NSI searches with atmospheric neutrinos in Deep Core: the mu-tau sector

Warren Wright
wright@psu.edu

Department of Physics
The Pennsylvania State University

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Outline

1. Introduction to Neutrino Oscillations
    - Vacuum, Standard Interactions and Best-Fit Values
    - Non Standard Interactions and Current Bounds
2. NSI Analysis
    - Experimental Guidelines, PREM and sPREM
    - Oscillation probability
    - Number Of Muons, Flux and Cross Section
3. The reduced $\epsilon_{\mu\tau}$ system and including $\epsilon_{\tau\tau}$
    - Derivation of the reduced $\epsilon_{\mu\tau}$ system
    - Comparisons to Full Numerics
    - The inclusion of $\epsilon_{\tau\tau}$
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Vacuum Oscillation Formalism

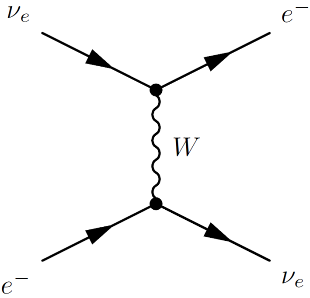
- Mass basis: $|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle$ with $k \in \{1,2,3\}$
- Flavor basis: $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle$ with $\alpha \in \{e,\mu,\tau\}$
- The PMNS parameterization (ignoring Majorana phases irrelevant for oscillations):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

Matter Oscillation Formalism

Charged current matter potential V_{CC}:



$$V_{CC} = \sqrt{2} G_F N_e = 7.6 \times 10^{14} Y_e \rho$$

$G_F =$ the Fermi constant

$N_e =$ the electron number

$Y_e =$ the electron fraction

$\rho =$ the density

This only effects ν_e.

Matter Oscillation Formalism

Schrödinger's Equation for Neutrino wave-functions in the presence of matter:

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left(\frac{1}{2E}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + H_I\right)\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

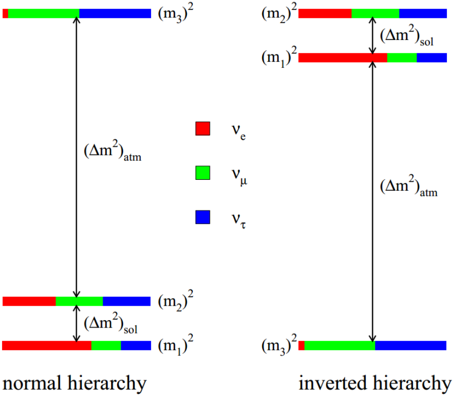
with:

$$H_I = V_{cc}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix} \ \& \ \Delta m^2_{kj} = m^2_k - m^2_j$$

Three flavor oscillations: parameter values

Mixing and mass bounds:

	Best Fit $\pm 1\sigma$
$\sin^2(\theta_{12})$	$0.302^{+0.013}_{-0.012}$
$\sin^2(\theta_{23})$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$
$\sin^2(\theta_{13})$	$0.0227^{+0.0023}_{-0.0024}$
Δm^2_{21}	$7.50^{+0.18}_{-0.19} \times 10^{-5} eV^2$
$\Delta m^2_{31}(N)$	$+2.473^{+0.070}_{-0.067} \times 10^{-3} eV^2$
$\Delta m^2_{32}(I)$	$-2.427^{+0.042}_{-0.065} \times 10^{-3} eV^2$



From a Global fit by Gonzalez-Garcia, Maltoni, Salvado and Schwetz (Dec 2012).

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Why consider Non Standard Interactions?

There are many ways to go about motivating the study of NSIs:

1. We expect physics beyond the SM to exist.
2. The neutrino sector is the least precisely tested part of the SM and is likely to connect with new physics since neutrino masses and mixings already point to new physics.
3. There are many theoretical models that can be built that extend the SM to incorporate neutrino masses and mixings. Many of these models lead to NSI.
4. Effective theory implications.

Effective Theory

If the Standard Model is a low-energy effective theory:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}}\mathcal{O}^{d=5} + \frac{1}{\Lambda_{\text{NP}}^2}\mathcal{O}^{d=6} + \frac{1}{\Lambda_{\text{NP}}^3}\mathcal{O}^{d=7} + \dots$$

- **Dim 5**: The Weinberg operator which gives a Majorana neutrino mass.
- **Dim 6**: Lots of operators, including the Four-Fermi operator:

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\left(\bar{\nu}_\alpha\gamma_\rho\nu_\beta\right)\left(\epsilon_{\alpha\beta}^{f\tilde{f}L}\bar{f}_L\gamma^\rho\tilde{f}_L + \epsilon_{\alpha\beta}^{f\tilde{f}R}\bar{f}_R\gamma^\rho\tilde{f}_R\right) + h.c.$$

This Lagrangian parameterizes NSI.

