Constraining NSI and Sterile Neutrino Physics with $\nu_\tau$ Appearance in DUNE

Anish Ghoshal

Laboratori Nazionale Frascati - INFN
University Roma Tre

anishghoshal1@gmail.com

October 8, 2019 CERN

Based on -
(i) A. Ghoshal, A.Giarnetti and D.Meloni, arXiv:1906.06212
(ii) A. Ghoshal, A.Giarnetti and D.Meloni, [draft in preparation - 1911.xxxxx]
Outline of talk:

• Neutrino Oscillation.
• Deep Underground Neutrino Experiment (DUNE).
• $\nu_\tau$ Appearance in DUNE.
• Standard Physics & Effect of Systematics.
• Sterile Neutrino in 3+1 scheme.
• Non-Standard Interaction (NSI).
• Neutrino Decay.
• Extracting Further New Physics with $\nu_\tau$. 
Neutrino Oscillation is now well-known phenomena.
Introduction:

Probability of Neutrino Oscillation:

\[
P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\Re \sum_{i>j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \sin^2 \left( \frac{\Delta m^2_{ij} L}{2E} \right) + 23 \sum_{i>j} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \sin \left( \frac{\Delta m^2_{ij} L}{2E} \right)
\]
Introduction:

NuFit values of the oscillation parameters:
DUNE in a nutshell:

- Intense beam of $\nu_\mu$ fired from FermiLab at a large detector 1300 KM away.
- Large (40 kt) Underground Liquid Argon detector at Sanford Underground Research Facility (SURF).
Deep Underground Neutrino Experiment:

Standard Phenomenology in DUNE:

**$\nu_e$ appearance**

\[ P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) \]

**$\nu_\mu$ disappearance**

\[ P(\nu_\mu \to \nu_\mu) \approx 1 - (\sin^2 2\theta_{23} \cos^4 \theta_{13} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) \]
### Calculation of Events – Standard

<table>
<thead>
<tr>
<th></th>
<th>$\nu$ mode (150 kt · MW · year)</th>
<th></th>
<th>$\bar{\nu}$ mode (150 kt · MW · year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ Signal NH (IH)</td>
<td>861 (495)</td>
<td>$\nu_\mu$ Signal</td>
<td>10842</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ Signal NH (IH)</td>
<td>13 (26)</td>
<td>$\bar{\nu}_\mu$ CC Bkgd</td>
<td>958</td>
</tr>
<tr>
<td>Total Signal NH (IH)</td>
<td>874 (521)</td>
<td>$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd</td>
<td>88</td>
</tr>
<tr>
<td>Beam $\nu_e + \bar{\nu}_e$ CC Bkgd</td>
<td>159</td>
<td>$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd</td>
<td>63</td>
</tr>
<tr>
<td>NC Bkgd</td>
<td>22</td>
<td>$\bar{\nu}_\tau$ CC Bkgd</td>
<td></td>
</tr>
<tr>
<td>$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd</td>
<td>42</td>
<td>$\nu_\mu$ CC Bkgd</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd</td>
<td>3</td>
<td>NC Bkgd</td>
<td></td>
</tr>
<tr>
<td>Total Bkgd</td>
<td>226</td>
<td>$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd</td>
<td></td>
</tr>
</tbody>
</table>

Detection

- $\nu_\mu \rightarrow \nu_\tau$ channel has never been considered in the simulations of DUNE hitherto. In fact tau neutrinos are difficult to observe. Furthermore, the interactions of these neutrinos have a rather high energy threshold (3.4), which is why the number of events expected for this process is low.

Disclaimer - - we do not say this is the most suitable channel for detection.
We consider $\tau \rightarrow e$ as the detection channel. ICARUS proposal followed this strategy.

**Signal**

$\nu_\mu \rightarrow \nu_\tau$ oscillation

**Backgrounds**

$\nu_\mu \rightarrow \nu_e$ oscillation
$\nu_e \rightarrow \nu_e$ from beam

We consider various configurations to understand their impact on final sensitivities.

