Sterile Neutrinos in the MINSIS Experiment

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Talk overview

- Brief overview of MINSIS
- Sterile neutrinos: the $3 + 1$ scenario
- MINSIS sensitivity - dependence on:
  - Efficiency
  - Background
  - Beam energy
  - Flux
- Summary.

MINSIS overview

MINSIS = Main Injector Non-Standard Interactions Search

Experiment overview (see Adam Para's talk for details):

- Beam: NuMI beam $\Rightarrow$ mainly ν_μ with some ν_e and ν_τ background.
- Baseline: $L = 1$ km.
- Detector: mass $\sim$ 1 ton ($\sim 10^6$ CC ν_μ events), can detect τ's

  $\Rightarrow$ Look for $\nu_\mu \to \nu_\tau$ oscillations.

Sterile ν: the $3+1$ model

- The $3+1$ model is excluded at 4σ by a global fit to all available data.
  M. Maltoni, T. Schwetz, [arXiv:0705.0107 [hep-ph]].

- But if we neglect only the LSND data, and keep data from all the remaining experiments, the model is no longer excluded.

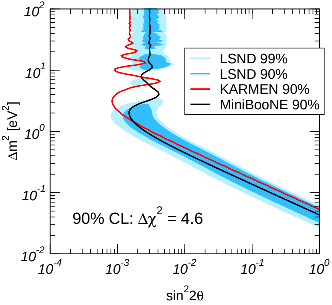
- There are 3 additional mixing angles (θ_{41}, θ_{42}, θ_{43}) involved, and 2 additional CP violating phases.

- Different experiments put bounds on different combinations of these parameters.

Sterile ν: current bounds

- E.g. LSND, MiniBooNE, KARMEN, looked for $\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow$ bounds on $4\sin^2\theta_{14}\sin^2\theta_{24} = \sin^2 2\theta$:

  M. Maltoni, T. Schwetz, [arXiv:0705.0107 [hep-ph]].



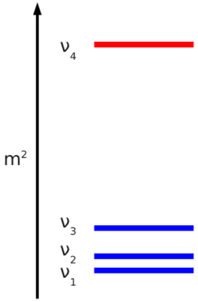
- MINSIS (like NOMAD and CHORUS) will be sensitive to $4\cos^2\theta_{14}\sin^2\theta_{24}\cos^2\theta_{24}\sin^2\theta_{34} = \sin^2 2\theta_s^{\mu\tau}$ (no sensitivity to CP phases).

The $3+1$ model: short baseline approximation

At $L = 1$ km, the **solar and atmospheric oscillations are irrelevant**:

$$\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \sim 10^{-10}$$

$$\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \sim 10^{-7}$$



So we can safely consider a **2 family approximation**, treating the 3 standard model ν as a single state.

In this approximation, we assume:

$$m_{\nu_4} \gg m_{\nu_3}, m_{\nu_2}, m_{\nu_1} \Rightarrow \Delta m^2_{43} \sim \Delta m^2_{42} \sim \Delta m^2_{41} = \Delta m^2_s.$$

The $3+1$ model: parameterization

The extended mixing matrix can be parameterized as:
J. N. Abdurashitov *et al.*, [arXiv:astro-ph/9907113].

$$U = R_{34}(\theta_{34})R_{24}(\theta_{24})R_{23}(\theta_{23},\delta_3)R_{14}(\theta_{14})R_{13}(\theta_{13},\delta_2)R_{12}(\theta_{12},\delta_1)$$

where R_{ij} are 2×2 rotation matrices.

Using this parameterization and the SBL approximation, we obtain the following oscillation probabilities for a beam of ν_μ:

The $3+1$ model: oscillation probabilities

$$P_{\nu_\mu \to \nu_e} = 4 s_{14}^2 c_{14}^2 s_{24}^2 \sin^2 \Delta_s \quad (e.g. MiniBooNE)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - 4 c_{14}^2 s_{24}^2 (1 - c_{14}^2 s_{24}^2) \sin^2 \Delta_s \quad (e.g. MINOS)$$

$$P_{\nu_\mu \to \nu_\tau} = 4 c_{14}^4 s_{24}^2 c_{24}^2 s_{34}^2 \sin^2 \Delta_s \quad (e.g. NOMAD)$$

$$P_{\nu_\mu \to \nu_s} = 4 c_{14}^2 s_{24}^2 c_{24}^2 c_{34}^2 \sin^2 \Delta_s$$

where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$ and $\Delta_s = \frac{\Delta m_s^2 L}{4E}$.

Experimental design

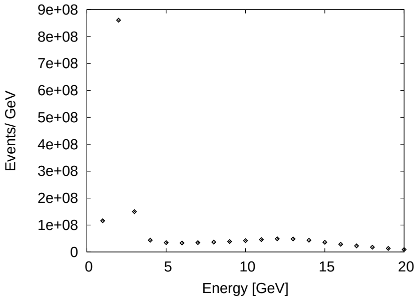
The experimental sensitivity will be affected by:

- Flux
- Energy
- Efficiency
- Backgrounds
- Systematics
- Energy resolution
- Anything else?

Beam: NOνA flux

Initially, consider NOνA flux, but only consider ν_μ for now:
D. Ayres *et al.*, [arXiv:hep-ex/0503053].

- 10^{21} PoT per year, 1.12 MW, running for 3 years.
- At $L = 1$ km, statistics are not a problem!
- Using a 4 kton detector, have $\sim 10^9$ CC ν_μ events for 1 GeV $< E <$ 20 GeV.
- Peak is at $\sim$ 2 GeV; have $\sim 10^8$ ν_μ above τ threshold.



Experimental sensitivities

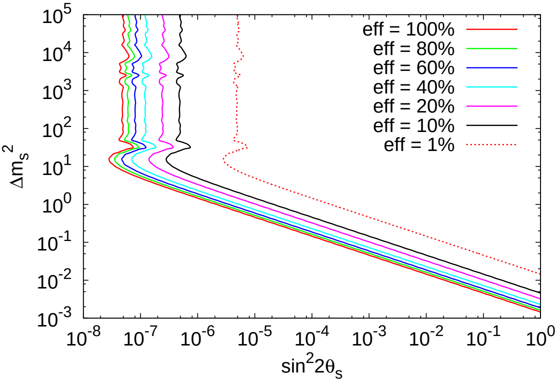
First simulate $\sin^2 2\theta_s^{\mu\tau} = \Delta m_s = 0$ (using GLoBES).

What bounds can we obtain on these parameters?

Will they be significantly better than current bounds?

Efficiency

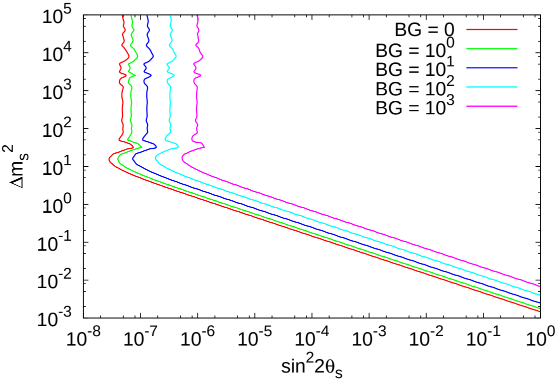
Consider a hypothetical **zero background**, and look at the effect of **altering the efficiency**:



Can place an upper bound on $\sin^2 2\theta_s^{\mu\tau}$ between $\sim 10^{-7}$ (100% efficiency) and $\sim 10^{-5}$ (1% efficiency) at 90% confidence.

Backgrounds

Consider a hypothetical **100% efficiency**, and look at the effect of **altering the number of background events**:



Can place an upper bound on $\sin^2 2\theta_s^{\mu\tau}$ between $\sim 10^{-7}$ (no background) and $\sim 10^{-6}$ (10^3 background events) at 90% confidence.

Is it worth detecting τ's?

If we don't detect τ's, then the other option is to detect μ's
$\Rightarrow$ Look at μ disappearance channel, $\nu_\mu \to \nu_\mu$.

Can't compare $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_\tau$ directly because these channels are sensitive to different combinations of angles:

$$P_{\nu_\mu \to \nu_\mu} = 1 - 4c_{14}^2 s_{24}^2 (1 - c_{14}^2 s_{24}^2) \sin^2 \Delta_s = 1 - \sin^2 2\theta_s^{\mu\mu} \sin^2 \Delta_s$$

$$P_{\nu_\mu \to \nu_\tau} = 4c_{14}^4 s_{24}^2 c_{24}^2 s_{34}^2 \sin^2 \Delta_s = \sin^2 2\theta_s^{\mu\tau} \sin^2 \Delta_s.$$

But can qualitatively compare sensitivities to $\sin^2 2\theta_s^{\mu\mu}$ and $\sin^2 2\theta_s^{\mu\tau}$.

τ appearance vs μ disappearance

Compare sensitivity to $\sin^2 2\theta_s^{\mu\mu}$ from 'perfect' μ detection (100% efficiency, zero background, 0.1% systematic errors)

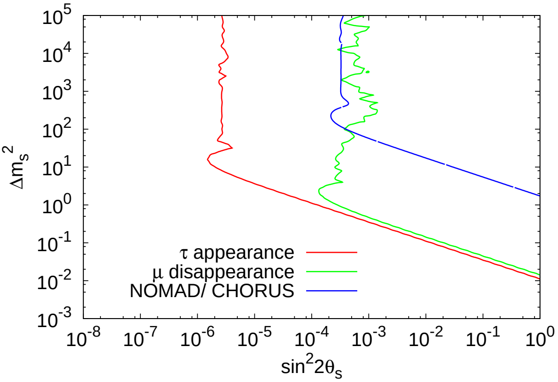
with sensitivity to $\sin^2 2\theta_s^{\mu\tau}$ from 'realistic' τ detection (10% efficiency, 2 background events, 10% systematic errors)

and sensitivity to $\sin^2 2\theta_s^{\mu\tau}$ from NOMAD and CHORUS.
E. Eskut *et al.*, [arXiv:0710.3361 [hep-ex]].

τ appearance vs μ disappearance

With μ disappearance, have similar sensitivity to $\sin^2 2\theta_s^{\mu\mu}$ as NOMAD and CHORUS have to $\sin^2 2\theta_s^{\mu\tau}$.

τ appearance is ~ 100 times more sensitive than μ disappearance.



Comparison with detector based on emulsion-silicon target

Yesterday we saw results from a 1 ton detector with 50% efficiency (2×10^6 CC ν_μ events detected):

J. J. Gomez-Cadenas, J. A. Hernando, Nuc. Inst. A, 281 (1996), 223-235.

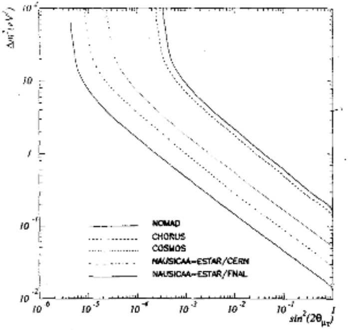
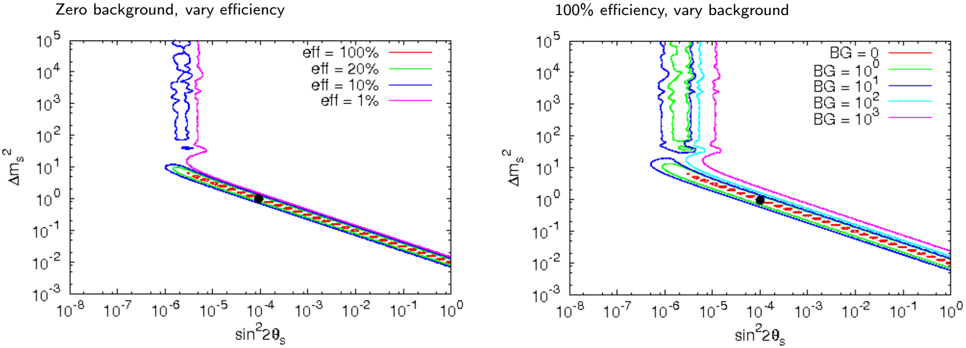


Fig. 11. Exclusion plot, showing the expected sensitivity of NAUSICAA-ESTAR at CERN and FNAL beams.

Suppose now that $\sin^2 2\theta_s^{\mu\tau} = 10^{-4}$ and $\Delta m_s^2 = 1$ eV^2.

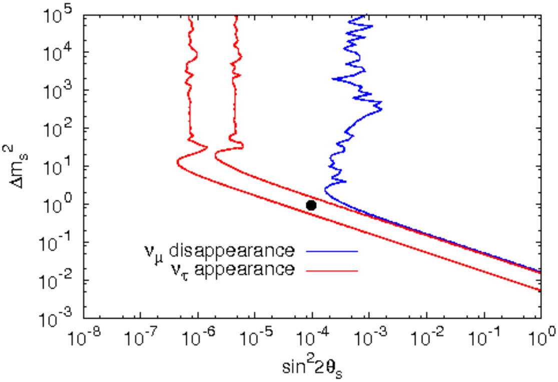
How precisely could we measure these parameters?

Obtain ~ 100 ν_τ events in total (taking into account τ cross-section, and assuming 100% efficiency).



Detecting non-zero $\theta_s^{\mu\tau}$, Δm_s^2

Again, compare 'perfect' μ detection with 'realistic' τ detection:



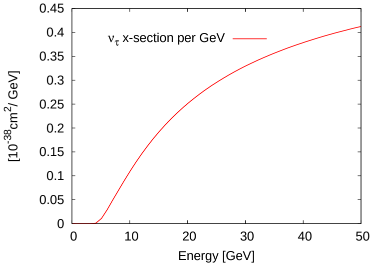
With 10% efficiency and 2 background events, MINSIS can significantly constrain the parameter space.

Energy dependence

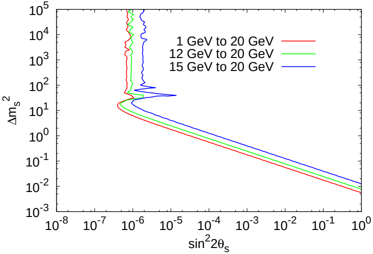
The energy dependence of the sensitivities comes from the energy dependence of the ν_τ cross-section.

M. Messier, UMI-99-23965; E. Paschos, J. Yu, [arXiv:hep-ph/0107261].

ν_τ cross-section (solid target)



Different energy thresholds

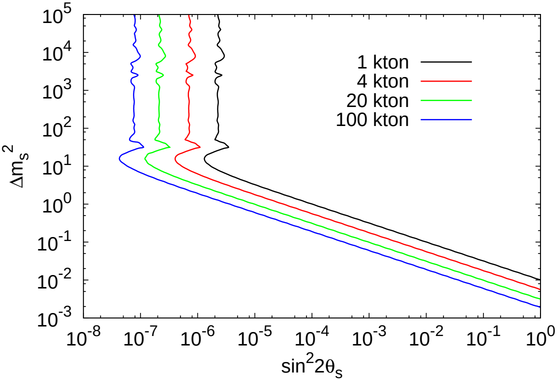


Events below $\sim$ 12 GeV don't help much.

$\Rightarrow$ **A higher energy beam, above $\sim$ 12 GeV, would be good!**

Flux dependence

Can increase the number of higher energy events by increasing beam energy, running for longer, using a larger detector:



Roughly: **a 25 times increase in flux improves sensitivity by an order of magnitude**.

Summary

- Detecting $\nu_\mu \to \nu_\tau$ oscillations in the **MINSIS experiment could improve on current bounds on the 3+1 model of sterile neutrinos, given an adequately large detector/ enough events**!
- The critical factors are efficiency, background rejection and energy.
- Energy resolution and systematics have very little effect.