From Friedland, Lunardini and Maltoni (arxiv/0408264).

Phenomenological approach

1. Neutrino-matter interactions are one of the least precisely tested parts of the Standard Model. Thus new interactions are a good place to look for new physical phenomena.
2. Adding non standard interactions to the standard oscillation framework might help explain sub-leading oscillation phenomena.
3. We can presume that the non standard interactions are small but we should rather be guided by experiment not by presumption.

Knowing the theory that generates NSI is not necessary in order to study NSI. All you need is a way to parameterize them.

NSI Framework

Schrödinger's Equation for Neutrino wave-functions in the presence of matter and NSI:

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left(\frac{1}{2E}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + H_I\right)\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

with:

$$H_I = V_{cc}\begin{pmatrix}1+\epsilon_{ee} & |\epsilon_{e\mu}|e^{i\delta_{e\mu}} & |\epsilon_{e\tau}|e^{i\delta_{e\tau}}\\ |\epsilon_{e\mu}|e^{-i\delta_{e\mu}} & \epsilon_{\mu\mu} & |\epsilon_{\mu\tau}|e^{i\delta_{\mu\tau}}\\ |\epsilon_{e\tau}|e^{-i\delta_{e\tau}} & |\epsilon_{\mu\tau}|e^{-i\delta_{\mu\tau}} & \epsilon_{\tau\tau}\end{pmatrix}$$

Parameter mapping

NSI can occur in production, detection and propagation. For propagation NSI:

$$\epsilon_{\alpha\beta} = \sum_{f,P} \epsilon_{\alpha\beta}^{ffP} \frac{n_f}{n_e}$$

$$\epsilon_{\alpha\beta}^{\text{Earth}} \lesssim \left\{ \sum_{P} \left[\left(\epsilon_{\alpha\beta}^{eeP}\right)^2 + \left(3\epsilon_{\alpha\beta}^{uuP}\right)^2 + \left(3\epsilon_{\alpha\beta}^{ddP}\right)^2 \right] \right\}^{1/2}$$

From Biggio, Blennow & Fernandez-Martinez (arxiv/0907.0097).

Sources of bounds: Model dependent

- Assume a model (eg see-saw), compute decay widths, compare to experimental constraints from lepton flavor violations and rare decays.
- Assume a two-flavor hybrid oscillation model and compare with atmospheric/reactor/accelerator neutrino experiments.

From Ohlsson (arxiv/1209.2710) and Biggio, Blennow & Fernandez-Martinez (arxiv/0907.0097).

Sources of bounds: Model independent

Start with the effective theory:

- compute changes to neutrino cross section, compare with LSND, CHARM and NuTeV neutrino scattering tests.
- compute changes to muon, beta and Kaon decay rates. These effect G_F which is well known.
- compute changes to pion decay rates and compare to experimental data.
- compute changes to production and detection zero-distance oscillations, compare to KARMEN and NOMAD.

From Ohlsson (arxiv/1209.2710) and Biggio, Blennow & Fernandez-Martinez (arxiv/0907.0097).

Current Bounds

Model independent bounds for neutral Earth-like matter with an equal number of neutrons and protons:

$$\begin{pmatrix} |\epsilon_{ee}| \leq 4.2 & |\epsilon_{e\mu}| \leq 0.33 & |\epsilon_{e\tau}| \leq 3.0 \\ & |\epsilon_{\mu\mu}| \leq 0.068 & |\epsilon_{\mu\tau}| \leq 0.33 \\ & & |\epsilon_{\tau\tau}| \leq 21 \end{pmatrix}$$

From Biggio, Blennow & Fernandez-Martinez (arxiv/0907.0097).

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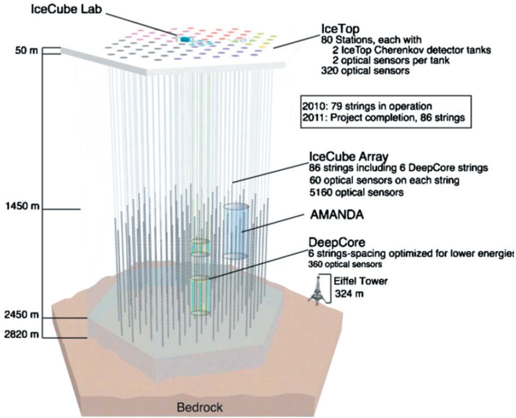
DeepCore

Where in the (E, L, ρ) parameter space should we look for evidence of NSI?

