Constraining NSI and Sterile Neutrino Physics with ν_τ Appearance in DUNE

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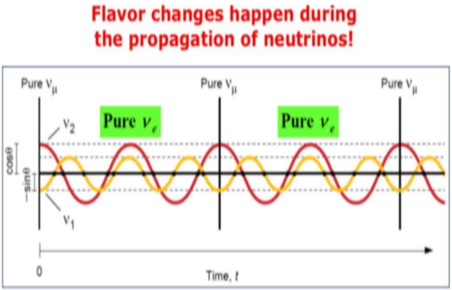
Based on -
(i) **A. Ghoshal**, A.Giarnetti and D.Meloni, arXiv:1906.06212
(ii) **A. Ghoshal**, A.Giarnetti and D.Meloni, [draft in preparation - 1911.xxxxx]

Outline of talk:

- Neutrino Oscillation.
- Deep Underground Neutrino Experiment (DUNE).
- ν_τ 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 ν_τ.

Neutrino Oscillation is now well-known phenomena.



Introduction:

Probability of Neutrino Oscillation:

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H^\nu \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$H^\nu = H_{\rm vac} + H_{\rm mat} \quad \text{and} \quad H^{\bar\nu} = (H_{\rm vac} - H_{\rm mat})^*$$

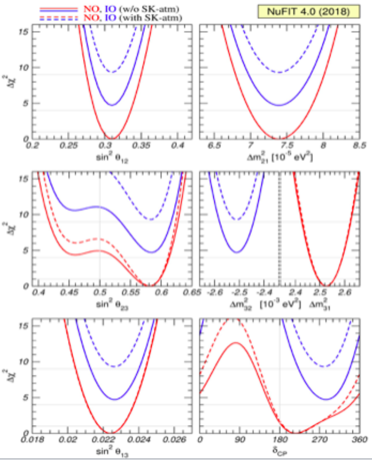
$$H_{vac} = U \cdot \mathrm{Diag}(m_1^2/2E_\nu, m_2^2/2E_\nu, m_3^2/2E_\nu) \cdot U^\dagger$$

$$U = \begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{bmatrix}\begin{bmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{bmatrix}\begin{bmatrix}\cos\theta_{12} & & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{bmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\Re\left[\sum_{i>j}^{3} U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)\right] + 2\Im\left[\sum_{i>j}^{3} U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)\right]$$

Introduction:

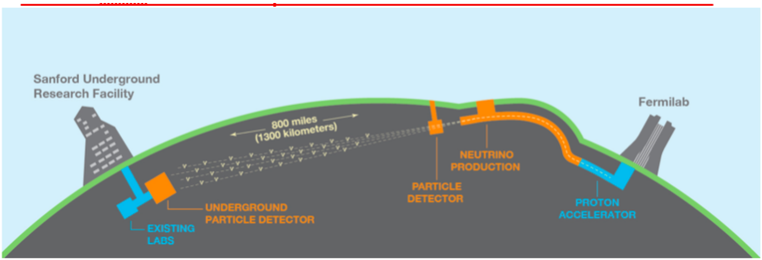
NuFit values of the oscillation parameters:



Deep Underground Neutrino Experiment:

DUNE in a nutshell:

- Intense beam of ν_μ 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:

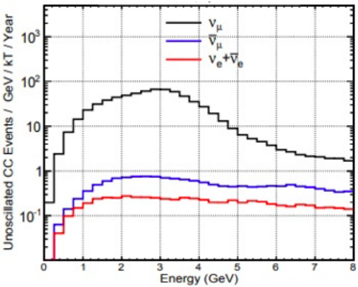
Standard Phenomenology in DUNE:

ν_e appearance

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

ν_μ 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

ν mode (150 kt · MW · year)	
ν_e Signal NH (IH)	861 (495)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)
Total Signal NH (IH)	874 (521)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159
NC Bkgd	22
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3
Total Bkgd	226
$\bar{\nu}$ mode (150 kt · MW · year)	
ν_e Signal NH (IH)	61 (37)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)
Total Signal NH (IH)	228 (415)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89
NC Bkgd	12
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2
Total Bkgd	126