- 20% & 10% Signal Uncertainties in the $\nu_\tau$ channel.
- 100% & 33% of electrons being detected (detection efficiency).
- S/B values of 2.46 and 18.6.
- Standard and Tau-Optimized Fluxes.
The standard flux consists of beam delivering $1.47 \times 10^{21}$ protons on target (POT) per year with 80 GeV energy running with 1.07 MW beam power and having 1.5 m NuMi (Neutrino Main Injector) style target. The $\tau-$ optimized flux is as per proposed by the DUNE collaboration consists of $1.1 \times 10^{21}$ protons on target (POT) per year with 120 GeV energy running with 1.2 MW beam power and having 1m NuMi style target.
Rate Estimation

A comparison of $\nu_\tau$ events:

<table>
<thead>
<tr>
<th>$\nu$ mode</th>
<th>value</th>
<th>$\bar{\nu}$ mode</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\tau$ Signal</td>
<td>277</td>
<td>$\nu_\tau$ Signal</td>
<td>68</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau$ Signal</td>
<td>26</td>
<td>$\bar{\nu}_\tau$ Signal</td>
<td>85</td>
</tr>
<tr>
<td>Total Signal</td>
<td>303</td>
<td>Total Signal</td>
<td>153</td>
</tr>
<tr>
<td>$\nu_e + \bar{\nu}_e$ CC Background (beam)</td>
<td>333 + 38</td>
<td>$\nu_e + \bar{\nu}_e$ CC Background (beam)</td>
<td>117 + 104</td>
</tr>
<tr>
<td>CC Background (oscillation)</td>
<td>1753 + 12</td>
<td>$\nu_e$ CC Background (oscillation)</td>
<td>90 + 188</td>
</tr>
</tbody>
</table>

Figure: Standard Flux

<table>
<thead>
<tr>
<th>$\nu$ mode</th>
<th>value</th>
<th>$\bar{\nu}$ mode</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\tau$ Signal</td>
<td>2673</td>
<td>$\nu_\tau$ Signal</td>
<td>98</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau$ Signal</td>
<td>34</td>
<td>$\bar{\nu}_\tau$ Signal</td>
<td>983</td>
</tr>
<tr>
<td>Total Signal</td>
<td>2707</td>
<td>Total Signal</td>
<td>1081</td>
</tr>
<tr>
<td>$\nu_e + \bar{\nu}_e$ CC Background (beam)</td>
<td>688 + 63</td>
<td>$\nu_e + \bar{\nu}_e$ CC Background (beam)</td>
<td>176 + 177</td>
</tr>
<tr>
<td>CC Background (oscillation)</td>
<td>1958 + 11</td>
<td>$\nu_e$ CC Background (oscillation)</td>
<td>76 + 324</td>
</tr>
</tbody>
</table>

Figure: Optimized Flux

Experiment run-time of (3.5 + 3.5) years. Latest NuFit values of the Oscillation parameters used.
Correlation Studies

Standard Physics does not improve using $\nu_\tau$ channel.

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E}\right)$$
Comparison with OPERA

OPERA has observed 10 events in the $\nu_\mu \rightarrow \nu_\tau$ channel. Using these events the $\Delta m_{31}^2$ parameter uncertainty is about 26%. Using the $\tau$ events in DUNE this can be largely improved.
Short Baseline Anomaly

Long Discussions Yesterday:

- LSND and MiniBooNE Anomaly
- Oscillation with small L/E.
- $\Delta m_{41}^2 \sim 1 \text{ eV}^2$
- Reactor Experiment Anomaly
The simplest model that includes sterile neutrinos is the 3 + 1 model, in which only one sterile neutrino is added.

\[ U_{PMNS} = R(\theta_{34})R(\theta_{24})R(\theta_{23}; \delta_2)R(\theta_{14})R(\theta_{13}; \delta_3)R(\theta_{12}; \delta_1) \]
Parameters

\[ U_{34} = \cos \theta_{14} \cos \theta_{24} \sin \theta_{34}. \]

We expect the addition of $\nu_\mu \rightarrow \nu_\tau$ appearance channel to improve $\theta_{34}$ sensitivity.
Effect of Systematics, detection efficiencies, S/B values and two fluxes on the measurement of $\theta_{34}$.