DeepCore, an extension to the IceCube Neutrino Observatory based near the South Pole, detects Cherenkov light emitted by charged particles emitted from neutrino interactions in the ice.

- Triggers on atmospheric neutrinos at energies between about 10 GeV and 1 TeV.
- Can detect neutrinos at any zenith angle.
- Neutrino-induced muons are the most prolific candidates.

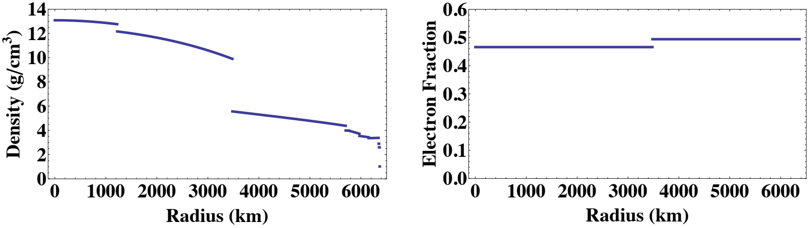


Parameter Space Focus

- Energy Range: 10 - 100 GeV
- Probability: $P_{\nu_\mu \to \nu_\mu}$
- Detectable particle: Muons (μ)
- Propagation Length: 15 - 13000km (any Earth Traversal)
- Density: Earth

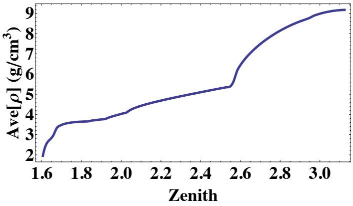
PREM Model

For propagation through Earth, V_{cc} is determined by the PREM (Preliminary Reference Earth Model):



PREM approximation: sPREM

- Using the full PREM model makes analytic solutions very intractable.
- A helpful approximation is to calculate the average density as a function of angle.
- Treat each Zenith angle trajectory as traversing a single constant density layer.



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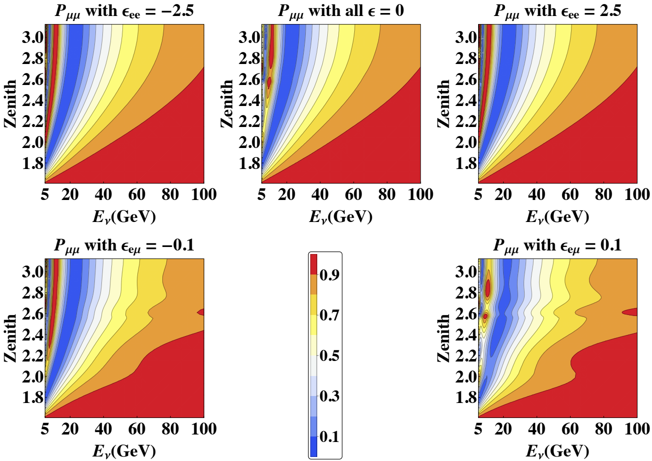
NSI Effects (Full numerics and PREM)



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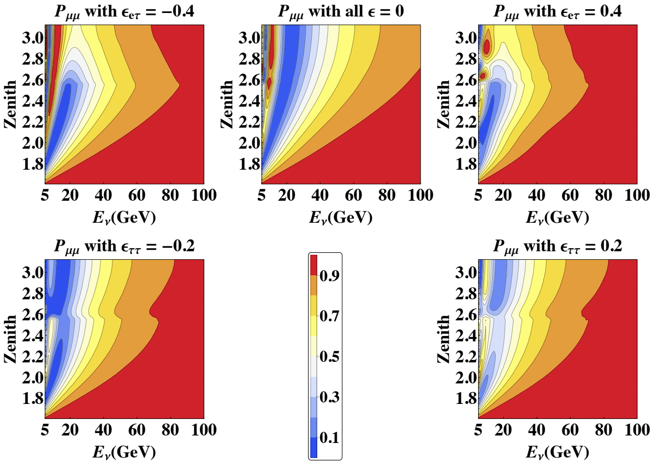