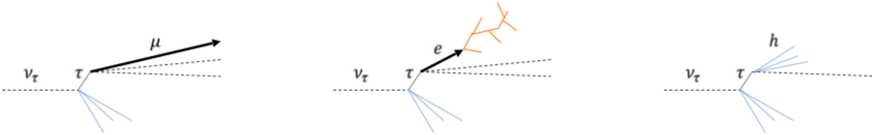
ν mode (150 kt · MW · year)	
ν_μ Signal	10842
$\bar{\nu}_\mu$ CC Bkgd	958
NC Bkgd	88
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	63
$\bar{\nu}$ mode (150 kt · MW · year)	
$\bar{\nu}_\mu$ Signal	3754
ν_μ CC Bkgd	2598
NC Bkgd	50
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	39

[DUNE Design Report Vol 2. (2016)]

Tau Detection

Detection

- $\nu_\mu \to \nu_\tau$ 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.



Muonic Decay of tau (B.R. of 18%)

Electronic Decay of tau (B.R. of 18%)

Hadronic Decay of tau (B.R. of 64%)

Disclaimer - - we do not say this is the most suitable channel for detection.

Signal and Backgrounds

We consider $\tau \to e$ as the detection channel. ICARUS proposal followed this strategy.

Signal

$\nu_\mu \to \nu_\tau$ oscillation

Backgrounds

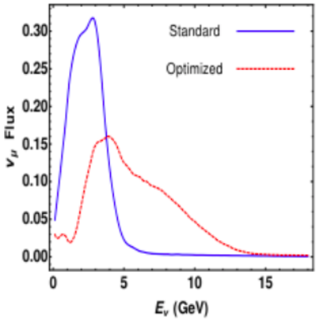
$\nu_\mu \to \nu_e$ oscillation
$\nu_e \to \nu_e$ from beam

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

- 20% & 10% Signal Uncertainties in the ν_τ channel.
- 100% & 33% of electrons being detected (detection efficiency).
- S/B values of 2.46 and 18.6.
- Standard and Tau-Optimized Fluxes.

Neutrino Flux

The standard flux consists of beam delivering 1.47×10^{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 1.1×10^{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 ν_τ events:

ν **mode**		$\bar{\nu}$ **mode**	
ν_τ Signal	277	ν_τ Signal	68
$\bar{\nu}_\tau$ Signal	26	$\bar{\nu}_\tau$ Signal	85
Total Signal	303	Total Signal	153
$\nu_e + \bar{\nu}_e$ CC Background (beam)	333 + 38	$\nu_e + \bar{\nu}_e$ CC Background (beam)	117 + 104
CC Background (oscillation)	1753 + 12	ν_e CC Background (oscillation)	90 + 188

Figure: Standard Flux

ν **mode**		$\bar{\nu}$ **mode**	
ν_τ Signal	2673	ν_τ Signal	98
$\bar{\nu}_\tau$ Signal	34	$\bar{\nu}_\tau$ Signal	983
Total Signal	2707	Total Signal	1081
$\nu_e + \bar{\nu}_e$ CC Background (beam)	688 + 63	$\nu_e + \bar{\nu}_e$ CC Background (beam)	176 + 177
CC Background (oscillation)	1958 + 11	ν_e CC Background (oscillation)	76 + 324