**Upper limit:** from 27.5° to 24.2° with the standard flux.

**Upper limit:** from 32.1° to 22° with the optimised flux.
We can see the maximum effect is on the improvement of $\theta_{34}$ only.
Correlation Studies
New Physics: NSI

Diligent way to capture the effect of new physics, in terms of four-fermion interaction.

\[ -\mathcal{L}_{\text{NSI}}^{\text{eff}} = \epsilon_{\alpha\beta}^f 2\sqrt{2} G_F (\bar{v}_\alpha \gamma_\rho L \nu_\beta) (\bar{f} \gamma^\rho P f) \]

\[ i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[U_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} + A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \]

\[ P(\nu_\alpha \to \nu_\beta; \varepsilon_{e\mu}, \varepsilon_{e\tau}, \varepsilon_{\mu\mu}, \varepsilon_{\mu\tau}, \varepsilon_{\tau\tau}) = P(\nu_\alpha \to \nu_\beta; 2 \text{ flavor in vacuum}) \]
\[ + \ P(\nu_\alpha \to \nu_\beta; \varepsilon_{e\mu}, \varepsilon_{e\tau}) \]
\[ + \ P(\nu_\alpha \to \nu_\beta; \varepsilon_{\mu\mu}, \varepsilon_{\mu\tau}, \varepsilon_{\tau\tau}), \]
New Physics: NSI

Tau Appearance Probability with NSI:

Figure: Solid/Dotted - - NH/IH. Green/Red/Blue - - $\delta_{CP} = [0, \pi/2, -\pi/2]$. Top/Bottom - - (No NSI; $[\epsilon_{\mu\tau}, \epsilon_{\tau\tau}]=(0.07,0.147)$)
NSI probability

$$P_{\mu\tau} = P_{\mu\tau}^{SM} + \left(\frac{1}{2}\epsilon_{\tau\tau}\cos^2(2\theta_{23}) + 2\cos(2\theta_{23})\text{Re}\{\epsilon_{\mu\tau}\}\right)(AL)\sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) + O(\epsilon^2)$$

In the optimized flux, we do not get the advantage of increased tau-statistics as $\nu_e$ & $\nu_\mu$ channels are also increased.
NSI Correlation Studies
NSI: Sensitivity on NSI parameter

Impact of Systematics, detection efficiencies, S/B values and two fluxes on the measurement of $|\epsilon_{\mu\tau}|$. 

---

**Figure:**

Four graphs showing the impact of systematics on the measurement of $|\epsilon_{\mu\tau}|$. The graphs compare the standard flux with 10% systematics and the optimized flux with 10% systematics, as well as the standard flux with 20% systematics and the optimized flux with 20% systematics. The Δ$\chi^2$ values are plotted against $|\epsilon_{\mu\tau}|$. The 90% CL is indicated by a green dotted line.
Neutrino Decay

Neutrino Decay - Introduction

$$\mathcal{L}_{\text{int}} = \frac{(g_s)_{ij}}{2} \bar{\nu}_i \nu_j S + \frac{(g_p)_{ij}}{2} \bar{\nu}_i \gamma_5 \nu_j S$$

$$\nu_i \to \nu + S,$$

$$\Gamma_i (L, E) = \exp (-\alpha_i \times L/E)$$

$$\alpha_i = \frac{m_i}{\tau_i}$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{PMNS} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_4 \end{pmatrix}$$

$$H = U \begin{bmatrix} \frac{1}{2E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} - i \frac{\alpha_3}{2E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{bmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$
Why Interesting for DUNE