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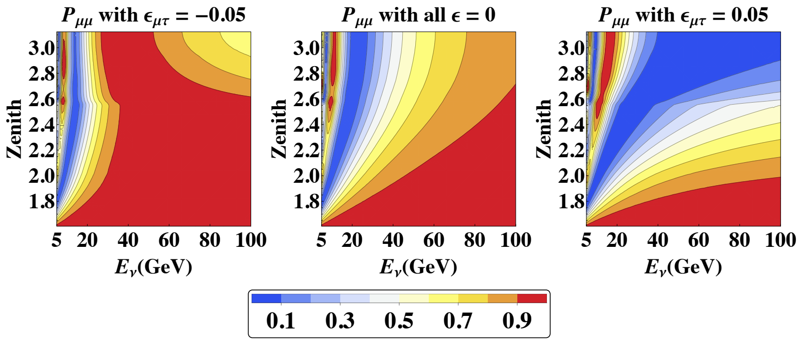

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Number Of Muons

Standard Case:

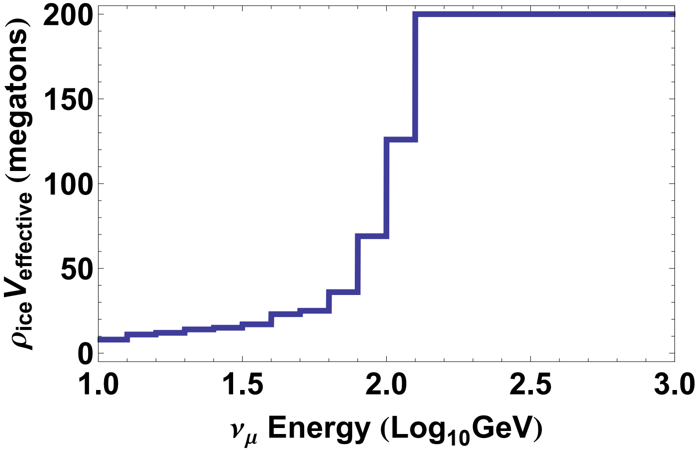
$$N_\mu\left(\Delta E_\mu, \Delta\theta_\nu\right) =$$

$$2\pi\rho t V N_A \int_{E_{\mu,i}}^{E_{\mu,f}} dE_\mu \int_{\theta_{\nu,i}}^{\theta_{\nu,f}} d\theta_\nu \int_{E_\mu}^{\infty} dE_\nu \frac{\partial\sigma_{\nu_\mu}^{CC}\left(E_\nu, E_\mu\right)}{\partial E_\nu \partial E_\mu} \times$$

$$\left(\frac{\partial\phi_{\nu_\mu}\left(\theta, E_\nu\right)}{\partial E_\nu \partial\theta} P_{\nu_\mu\to\nu_\mu}\left(E_\nu, \theta\right) + \frac{\partial\phi_{\nu_e}\left(\theta, E_\nu\right)}{\partial E_\nu \partial\theta} P_{\nu_e\to\nu_\mu}\left(E_\nu, \theta\right)\right)$$

	Core	Mantle	Crust
$\cos(\theta)$ Range:	$(-1, -0.837)$	$(-0.837, -0.446)$	$(-0.446, 0)$

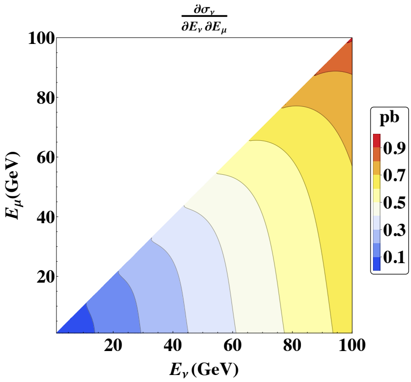
ICDC Effective Volume

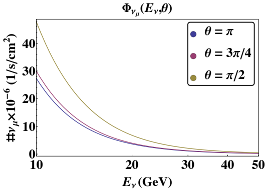


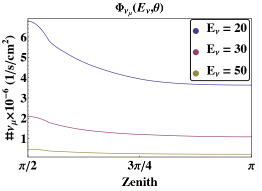
From ICDC Design Document (arxiv/1109.6096).