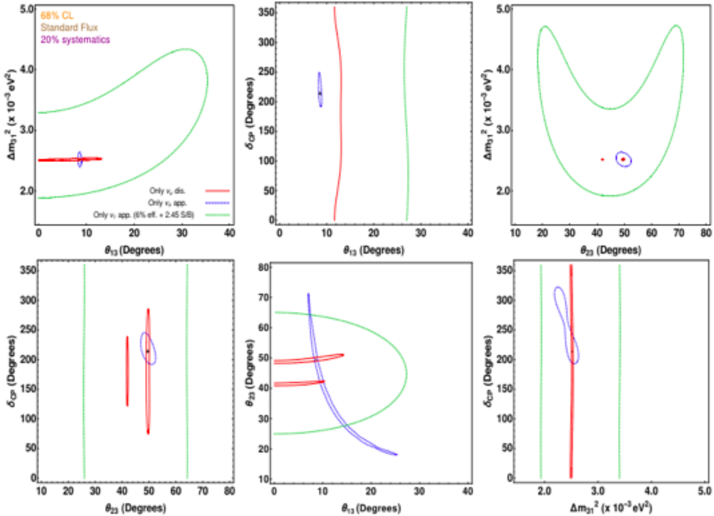
Figure: Optimized Flux

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

Correlation Studies

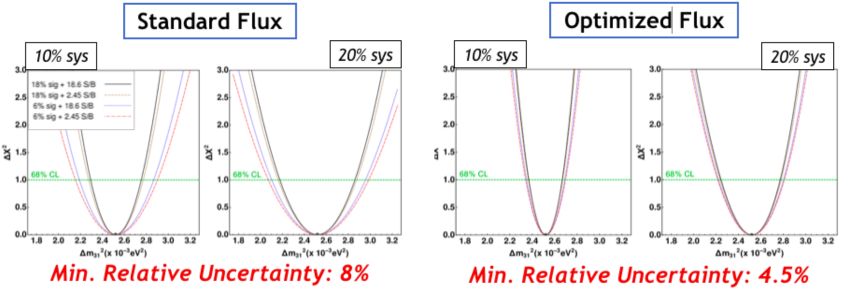
Standard Physics does not improve using ν_τ channel.

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



Comparison with OPERA

OPERA has observed 10 events in the $\nu_\mu \to \nu_\tau$ channel. Using these events the Δm^2_{31} parameter uncertainty is about 26%. Using the τ events in DUNE this can be largely improved.



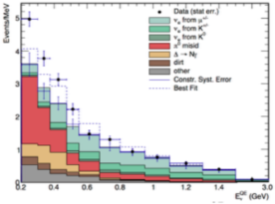
Long Discussions Yesterday:

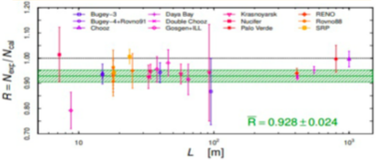
LSND and MiniBooNE Anomaly

Oscillation with small L/ E.

Reactor Experiment Anomaly

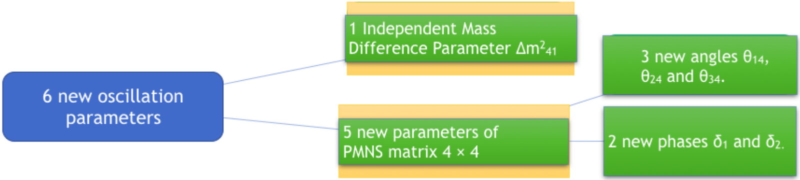
$\Delta m_{41}^2 \sim 1\ eV^2$





Sterile Neutrinos in 3+1 Scheme

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

$$P(\nu_\mu \to \nu_e) = 2|U_{14}|^2|U_{24}|^2 + 4\Re[U_{23}^* U_{13}(U_{23}U_{13}^* + U_{24}U_{14}^*)]\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) + \\ - 2\Im(U_{23}^* U_{13} U_{24} U_{14}^*)\sin\left(\frac{\Delta m_{32}^2 L}{2E}\right) \quad (4.2)$$

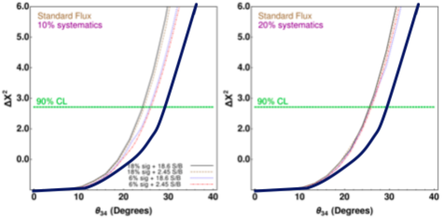
$$U_{34} = \cos\theta_{14}\cos\theta_{24}\sin\theta_{34}.$$

$$P(\nu_\mu \to \nu_\tau) = 2|U_{34}|^2|U_{24}|^2 + 4\Re[U_{23}^* U_{33}(U_{23}U_{33}^* + U_{24}U_{34}^*)]\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) + \\ - 2\Im(U_{23}^* U_{33} U_{24} U_{34}^*)\sin\left(\frac{\Delta m_{32}^2 L}{2E}\right) \quad (4.3)$$