\[ P_{\mu\mu}(E, L, \alpha_3) = \left( \cos^2 \theta_{23} + \sin^2 \theta_{23} e^{-\frac{\Delta m_{31}^2}{2E} L} \right)^2 \]

\[ P_{\mu\tau}(E, L, \alpha_3) = \cos^2 \theta_{23} \sin^2 \theta_{23} \left( 1 - e^{-\frac{\Delta m_{31}^2}{2E} L} \right)^2 \]

\[ - 4 \cos^2 \theta_{23} \sin^2 \theta_{23} e^{-\frac{\Delta m_{31}^2}{2E} L} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]

\[ + 4 \cos^2 \theta_{23} \sin^2 \theta_{23} e^{-\frac{\Delta m_{31}^2}{2E} L} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]

Decay term causes vanishing of interference effects. Increase in Probability.
DUNE is very suited to explore this increased probability region due to its $L/E$. 

![Graph showing $P_{\mu^\tau}$ vs $L/E$ (km/GeV) with curves for $\log \alpha = 11$ and $\log \alpha = 13$, and a no-decay line.](image-url)
Some Preliminary Results

Expected number of $\nu_\tau$ events:

$$N_\tau = \epsilon_{det} \times n_{p.o.t.} \times N_{Ar} \times \int dE_\mu(\phi)\sigma_{\nu_\tau}(E)P_{\mu\tau}(E, \alpha_3)$$

Disclaimer -- preliminary calculations only. Final results may differ!
Some Preliminary Results

Sensitivity of measurement of $\alpha$:
Some Preliminary Results

Chi-squared Fit Analysis:
Conclusions

• In the case of standard physics, the addition of $\nu_\tau$ appearance channel does not improve the sensitivities of any of the neutrino oscillation parameter set by the other two channels already being considered in DUNE.

• We studied the impact of various systematics, $\nu_\tau$ detection efficiencies, experimental reaches (2 different $S/B$ ratios) and the two fluxes on the sensitivities of the oscillation parameters. The performances of the tau optimized flux in the $\nu_e$ appearance and $\nu_\mu$ disappearance channels result in worsening the sensitivities overshadowing the advantage one may get from the increase in the $\nu_\tau$ statistics. This is mainly due to the increased background events in both the $\nu_e$ and $\nu_\mu$ channels.

• In the new physics cases, NSI parameter sensitivities remains less unaffected after the addition of the new channel, except for the coupling $|\epsilon_{\mu\tau}|$ for which improved limits (about 15% better) was found.

• For the sterile neutrino (3+1) case, the only parameter that shows an increase in sensitivity is the mixing angle $\theta_{34}$ and we estimated the improvement to be about 20%.

• Neutrino Invisible Decay constant parameter can be constrained using the $\nu_\tau$ appearance channel due to a suitable L/E configuration that DUNE provides.
Future Directions

- Study involving shared run-time between Standard and Optimized fluxes so as to maximize the tau channel capabilities.
- Combining electronic and hadronic channels of tau decay so as to maximize the tau detection efficiency and consequently increase in tau-statistics.
- $\nu_\mu \rightarrow \nu_\tau$ maybe suited to study Large Extra Dimension scenarios.
- $\nu_\mu \rightarrow \nu_\tau$ maybe suited to study dark matter scenarios especially searches in dark sector involving $L_\mu - L_\tau$ symmetries and its corresponding mediators.
- Probe of Non-Unitary and Lorentz Violating Operators using $\nu_\tau$—appearance channel.
- Other suggestions are welcome.

Stay tuned. Work in Progress!!
Essential References

- arxiv 1811.05487
- arxiv 1512.06148
- arxiv 1606.09550
- arxiv 0407333
- arxiv 0110393
- arxiv 0402175
- arxiv 0705.0107
- arxiv 1209.2710
- arxiv 010317
- arxiv 1603.08696
- arxiv 1805.01747
- arxiv 1811.00095
- arxiv 1904.07265
- http://home.fnal.gov/ ljf26/DUNEFluxes
Thank You
Backup Slides

![Graph showing contour lines with labels and values]

<table>
<thead>
<tr>
<th>Standard Flux</th>
<th>Optimized Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CC</td>
<td>$\nu$ mode $\nu$ mode $\nu$ mode $\nu$ mode</td>
</tr>
<tr>
<td>$30175$</td>
<td>$3225$</td>
</tr>
<tr>
<td>$1025$</td>
<td>$9879$</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>$371$</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ CC</td>
<td>$44$</td>
</tr>
</tbody>
</table>
### Backup Slides

<table>
<thead>
<tr>
<th>Neutrino mode</th>
<th>Signal</th>
<th>Backgrounds</th>
<th>(\text{intrinsic } \nu_e)</th>
<th>(\text{mis } \nu_\mu)</th>
<th>(\text{mis } \nu_\tau)</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_\mu \rightarrow \nu_e \oplus \bar{\nu}_\mu \rightarrow \bar{\nu}_e)</td>
<td>1188 + 11.5</td>
<td>288.2</td>
<td>3.1</td>
<td>19.9</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>(\nu_\mu \rightarrow \nu_\mu \oplus \bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu)</td>
<td>7601 + 519.2</td>
<td>28.2</td>
<td>75.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antineutrino mode</th>
<th>Signal</th>
<th>Backgrounds</th>
<th>(\text{intrinsic } \bar{\nu}_e)</th>
<th>(\text{mis } \nu_\mu)</th>
<th>(\text{mis } \nu_\tau)</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{\nu}_\mu \rightarrow \bar{\nu}<em>e \oplus \nu</em>\mu \rightarrow \nu_e)</td>
<td>209 + 64</td>
<td>171.8</td>
<td>2.9</td>
<td>13.4</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>(\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu \oplus \nu_\mu \rightarrow \nu_\mu)</td>
<td>2591 + 1489</td>
<td>16.5</td>
<td>44.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### \(\nu_e\) Appearance Channel

<table>
<thead>
<tr>
<th>Signal</th>
<th>(\nu_e) and (\bar{\nu}<em>e) CC events from (\nu</em>\mu) oscillations</th>
<th>2% sys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backgrounds</td>
<td>Beam (\nu_e) and (\bar{\nu}_e) CC events</td>
<td>5% sys</td>
</tr>
<tr>
<td>Misidentified (\nu_\mu) and (\bar{\nu}_\mu) CC events</td>
<td>5% sys</td>
<td></td>
</tr>
<tr>
<td>Misidentified (\nu_\tau) and (\bar{\nu}_\tau) CC events</td>
<td>20% sys</td>
<td></td>
</tr>
<tr>
<td>Misidentified NC events</td>
<td>10% sys</td>
<td></td>
</tr>
</tbody>
</table>

#### \(\nu_\mu\) Disappearance Channel

<table>
<thead>
<tr>
<th>Signal</th>
<th>(\nu_\mu) and (\bar{\nu}_\mu) CC events</th>
<th>5% sys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backgrounds</td>
<td>Misidentified (\nu_\tau) and (\bar{\nu}_\tau) CC events</td>
<td>20% sys</td>
</tr>
<tr>
<td>Misidentified NC events</td>
<td>10% sys</td>
<td></td>
</tr>
</tbody>
</table>
Backup Slides
## Backup Slides

<table>
<thead>
<tr>
<th>NSI parameters</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{ee} - \epsilon_{\mu\mu}$</td>
<td>(-0.2, 0.45)</td>
</tr>
<tr>
<td>$</td>
<td>\epsilon_{e\mu}</td>
</tr>
<tr>
<td>$</td>
<td>\epsilon_{e\tau}</td>
</tr>
<tr>
<td>$\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$</td>
<td>(-0.02, 0.175)</td>
</tr>
<tr>
<td>$</td>
<td>\epsilon_{\mu\tau}</td>
</tr>
</tbody>
</table>