Flux and Cross Section

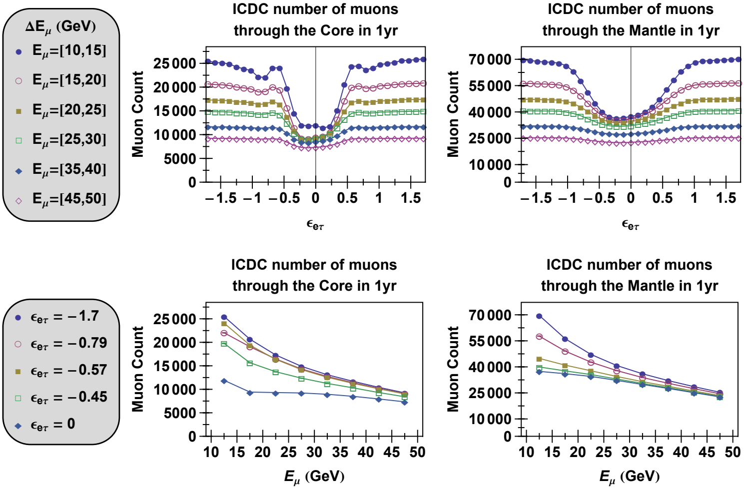
1. Flux from Agraval, Gaisser, Lipari and Stanev.
2. Cross sections from Gandhi, Quigg, Reno and Sarcevic.



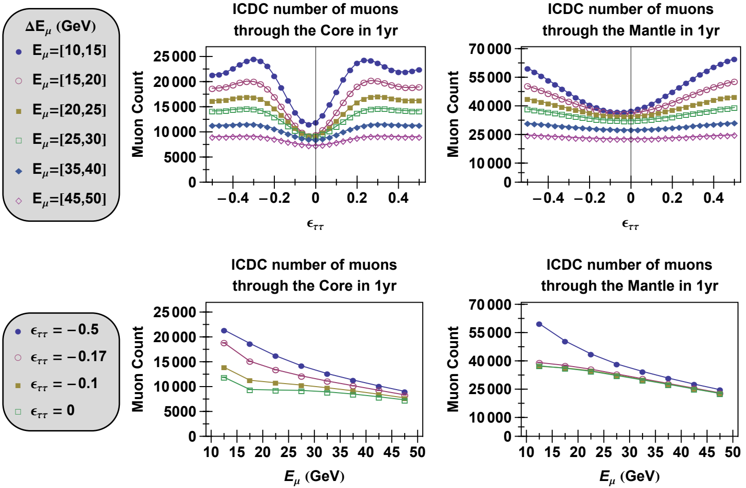




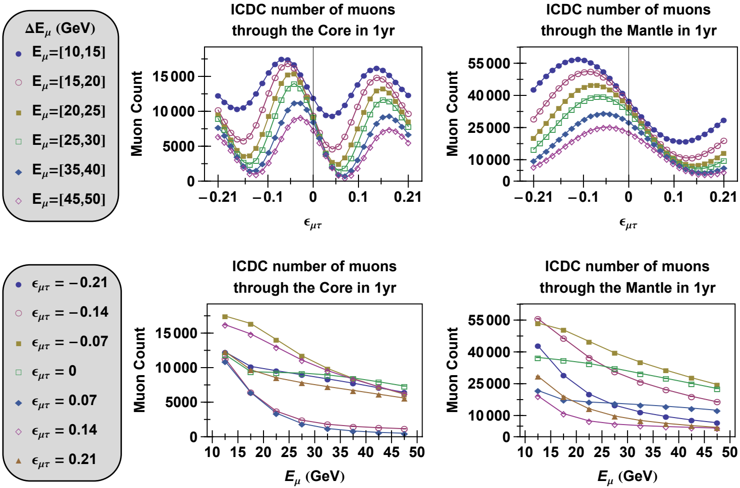
Number Of Muons: ETau



Number Of Muons: TauTau



Number Of Muons: MuTau



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Assumptions

In order to analytically analyze the $\epsilon_{\mu\tau}$ asymmetry the following assumptions are made:

$$V_{cc} = \sqrt{2} G_F N_e = \text{constant}$$
$$\Delta m^2_{21} = \theta_{12} = \theta_{13} = \delta_{cp} = 0 \text{ and } \theta_{23} = \pi/4$$
$$\epsilon_{ee} = \epsilon_{e\mu} = \epsilon_{e\tau} = \epsilon_{\mu\mu} = \epsilon_{\tau\tau} = 0$$
$$\delta_{\mu\tau} = 0$$

Schrödinger's Equation:

$$i\frac{d}{dL}\begin{pmatrix}\nu_e(L)\\ \nu_\mu(L)\\ \nu_\tau(L)\end{pmatrix} = \begin{pmatrix} V_{cc} - \frac{\Delta m^2_{31}}{4E_\nu} & 0 & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau} \\ 0 & \frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau} & 0 \end{pmatrix}\begin{pmatrix}\nu_e(L)\\ \nu_\mu(L)\\ \nu_\tau(L)\end{pmatrix}$$