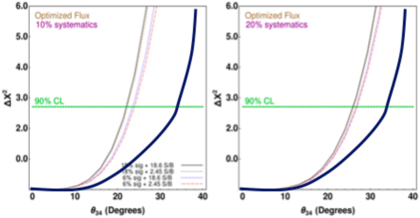
We expect the addition of $\nu_\mu \to \nu_\tau$ appearance channel to improve θ_{34} sensitivity.

$$P(\nu_\mu \to \nu_\mu) = 1 - 2|U_{24}|^2(1-|U_{24}|^2) - 4[|U_{23}|^2(1-|U_{23}|^2-|U_{24}|^2)]\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) \quad (4.4)$$

Effect of Systematics, detection efficiencies, S/B values and two fluxes on the measurement of θ_{34}.

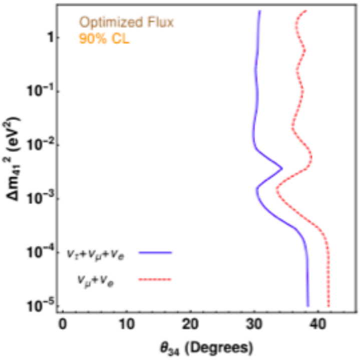


Upper limit: from 27.5° to 24.2° with the standard flux.

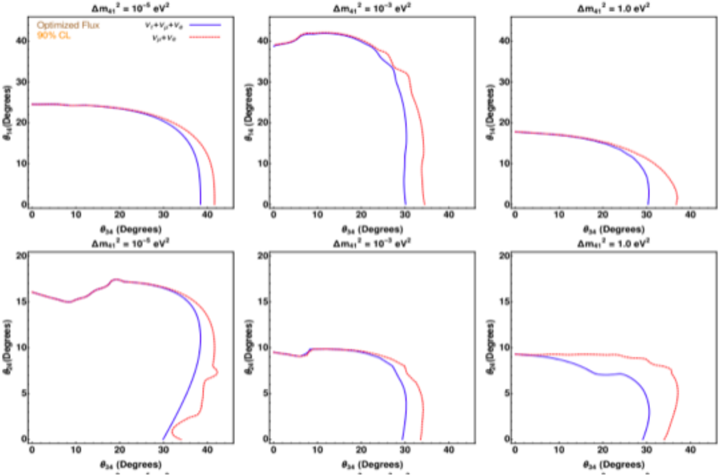


Upper limit: from 32.1° to 22° with the optimised flux.

We can see the maximum effect is on the improvement of θ_{34} only.



Correlation Studies



New Physics: NSI

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

$$-\mathcal{L}^{eff}_{\text{NSI}} = \varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f}\gamma^\rho P f)$$

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

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta; \varepsilon_{e\mu}, \varepsilon_{e\tau}, \varepsilon_{\mu\mu}, \varepsilon_{\mu\tau}, \varepsilon_{\tau\tau}) &= P(\nu_\alpha \to \nu_\beta; 2 \text{ flavor in vacuum}) \\ &+ P(\nu_\alpha \to \nu_\beta; \varepsilon_{e\mu}, \varepsilon_{e\tau}) \\ &+ P(\nu_\alpha \to \nu_\beta; \varepsilon_{\mu\mu}, \varepsilon_{\mu\tau}, \varepsilon_{\tau\tau}), \end{aligned}$$

New Physics: NSI

Tau Appearance Probability with NSI:

