Non-Standard Neutrino Interactions in the mu tau sector

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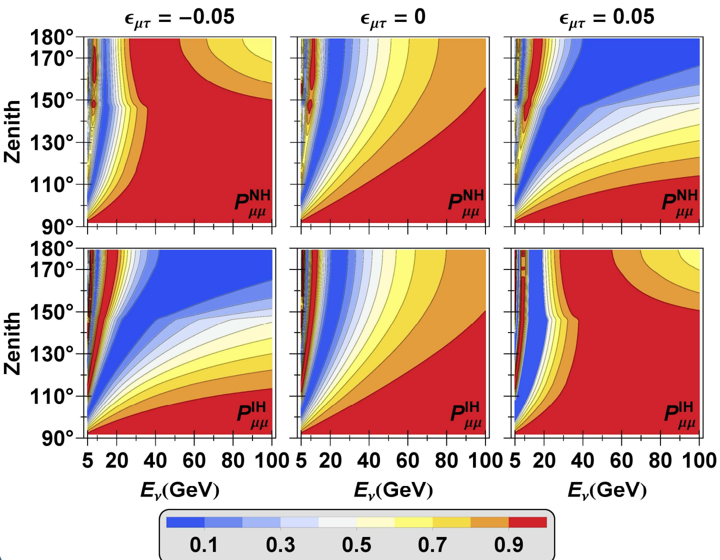
This research focuses on Non-Standard Interactions (NSI) and their effects on neutrino oscillations. In particular, we focus on the effects of the parameter $\epsilon_{\mu\tau}$ on muon neutrino survival probability and the number of muons measured in IceCube's DeepCore (ICDC) detector. Furthermore, the effects are found to be sign asymmetric and an analytic model is presented that predicts points of maximum sign asymmetry. Furthermore, we discuss the implications these sign asymmetric effects have on mass hierarchy determination.

Effects on oscillation probability and the number of muons measured at DeepCore

NSIs are expected in to play a part in new physics that is beyond the Standard Model.

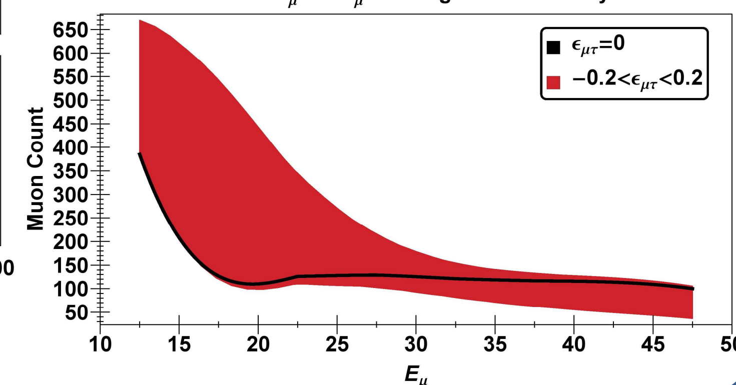


Schrödinger equation including all NSI parameters:

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left(H_{\text{vac}} + V_{\text{cc}}\begin{pmatrix}1+\epsilon_{ee} & |\epsilon_{e\mu}|e^{i\delta_{e\mu}} & |\epsilon_{e\tau}|e^{i\delta_{e\tau}}\\ |\epsilon_{e\mu}|e^{-i\delta_{e\mu}} & \epsilon_{\mu\mu} & |\epsilon_{\mu\tau}|e^{i\delta_{\mu\tau}}\\ |\epsilon_{e\tau}|e^{-i\delta_{e\tau}} & |\epsilon_{\mu\tau}|e^{-i\delta_{\mu\tau}} & \epsilon_{\tau\tau}\end{pmatrix}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Notable effects of $\epsilon_{\mu\tau}$ on $P_{\mu\mu}$ and N_μ:
- $P_{\mu\mu}$ and N_μ are greatly altered by even small values.
- Effects are significantly more sign dependent than other NSI parameters.
- Effects on N_μ are very dependent on angle. Greater effects are found for neutrinos that traverse the Core and Mantle.

ICDC $N_\mu^{NH} + N_{\bar{\mu}}^{NH}$ through the core in 1yr



Asymmetry Effects

Consider an oscillation model with all $\delta = 0$ and all $\epsilon = 0$ except $\epsilon_{\mu\tau}$.

Furthermore, set: $\Delta m^2_{21} = \theta_{12} = \theta_{13} = \delta_{cp} = 0 \ \& \ \theta_{23} = \pi/4$

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

A useful measure of sign asymmetry:

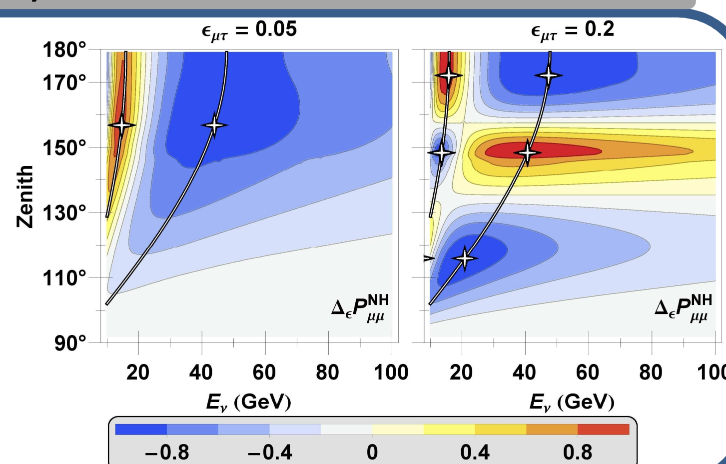
$$\Delta_\epsilon P_{\mu\mu} = P_{\mu\mu}(\epsilon_{\mu\tau}) - P_{\mu\mu}(-\epsilon_{\mu\tau}) = -\sin\left(2L\frac{\Delta m^2_{31}}{4E_\nu}\right)\sin(2LV_{cc}\epsilon_{\mu\tau})$$

This measure can be maximized to find points of maximal asymmetry:

$$E_\nu = \left(\frac{2m+1}{2n+1}\right)\frac{\Delta m^2_{31}}{4V_{cc}\epsilon_{\mu\tau}} \quad \text{and} \quad x = \frac{(2m+1)\pi}{4V_{cc}\epsilon_{\mu\tau}} \quad \text{or} \quad x = \frac{(2n+1)\pi}{\Delta m^2_{31}}E_\nu$$

where $m, n \in \mathbb{Z} \ \& \ m, n \geq 0$

- These analytic predictions are shown to be in good agreement with numeric simulations .
- The sign degeneracy of $\epsilon_{\mu\tau}$ can now be broken by analyzing the predicted regions of maximal asymmetry in experimental data.



Mass Hierarchy Implications

ICDC $N_\mu + N_{\bar{\mu}}$ through the core in 1yr