Non-Standard Neutrino Interactions in the mu tau sector

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Standard Interactions

\[ P_{e\mu} (L=9000\text{Km}) \]

Vacuum

\[ e^- \rightarrow \nu_e + W \]

\[ e^- \rightarrow e^- + \nu_e \]

\[ P_{e\mu} (L=9000\text{Km}) \]

Earth
More Interactions?

What about: 

\[ \nu_{\mu}, \nu_{\tau}, e^- \]
Beyond SM physics is expected
  – Effective theory
  – Many BSM models give NSI

Neutrino Sector is least constrained
  – New Interactions = New phenomena?
  – Describe current sub-leading phenomena
NSI Effects on Oscillation Probability

\[ \epsilon_{\mu\tau} = -0.05 \]

\[ \epsilon_{\mu\tau} = 0 \]

\[ \epsilon_{\mu\tau} = 0.05 \]

Zenith

\[ P^{\text{NH}}_{\mu\mu} \]

\[ E_\nu(\text{GeV}) \]

\[ 0.1 \quad 0.3 \quad 0.5 \quad 0.7 \quad 0.9 \]
• PREM model
• Atmospheric Fluxes (Agraval, Gaisser, Lipari and Stanev)
• Cross Sections (Gandhi, Quigg, Reno and Sarcevic)
• Sum over contributions from:
  \[ P_{e\mu}, P_{\mu\mu}, \overline{P_{e\mu}}, \overline{P_{\mu\mu}} \]
• 1yr of IceCube DeepCore Simulated Data
  – Using \( V_{\text{eff}} \) from ICDC Design Document
• Energy Bin Width = 5GeV
• 3 Zenith Bins: Core, Mantle and Crust
NSI Effects on Muon Count

Muon count from 1yr of ICDC$^{NH}$

\[ \Delta E_\mu \text{ (GeV)} \]
- $E_\mu=\{10.,15.\}$
- $E_\mu=\{15.,20.\}$
- $E_\mu=\{20.,25.\}$
- $E_\mu=\{25.,30.\}$
- $E_\mu=\{35.,40.\}$
- $E_\mu=\{45.,50.\}$

\[ \epsilon_\mu = \{-0.2, -0.1, 0, 0.1, 0.2\} \]

\[ E_\mu \text{ (GeV)} \]

Core, Mantle, Crust
\[ \Delta m_{21}^2 = \theta_{12} = \theta_{13} = \delta_{cp} = \epsilon_{\alpha \beta \neq \mu \tau} = \delta_{\mu \tau} = 0 \]

\[ \theta_{23} = \frac{\pi}{4} \]

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

\[ \Delta_\epsilon P_{\mu \mu} = P_{\mu \mu} (\epsilon_{\mu \tau}) - P_{\mu \mu} (-\epsilon_{\mu \tau}) \]

\[ L = \frac{(2n + 1) \pi}{\Delta m_{31}^2} E_\nu, \text{ Where } n \in \mathbb{Z} \text{ and } n \geq 0 \]
Analytical vs. Numerical

\[ \Delta \varepsilon P_{\mu\mu}^{\text{NH}} \text{ with } \varepsilon_{\mu\tau} = 0.05 \]

\[ \Delta \varepsilon P_{\mu\mu}^{\text{NH}} \text{ with } \varepsilon_{\mu\tau} = 0.2 \]
Mass Hierarchy Implications

\( N_{\mu}^{ICDC} \) through the core in 1yr

- \( N_{\mu}^{NH}(\epsilon_{\mu\tau} = 0) \pm 10\% \)
- \( N_{\mu}^{IH}(0 < \epsilon_{\mu\tau} < 0.01) \)

Muon Count

\( E_{\mu} \)
Mass Hierarchy Implications

$N_{\mu}^{\text{ICDC}}$ through the core in 1yr

- $N_{\mu}^{\text{NH}}(\epsilon_{\mu\tau}=0)$
- $\frac{1}{2} N_{\mu}^{\text{IH}}(\epsilon_{\mu\tau}=0)$
- $\frac{1}{2} N_{\mu}^{\text{NH}}(\epsilon_{\mu\tau}=0.00555)$
- $N_{\mu}^{\text{IH}}(\epsilon_{\mu\tau}=0.00743)$

Muon Count

$E_{\mu}$ (GeV)
Sensitivity (IH True)

$\chi^2$ $N^{\text{NH,IH}}_\mu$ vs. $N^{\text{IH,Null}}_\mu$ (1yr)

$\chi^2$ $N^{\text{NH,IH}}_\mu$ vs. $N^{\text{IH,Null}}_\mu$ (4yr)

- $\sigma$, $2\sigma$, $3\sigma$, $5\sigma$
- NH vs IH$^{\text{null}}$
- IH vs IH$^{\text{null}}$
Summary

- NSIs have significant effects on:
  - Oscillation probability
  - Muon count

- EpsilonMuTau is sign asymmetric (unlike other NSI)
  - From numerical simulations
  - From a reduced analytic model

- This asymmetry has mass hierarchy implications
  - Hierarchy imitation
  - Hierarchy misidentification
  - Can separate effects with different experiments