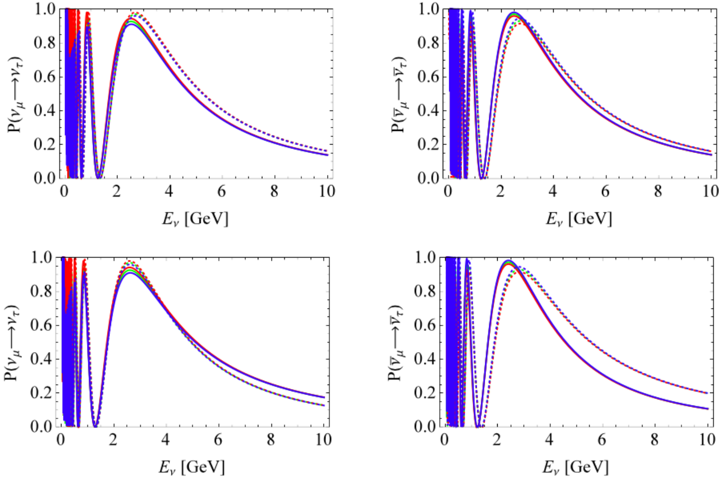
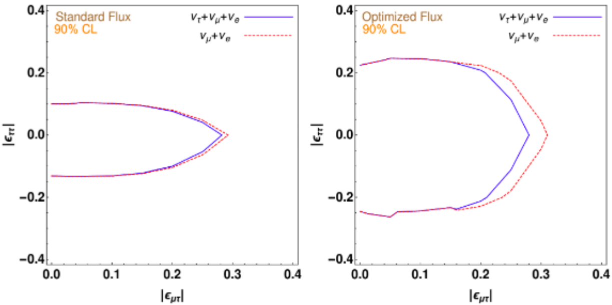


Figure: Solid/Dotted - - NH/IH. Green/Red/Blue - - $\delta_{CP} = [0, \pi/2, -\pi/2]$. Top/Bottom - - (No NSI; $[\epsilon_{\mu\tau}, \epsilon_{\tau\tau}]$=(0.07,0.147))

NSI:Correlation Studies

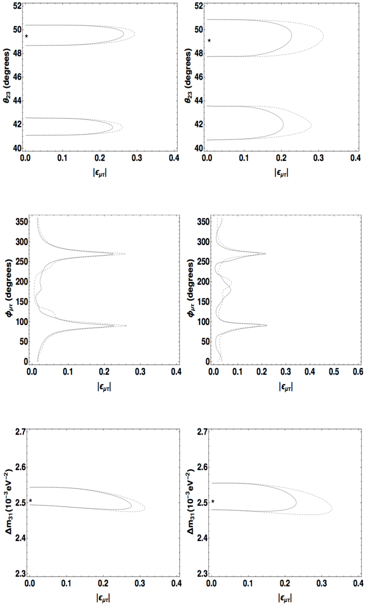
NSI probability

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



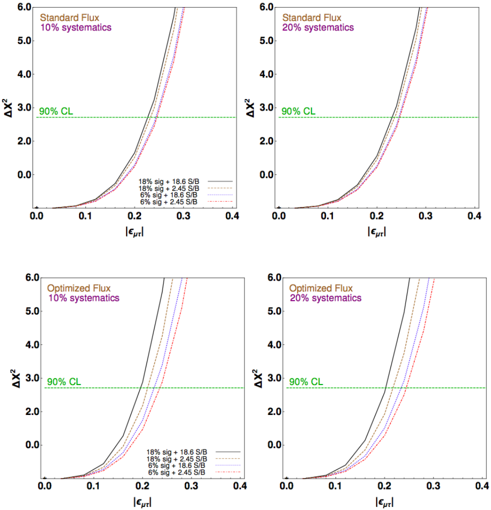
In the optimized flux, we do not get the advantage of increased tau-statistics as ν_e & ν_μ channels are also increased.

