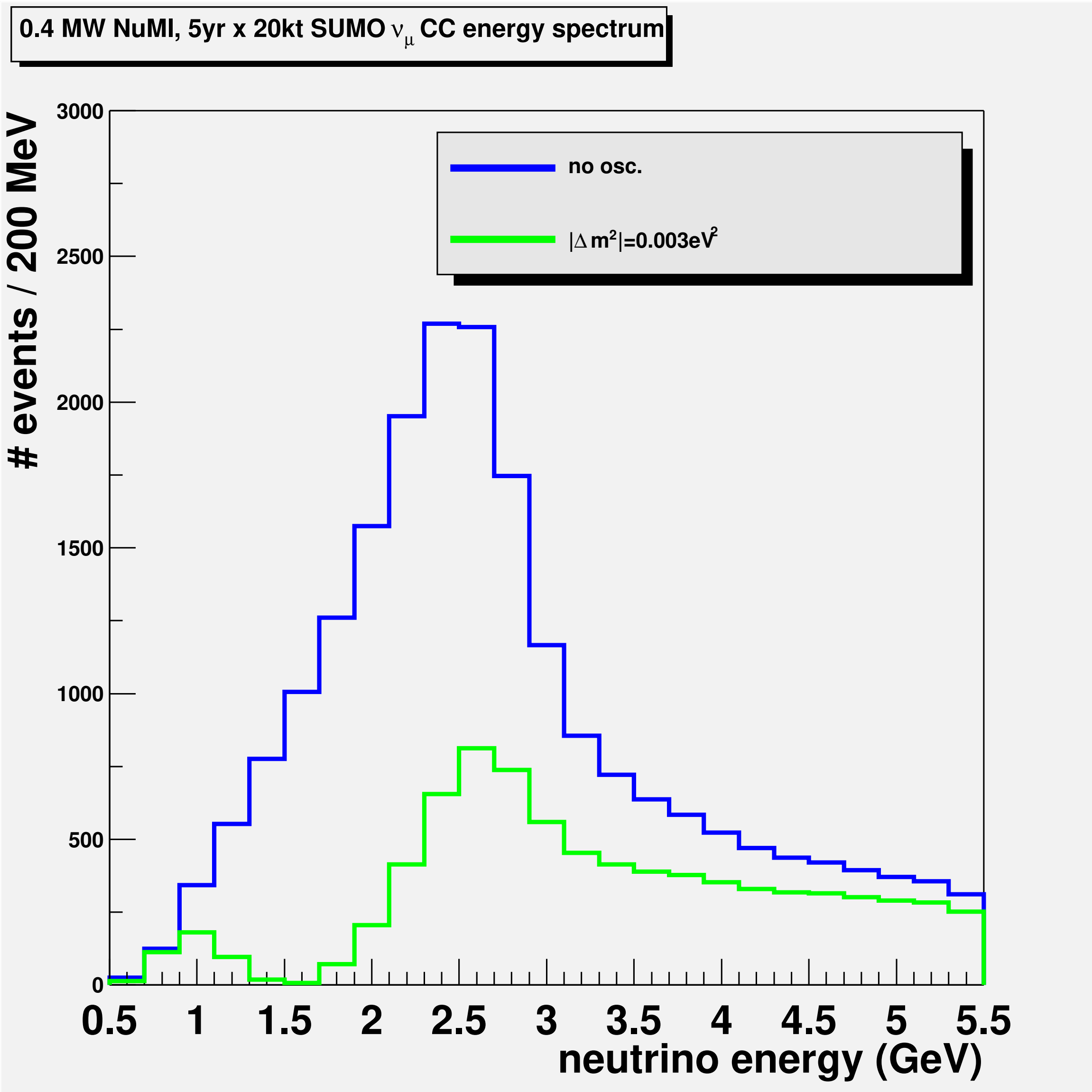

Figure 4: Number of muon neutrino charged current events with and without oscillations. We have assumed a 5yr exposure of 20kt isoscalar target.