Oscillation Amplitudes

Solution to Schrödinger's Equation:

$$\begin{pmatrix} \nu_e(L) \\ \nu_\mu(L) \\ \nu_\tau(L) \end{pmatrix} = \begin{pmatrix} e^{-\frac{1}{4}iL\left(4V_{cc}-\frac{\Delta m^2_{31}}{E_\nu}\right)} & 0 & 0 \\ 0 & \cos(L\Lambda) & -i\sin(L\Lambda) \\ 0 & -i\sin(L\Lambda) & \cos(L\Lambda) \end{pmatrix} \begin{pmatrix} \nu_e(0) \\ \nu_\mu(0) \\ \nu_\tau(0) \end{pmatrix}$$

with $\Lambda = \frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau}$. Thus:

$$P_{\mu\mu} = \cos^2\left(L\left(\frac{\Delta m^2_{31}}{4E_\nu} + V_{cc}\epsilon_{\mu\tau}\right)\right)$$

Measuring sign symmetry

A useful measure of the sign symmetry is:

$$\Delta_\epsilon P_{\mu\mu} = P_{\mu\mu}\left(\epsilon_{\mu\tau}\right) - P_{\mu\mu}\left(-\epsilon_{\mu\tau}\right)$$
$$= -\sin\left(2L\frac{\Delta m_{31}^2}{4E_\nu}\right)\sin\left(2LV_{cc}\epsilon_{\mu\tau}\right)$$

Thus max$|\Delta_\epsilon P_{\mu\mu}|$ when:

$$2L\frac{\Delta m_{31}^2}{4E_\nu} = (2n+1)\frac{\pi}{2}$$
$$2LV_{cc}\epsilon_{\mu\tau} = (2m+1)\frac{\pi}{2}$$

Where $m,n \in \mathbb{Z}$ and $m,n \geq 0$

Max sign asymmetry implications

The equations that specify the location of maximum or sign asymmetry (with m, $n \in \mathbb{Z}$ and m, $n \geq 0$):

$$\therefore E_\nu = \left(\frac{2m+1}{2n+1}\right) \frac{\Delta m^2_{31}}{4 V_{cc} \epsilon_{\mu\tau}} \tag{1}$$

$$\therefore L = \frac{(2m+1)\,\pi}{4 V_{cc} \epsilon_{\mu\tau}} \tag{2}$$

$$\text{also } L = \frac{(2n+1)\,\pi}{\Delta m^2_{31}} E_\nu \tag{3}$$

Where:

$$L = 2 R_E \sin\left(\theta - \frac{\pi}{2}\right)$$

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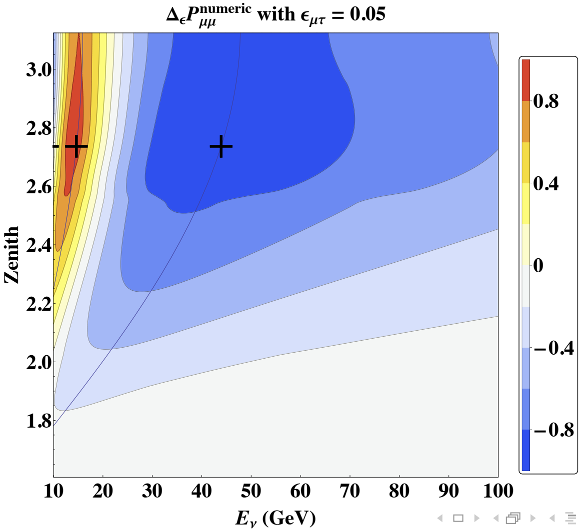
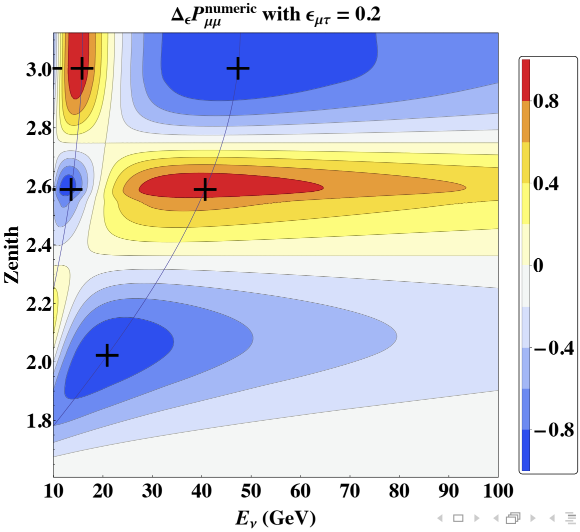
Earth Traversal Comparison with low NSI Value