NSI Correlation Studies



NSI:Sensitivity on NSI parameter

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



Neutrino Decay - - Introduction

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

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

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

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

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

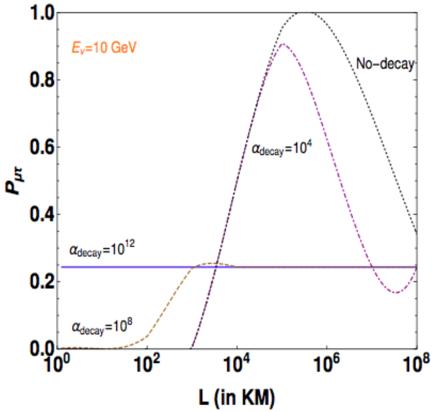
$$H = U\left[\frac{1}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix} - i\frac{\alpha_3}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 1\end{pmatrix}\right]U^\dagger + \begin{pmatrix}A & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

Why Interesting for DUNE

$$P_{\mu\mu}(E,L,\alpha_3) = \left(\cos^2\theta_{23} + \sin^2\theta_{23} e^{-\frac{\alpha_3}{2E}L}\right)^2 - 4\cos^2\theta_{23}\sin^2\theta_{23} e^{-\frac{\alpha_3}{2E}L}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

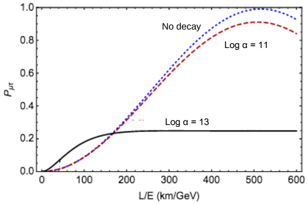
$$P_{\mu\tau}(E,L,\alpha_3) = \cos^2\theta_{23}\sin^2\theta_{23}\left(1 - e^{-\frac{\alpha_3}{2E}L}\right)^2 + 4\cos^2\theta_{23}\sin^2\theta_{23} e^{-\frac{\alpha_3}{2E}L}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

Decay term causes vanishing of interference effects. Increase in Probability.



Why Interesting for DUNE

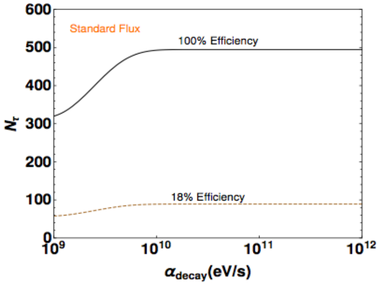
DUNE is very suited to explore this inrceased probability region due to its L/E.

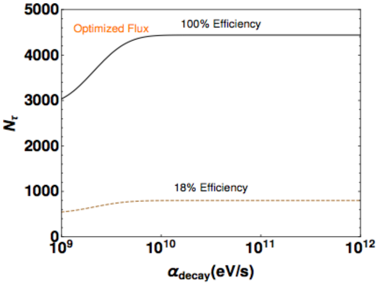


Some Preliminary Results

Expected number of ν_τ events:

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

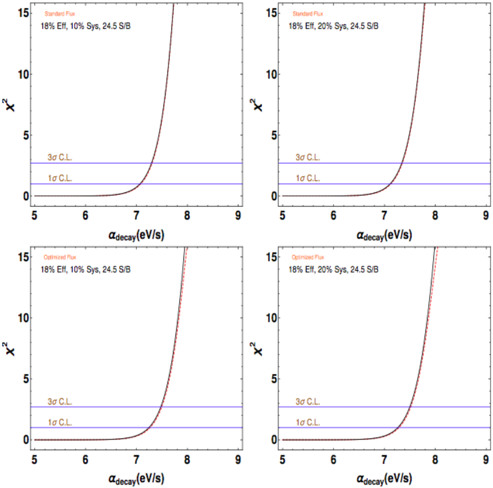




Disclaimer - - preliminary calculations only. Final results may differ !

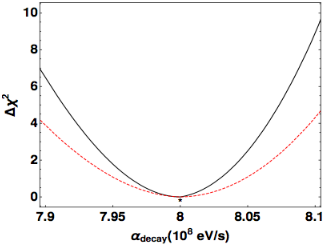
Some Preliminary Results

Sensitivity of measurement of α:



Some Preliminary Results

Chi-squared Fit Analysis:



Conclusions

- In the case of standard physics, the addition of ν_τ 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, ν_τ 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 ν_e appearance and ν_μ disappearance channels result in worsening the sensitivities overshadowing the advantage one may get from the increase in the ν_τ statistics. This is mainly due to the increased background events in both the ν_e and ν_μ 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 θ_{34} and we estimated the improvement to be about 20%.
- Neutrino Invisible Decay constant parameter can be constrained using the ν_τ 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.
- $\nu_\mu \to \nu_\tau$ maybe suited to study Large Extra Dimension scenarios.
- $\nu_\mu \to \nu_\tau$ maybe suited to study dark matter scenarios especially searches in dark sectorinvolving $L_\mu - L_\tau$ symmetries and its corresponding mediators.
- Probe of Non-Unitary and Lorentz Violating Operators using $\nu_\tau -$appearance channel.
- Other suggestions are welcome.

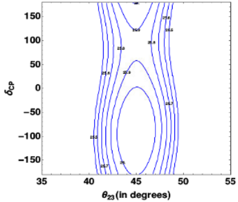
Stay tuned. Work in Progress !!

Essential References

- arxiv 1811.05487
- arxiv 1512.06148
- arxiv 1606.09550
- arxiv 0407333
- ICARUS: http://cds.cern.ch/record/574836/files/spsc-p-323.pdf
- 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



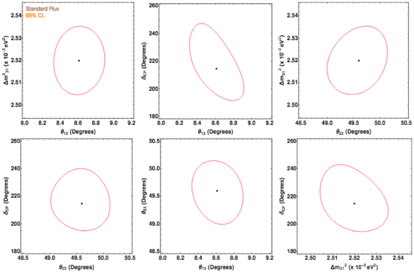
	Standard Flux		Optimized Flux	
	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode
ν_μ CC	30175	3225	85523	4933
$\bar{\nu}_\mu$ CC	1025	9879	1256	26221
ν_e CC	371	136	856	258
$\bar{\nu}_e$ CC	44	109	84	215

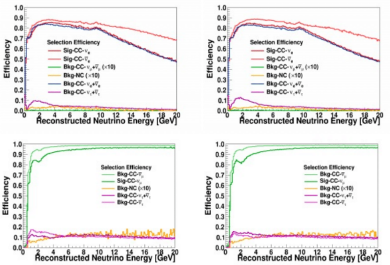
Backup Slides

	signal	backgrounds			
		intrinsic ν_e	mis ν_μ	mis ν_τ	NC
neutrino mode	$\nu_\mu \to \nu_e \oplus \bar{\nu}_\mu \to \bar{\nu}_e$ $1188 \oplus 11.5$	288.2	3.1	19.9	26
	$\nu_\mu \to \nu_\mu \oplus \bar{\nu}_\mu \to \bar{\nu}_\mu$ $7601 \oplus 519.2$			28.2	75.3
antineutrino mode	$\bar{\nu}_\mu \to \bar{\nu}_e \oplus \nu_\mu \to \nu_e$ $209 \oplus 64$	171.8	2.9	13.4	15.2
	$\bar{\nu}_\mu \to \bar{\nu}_\mu \oplus \nu_\mu \to \nu_\mu$ $2591 \oplus 1489$			16.5	44.1

ν_e **appearance channel**		
Signal	ν_e and $\bar{\nu}_e$ CC events from ν_μ oscillations	2% sys
Backgrounds	Beam ν_e and $\bar{\nu}_e$ CC events	5% sys
	Misidentified ν_μ and $\bar{\nu}_\mu$ CC events	5% sys
	Misidentified ν_τ and $\bar{\nu}_\tau$ CC events	20% sys
	Misidentified NC events	10% sys
ν_μ **disappearance channel**		
Signal	ν_μ and $\bar{\nu}_\mu$ CC events	5% sys
Backgrounds	Misidentified ν_τ and $\bar{\nu}_\tau$ CC events	20% sys
	Misidentified NC events	10% sys

Backup Slides





Backup Slides

NSI parameters	Limits
$\epsilon_{ee} - \epsilon_{\mu\mu}$	(-0.2, 0.45)
$\lvert\epsilon_{e\mu}\rvert$	< 0.1
$\lvert\epsilon_{e\tau}\rvert$	< 0.3
$\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$	(-0.02, 0.175)
$\lvert\epsilon_{\mu\tau}\rvert$	< 0.03