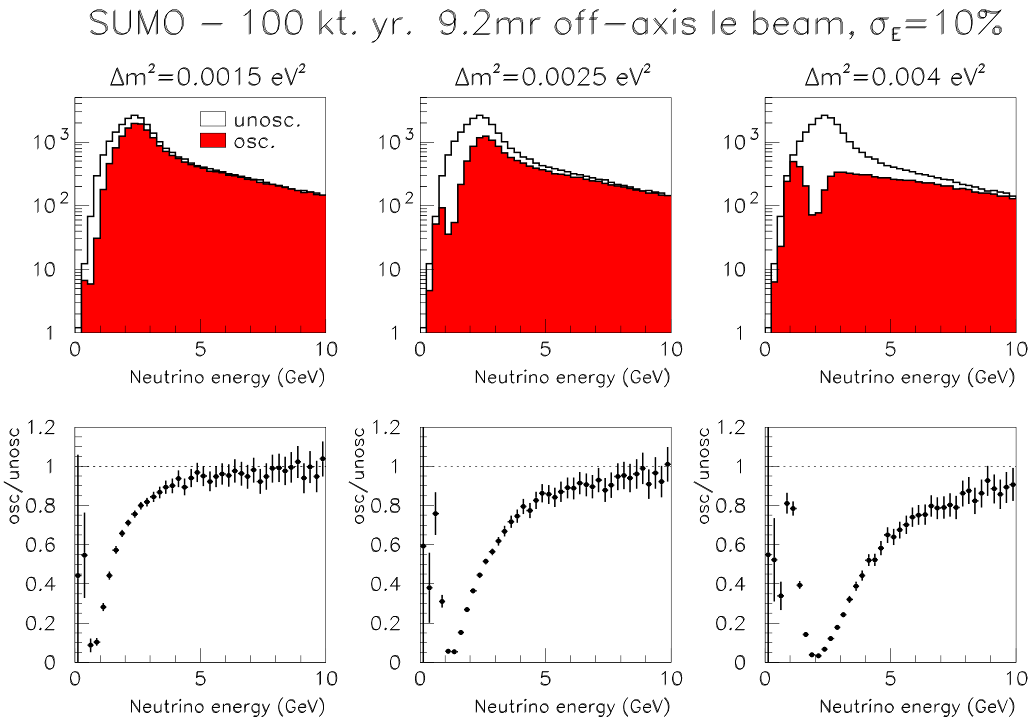

Figure 5: Ratio of oscillated/unoscillated muon neutrino charged current events for three different values of Δm^2_{23}. We have assumed 10% neutrino energy resolution and a 100kt-yr exposure of an isoscalar target.

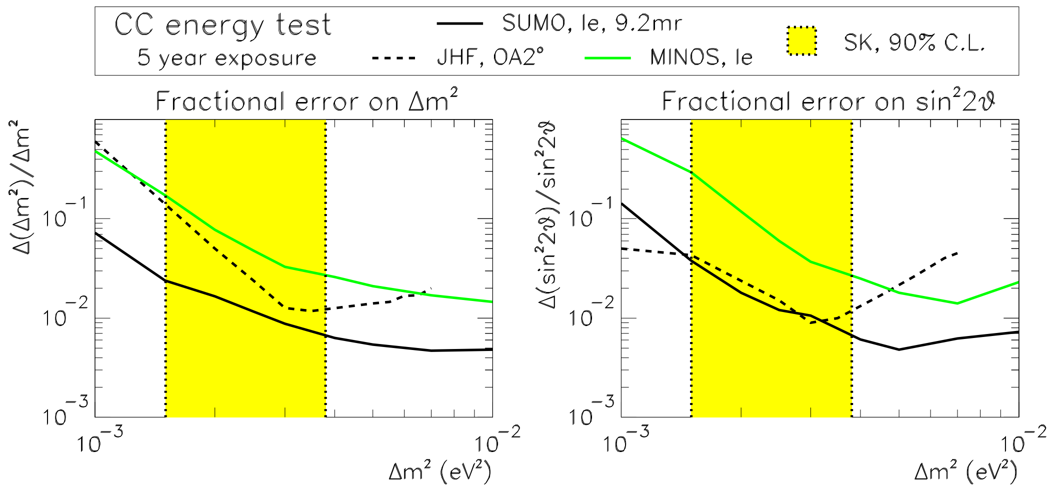

Figure 6: Fractional errors on measurements of Δm^2_{23} and $sin^2 2\Theta$. For SUMO we have assumed a 10% neutrino energy resolution and a 100kt-yr exposure of an isoscalar target.

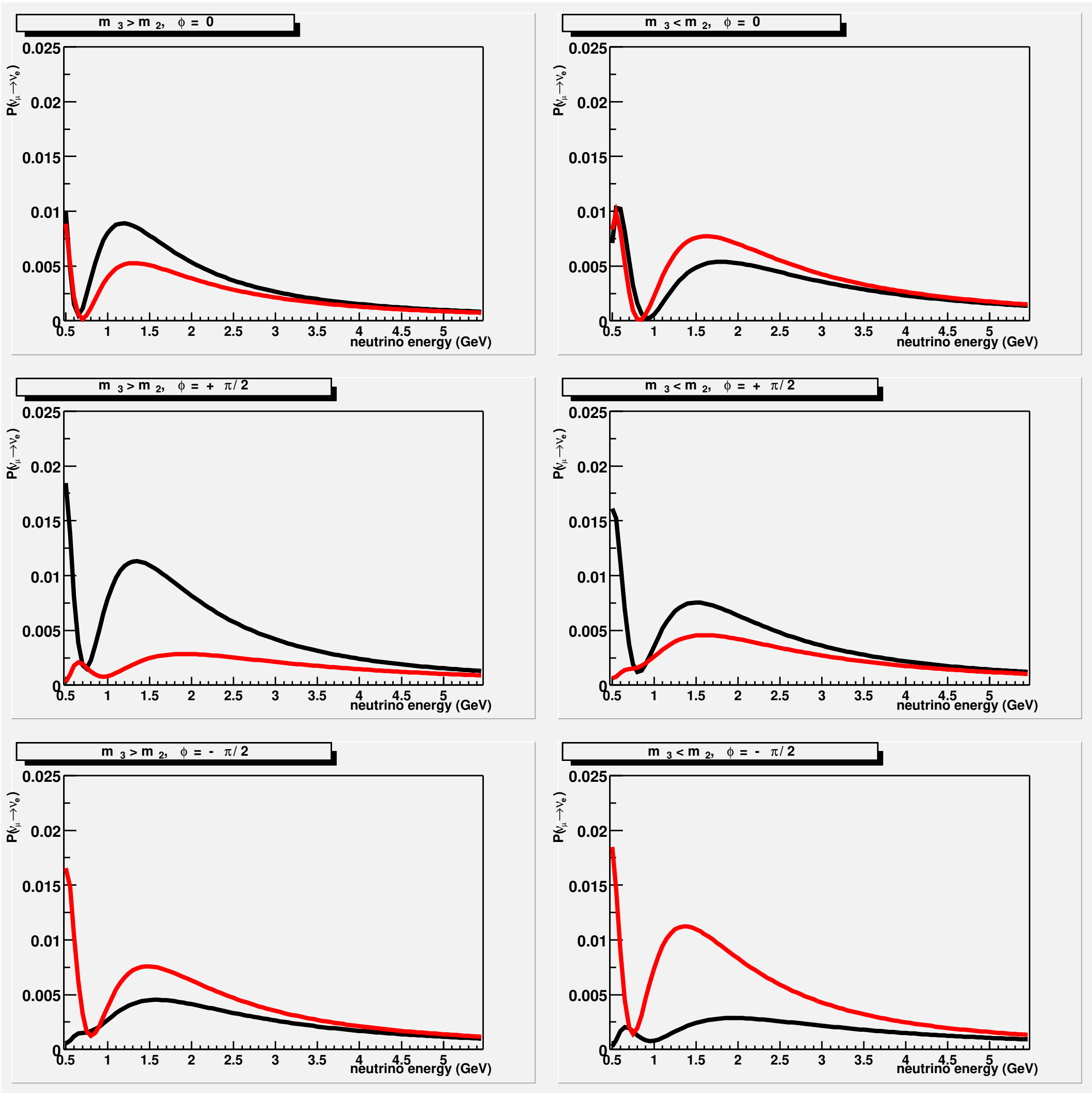

Figure 7: Probability for $\nu_\mu \to \nu_e$ for NuMI-SUMO (L=631km), given $|U_{e3}|^2 = 0.003$ (ie. $\theta_{13} = 3^o$), $\Delta m^2_{23} = 3 \cdot 10^{-3} eV^2$, $\Delta m^2_{12} = 5 \cdot 10^{-5} eV^2$, $U^2_{\mu 3} = U^2_{\tau 3}$, and $U^2_{e1} = U^2_{e2}$. The black lines are for neutrinos, and the red lines are for anti-neutrinos. The panels on the left side have regular mass hierarchy, and the panels on the right side have inverted mass hierarchy. The upper panels have zero phase, the middle panels have +90 degrees phase, and the lower panels have -90 degrees phase.

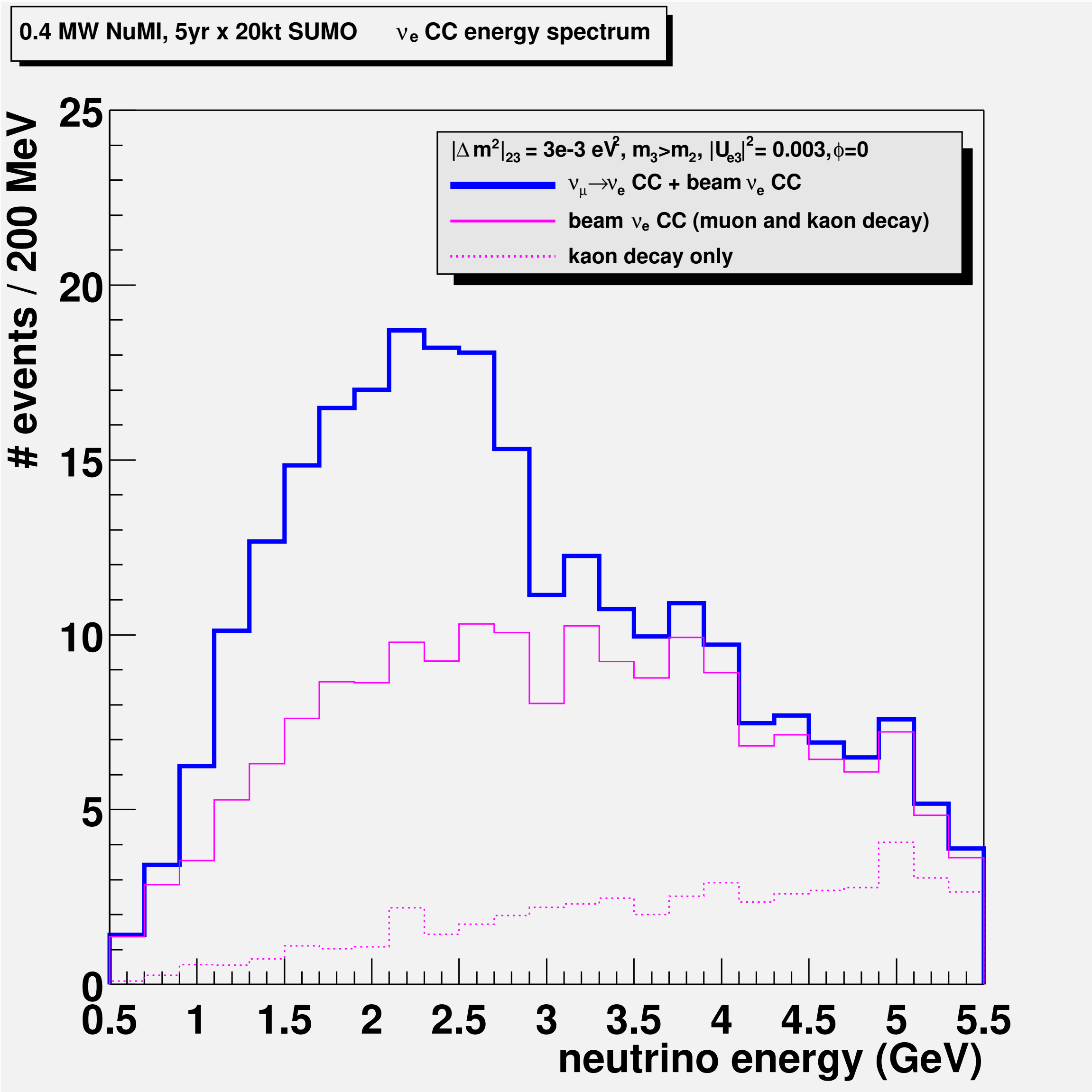

Figure 8: Number of electron neutrino charged current events from oscillation and also from intrinsic neutrino beam background. We have assumed a 5yr exposure of 20kt isoscalar target. Note that in the signal region electron neutrinos from kaon decay are not the dominant background.

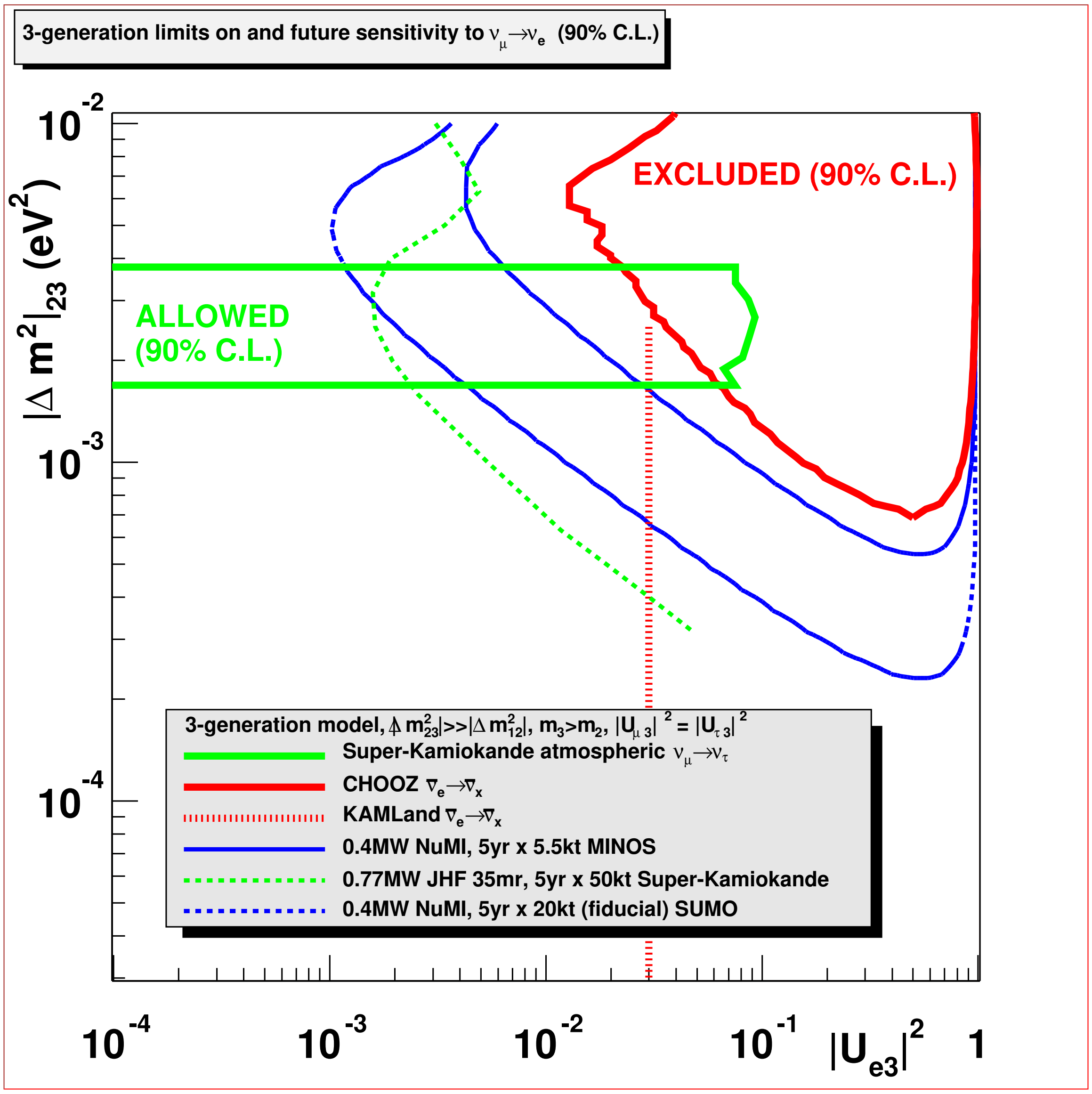

Figure 9: 90% confidence level regions in $|\Delta m^2_{23}|$,$|U_{e3}|^2$. A systematic error of 10% on the number of background events has been assumed. For the NuMI-SUMO case, we have assumed that the dominant background is ν_e CC with $E_\nu < 3GeV$. An exact calculation of the oscillation probability in matter was used for regular mass hierarchy, $U^2_{\mu 3} = U^2_{\tau 3}$, $U^2_{e1} = U^2_{e2}$, $|\Delta m^2_{12}| = 5 \cdot 10^{-5} eV^2$, and phase $\phi = 0$.