Earth Traversal Comparison with high NSI Value



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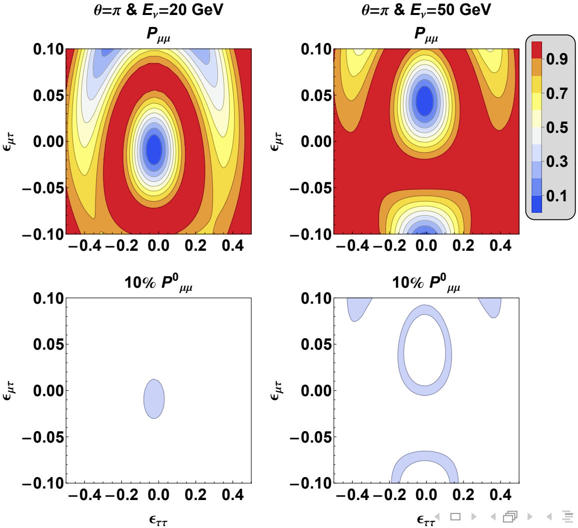
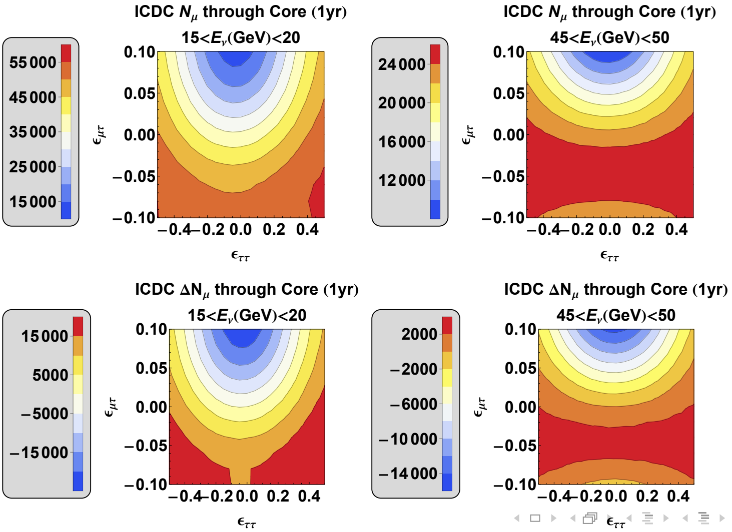
Oscillation Probability



Muon Count


ICDC N_μ through Core (1yr)
$15<E_\nu$(GeV)<20
55000
45000
35000
25000
15000
0.10
0.05
0.00
−0.05
−0.10
$\epsilon_{\mu\tau}$
−0.4 −0.2 0.0 0.2 0.4
$\epsilon_{\tau\tau}$
ICDC N_μ through Core (1yr)
$45<E_\nu$(GeV)<50
24000
20000
16000
12000
ICDC ΔN_μ through Core (1yr)
$15<E_\nu$(GeV)<20
15000
5000
−5000
−15000
ICDC ΔN_μ through Core (1yr)
$45<E_\nu$(GeV)<50
2000
−2000
−6000
−10000
−14000

Summary

1. NSI parameters can have a significant effect on oscillation probability and muon count, for even small values.
2. In the energy region analyzed, the effect of $\epsilon_{\mu\tau}$ is sign asymmetric. This is contrasted with the other NSI parameters being mostly sign symmetric.
3. A reduced analytic solution describing the $\epsilon_{\mu\tau}$'s behavior has been found and can predict points of maximal asymmetry in the (θ, E_ν) plane.
4. There seem to be interesting regions in the $(\epsilon_{\mu\tau}, \epsilon_{\tau\tau})$ parameter space that need to be confirmed and quantified.

Thank you for your time.

Backup

Measuring Symmetry

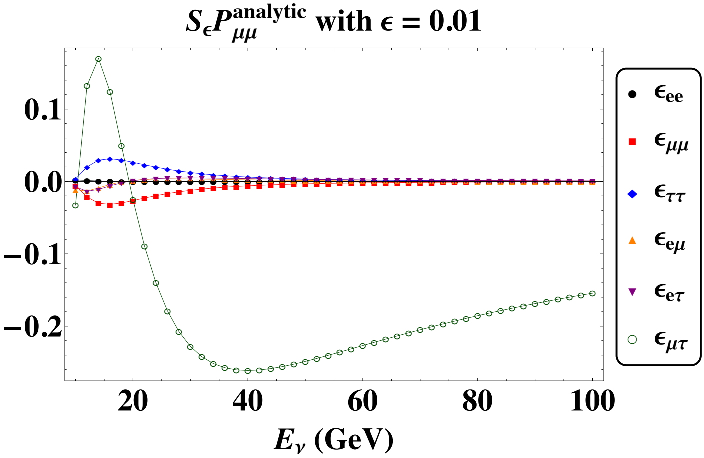
- A particularly striking feature is the sign symmetry or asymmetry of the NSI parameters.
- A useful measure of the sign symmetry is:

$$\Delta_\epsilon P_{\mu\mu} = P_{\mu\mu}(\epsilon) - P_{\mu\mu}(-\epsilon)$$

- This measure also would give an indication of the NSI parameter's first order sensitivity.
- Using the single layer Earth density averaging, the following integral can be evaluated to see the energy dependence of the symmetry:

$$S_\epsilon P_{\mu\mu}(E_\nu, \epsilon) = \int_{\theta=\pi/2}^{\theta=\pi} \Delta_\epsilon P_{\mu\mu} d\theta$$

High Energy Asymmetry for very low NSI value



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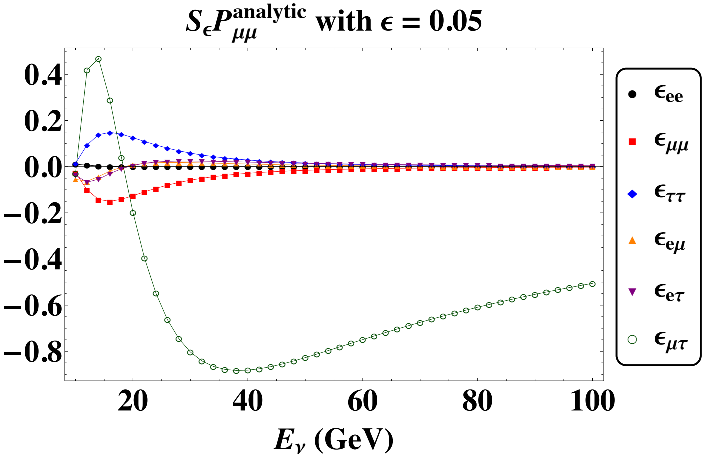
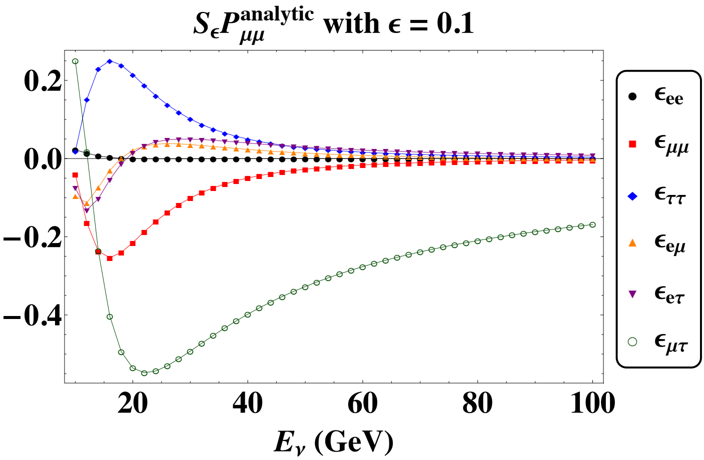
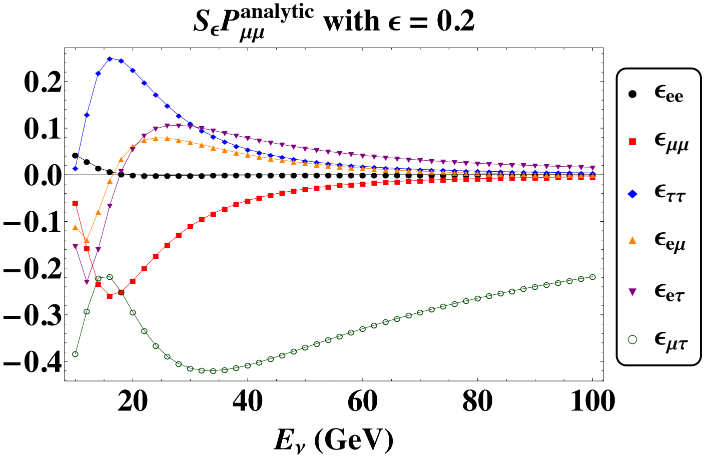


High Energy Asymmetry for medium NSI value



High Energy Asymmetry for high NSI value



Approximation Accuracy

Compare the oscillation probabilities of the reduced system using single layer averaging of the Earth's density profile: