New Physics in the Lepton sector from future Neutrino Experiments

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Neutrino Physics and the Precision Era

around 36000 paper with the word “neutrino” in the title (Inspirehep.net)

- SK results
- SNO results
- $\Theta_{13} \neq 0$
- $\sim 2000$
- $\sim 2010$
- $\sim 1980$
- solar neutrino problem
- $O(1)$ effects
- $O(0.1)$ effects
- $\delta_{CP}$
- NP
- $\Theta_{13} \neq 0$
- New Physics?
Current experimental situation

- standard 3-ν paradigm (well) established

http://www.nu-fit.org

<table>
<thead>
<tr>
<th></th>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering ($\Delta \chi^2 = 7.1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$bfp \pm 1\sigma$</td>
<td>$3\sigma$ range</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.304^{+0.012}_{-0.012}$</td>
<td>$0.269 \rightarrow 0.343$</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$33.44^{+0.77}_{-0.74}$</td>
<td>$31.27 \rightarrow 35.86$</td>
</tr>
<tr>
<td>$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$</td>
<td>$7.42^{+0.21}_{-0.20}$</td>
<td>$6.82 \rightarrow 8.04$</td>
</tr>
</tbody>
</table>

Errors at the level of 3-4 %
Current experimental situation

- standard 3-ν paradigm (well) established

| $\sin^2 \theta_{23}$ | $0.573^{+0.010}_{-0.020}$ | 0.415 → 0.616 | $0.575^{+0.010}_{-0.019}$ | 0.419 → 0.617 |
| $\theta_{23}/^\circ$ | $49.2^{+0.9}_{-1.2}$ | 40.1 → 51.7 | $49.3^{+0.9}_{-1.1}$ | 40.3 → 51.8 |

| $\frac{\Delta m^2_{31}}{10^{-3} \text{ eV}^2}$ | $+2.517^{+0.026}_{-0.028}$ | $2.435 \rightarrow +2.598$ | $-2.498^{+0.028}_{-0.028}$ | $-2.581 \rightarrow -2.414$ |
Current experimental situation

- standard 3-$\nu$ paradigm (well) established

Existence of CP violation in the lepton sector (?)
Where is New Physics (in neutrino oscillations) ?

\[ P \sim |A^{SM} + \epsilon A^{NP}|^2 \sim P^{SM} + 2 \epsilon \Re (A^{SM} A^{NP}) \]

- in the absence of correlation between NP and standard parameters, strong constraints
- if correlation is strong, thus bounds can be (partially) relaxed
New Physics in Neutrino Oscillations

- scenarios where neutrinos new interactions:
  - neutrino decay
  - modified interactions with detector atoms
  - modified interactions with matter

- scenarios where the number of neutrino species is larger than 3
  - sterile neutrino models – loss of unitarity
    - imprint on short-baseline experiments
    - imprint on cosmological observables such as the cosmic microwave background and the distribution of matter at large scale

also Palazzo’s Talk

“interdisciplinary” NP
  imprint on laboratory experiments
  imprint on “astrophysical” neutrinos

also Joaquim and Saviano’s Talks
Future Experimental Alternatives
(some of them)

Goals
- measure of $\delta_{CP}$
- determination of mass hierarchy
- New Physics

Accelerator-based long-baseline experiments
- Hyper-Kamiokande, DUNE

Accelerator-based short-baseline experiments
- MINERvA, MicroBooNE, SHiP
- COHERENT

Reactor neutrino experiments
- JUNO
- PROSPECT, SoLid, Watchman
- SOX

Astrophysical neutrino measurements
- PINGU, ORCA
- Hyper-Kamiokande, Jinping
- Super-Kamiokande-Gd
- IceCube-Gen2, KM3NeT, ARA
- PTOLEMY
Neutrino Decay

- Neutrino decay

massless scalar field: Majoron

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

neutrino decay

\[ \nu_i \rightarrow \nu + S \]

visible decay: active neutrinos

in invisible decay (either because it is sterile or because its energy is too low to produce a signal through scattering)

Relevant parameter for phenomenology: depletion factor \( (m_i \rightarrow m_i - i \Gamma/2) \)

\[ D_i = e^{-t/\tau_i} = e^{m_i L / \tau_i E} = e^{1 L / \beta^i E} = e^{\alpha_i L / E} \]

decay is relevant when \( L / (E \beta) \gg 1 \)


Neutrino Decay

- Simplified 2-flavor approach

One unstable neutrino:

\[
i \frac{d}{dx} \left( \nu_\alpha \nu_\beta \right) = U \left[ \frac{\Delta m^2}{2E} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} - i \frac{\alpha}{2E} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \right] U^+ \left( \nu_\alpha \nu_\beta \right)
\]

\[
\alpha = \frac{m}{\tau} \\
U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}
\]

\[
P(\nu_\alpha \rightarrow \nu_\alpha) = \cos^4 \theta + \frac{1}{2} \sin^2(2\theta) e^{-\frac{\alpha x}{E_v}} \cos \left( \frac{\Delta m^2 x}{2E_v} \right) + e^{-\frac{\alpha x}{E_v}} \sin^4 \theta
\]

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \frac{1}{2} \sin^2(2\theta) e^{-\frac{\alpha x}{E_v}} \left[ 1 + e^{-\frac{\alpha x}{E_v}} - 2 e^{-\frac{\alpha x}{E_v}} \cos \left( \frac{\Delta m^2 x}{2E_v} \right) \right]
\]

\[
P(\nu_\alpha \rightarrow \nu_\alpha) + P(\nu_\alpha \rightarrow \nu_\beta) = \cos^2 \theta + e^{-\frac{\alpha x}{E_v}} \sin^2 \theta \neq 1
\]
Neutrino Decay - The Future

- $\nu_3 \rightarrow \nu_4 + S$, 3-flavor effects taken into account

$$H = U \left[ \frac{1}{2E} \begin{pmatrix} 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} - i \frac{1}{2\beta_3 E} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right] U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$  

unstable third mass eigenstates  
standard matter effects

At very long-baseline accelerator experiments:

damping factor  
"constant term"

\[
\begin{align*}
P_{\mu e}^{(0)} &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \left[ e^{-\frac{1}{\beta_3} \frac{L}{2E}} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) + \left( 1 - e^{-\frac{1}{\beta_3} \frac{L}{2E}} \right)^2 \right] \\
P_{\mu\tau}^{(0)} &= \cos^4 \theta_{13} \sin^2 2\theta_{23} \left[ e^{-\frac{1}{\beta_3} \frac{L}{2E}} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) + \left( 1 - e^{-\frac{1}{\beta_3} \frac{L}{2E}} \right)^2 \right] \\
P_{\mu\mu}^{(0)} &= 1 + 2 \left( e^{-\frac{1}{\beta_3} \frac{L}{2E}} - 1 \right) \cos^2 \theta_{13} \sin^2 \theta_{23} + \left( e^{-\frac{1}{\beta_3} \frac{L}{2E}} - 1 \right)^2 \cos^4 \theta_{13} \sin^4 \theta_{23} \\
& \quad - e^{-\frac{1}{\beta_3} \frac{L}{2E}} \left( \cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23} \right) \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right).
\end{align*}
\]

Ghoshal, Giarnetti, Meloni, 2003.09012, accepted in Journal of Physics G
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**Introducing DUNE**

"Deep Underground Neutrino Experiment"

- 1300 km baseline
- Large (70 kt) LArTPC far detector
- 1.5 km underground
- Near Detector (ND) w/LAr component

"Physics goals"

- $\nu$ and $\bar{\nu}$ oscillations ($\delta_{CP}$, $\theta_{13}$, $\theta_{23}$, ordering of nu masses)
- Supernova burst neutrinos
- Beyond Standard Model processes

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**Diagram:**

- **SURF**
- Deep Underground Neutrino Experiment
- **FNAL**

**ND** (574 m from neutrino beam target)

**Graph:**

- Probability of detecting electron, muon and tau neutrinos
- Incoming beam: 100% muon neutrinos
DUNE events

- **neutrino signal channels:**
  - $\nu_e$ appearance and $\nu_\mu$ disappearance channels
    (2% and 5% systematic normalization errors)

- **$\nu_\tau$ appearance channel**

- **neutral current events**
  (hadronic shower with a certain visible energy)

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### Background

<table>
<thead>
<tr>
<th>Background</th>
<th>Normalization Uncertainty</th>
<th>Correlations</th>
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<tbody>
<tr>
<td>For $\nu_e/\bar{\nu}_e$ appearance:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam $\nu_e$</td>
<td>5%</td>
<td>Uncorrelated in $\nu_e$ and $\bar{\nu}_e$ samples</td>
</tr>
<tr>
<td>NC</td>
<td>5%</td>
<td>Correlated in $\nu_e$ and $\bar{\nu}_e$ samples</td>
</tr>
<tr>
<td>$\nu_\mu$ CC</td>
<td>5%</td>
<td>Correlated to NC</td>
</tr>
<tr>
<td>$\nu_\tau$ CC</td>
<td>20%</td>
<td>Correlated in $\nu_e$ and $\bar{\nu}_e$ samples</td>
</tr>
<tr>
<td>For $\nu_\mu/\bar{\nu}_\mu$ disappearance:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC</td>
<td>5%</td>
<td>Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>20%</td>
<td>Correlated to $\nu_e/\bar{\nu}<em>e$ $\nu</em>\tau$ background</td>
</tr>
</tbody>
</table>

- 6% overall detection efficiency for the signal
- signal-to-background ratio of 2.45
- signal systematic uncertainty of 20%
- we take into account that only 30% of the $\tau$-s are detected
- 0.5% of the NC events as a background
- overall 90% signal detection efficiency
- systematic uncertainty at 10%
- backgrounds come from the mis-identification of CC events
  (mainly a conservative 10% of the $\nu_\mu$ and $\nu_e$ CC events)
Latest sensitivities to nu lifetime

- sensitivity

results from other future experiments

- a muon-decay medium-baseline neutrino beam facility

- reactor neutrinos

- atmospheric neutrinos

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**Best 90% CL long-baseline limit**

\[ \beta_3 > 5.1 \times 10^{-11} \text{ s/eV} \]

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**Choubey, Goswami, Pramanik**

*JHEP02 (2018), 055*

**Ghoshal, Giarnetti, Meloni**

*2003.09012, accepted in Journal of Physics G*

**DUNE**
Latest sensitivities to nu lifetime

- precision measurement in DUNE

assuming $\beta_3 \neq 0$, uncertainty of about [10–30]% can be set at 90% CL, depending on the central value used.

- Impact on measurements in MOMENT

Tang, Wang and Zhang, JHEP02 (2018), 055

little correlations between $\theta_{23}$ and $\Delta m^2_{31}$ at 3σ confidence level
Non-standard Neutrino Interactions (NSI)

- In the low energy regime, weak neutrino interactions can be described by effective four-fermion operators

\[ \mathcal{L}_\nu = \frac{G_F}{\sqrt{2}} [\bar{\nu}_\alpha \gamma^\rho (1 - \gamma^5) \ell_\alpha] [\bar{f}' \gamma_\rho (1 - \gamma^5) f] \]

\[ \mathcal{L}_{\text{MSW}} = \frac{G_F}{\sqrt{2}} [\bar{\nu}_\alpha \gamma^\rho (1 - \gamma^5) \nu_\alpha] [\bar{f} \gamma_\rho (1 - \gamma^5) f] \]

- Low-energy fingerprint of many “new physics” scenarios (similar structure as above)

\[ \mathcal{L}_{\text{NSI}} = \mathcal{L}_{V^\pm A} + \mathcal{L}_{S^\pm P} + \mathcal{L}_T \]

\( \varepsilon \) represents the strength of the new interaction compared to \( G_F \)

Source and detector interactions

\[ \mathcal{L}_{S^\pm P} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} [\bar{\nu}_\beta \gamma^\rho (1 - \gamma^5) \ell_\alpha] [\bar{f}' \gamma_\rho (1 - \gamma^5) f] \]

Non-standard matter effects

\[ \mathcal{L}_T = \frac{G_F}{\sqrt{2}} \sum_{f,f'} [\bar{\nu}_\beta \sigma^{\rho\tau} \ell_\alpha] [\bar{f}' \sigma_{\rho\tau} f] \]
Modified Oscillation Probabilities

- Standard oscillations:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | e^{-iH_L} | \nu_\alpha \rangle \right|^2 \]

- Oscillations with Neutral Current NSI:

\[ |\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\beta=\epsilon,\mu,\tau} \varepsilon_{\alpha\beta}^s |\nu_\beta\rangle \]
\[ \langle \nu_\beta^d | = \langle \nu_\beta | + \sum_{\alpha=\epsilon,\mu,\tau} \varepsilon_{\alpha\beta}^d \langle \nu_\alpha | \]

\[ P(\nu_\alpha^s \rightarrow \nu_\beta^d) = \left| \left( \nu_\beta^d | e^{-i(H+V_{NSI})_L} | \nu_\alpha^s \right) \right|^2 \]

\[ V_{NSI} = \sqrt{2} G_F N_e \begin{pmatrix} 
\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\
\varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\
\varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} 
\end{pmatrix} \]

\[ P(\nu_\alpha^s \rightarrow \nu_\beta^d) = \left| \left( 1 + \epsilon^d \right)^T e^{-i(H+V_{NSI})_L} \left( 1 + \epsilon^s \right) \right|_{\beta\alpha}^2 \]
Modified Oscillation Probabilities

- **Existing bounds**

  from $G_F$, pion decay, unitarity of CKM, oscillation experiments

  \[
  \begin{bmatrix}
  0.041 & 0.025 & 0.041 \\
  0.026 & 0.078 & 0.013 \\
  0.12 & 0.018 & 0.13
  \end{bmatrix} < \begin{bmatrix}
  4.2 & 0.3 & 3.0 \\
  0.3 & - & 0.04 \\
  3.0 & 0.04 & 0.15
  \end{bmatrix}
  \]

  since the existing bounds on matter NSIs are weaker, they affect the probability more more
The **Future**: signals at the DUNE Far Detector

- Introducing tau neutrinos into the game

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

\[
\Delta X^2
\]

assumptions on the signal-to-background ratio

limits approximately 35% smaller than those set by DUNE using only $\nu_e$ appearance and $\nu_\mu$ disappearance channels with standard flux, $|\epsilon_{\mu \tau}| < 0.32$
The **future**: signals at the DUNE Near Detector

- Source and detecton NSI

$$P(\nu_{\alpha}^s \rightarrow \nu_{\beta}^d) = \left| \left( 1 + \epsilon^d \right)^T e^{-i(H+V_{NSI})L} \left( 1 + \epsilon^s \right)^T \right|_{\beta\alpha} \]^{2 \ L=0} \rightarrow P_{\alpha\beta} = \left| \left( 1 + \epsilon^d \right)^T \left( 1 + \epsilon^s \right)^T \right|_{\beta\alpha}^{2}$$

**Perturbation theory**

- dependence on the diagonal NSI parameters appears already at the first order

$$P_{\alpha\alpha} = 1 + 2|\epsilon_{\alpha\alpha}^s| \cos \Phi_{\alpha\alpha}^s + 2|\epsilon_{\alpha\alpha}^d| \cos \Phi_{\alpha\alpha}^d$$

$$P_{\alpha\beta} = |\epsilon_{\alpha\beta}^s|^2 + |\epsilon_{\alpha\beta}^d|^2 + 2|\epsilon_{\alpha\beta}^s||\epsilon_{\alpha\beta}^d| \cos (\Phi_{\alpha\beta}^s - \Phi_{\alpha\beta}^d)$$

- main dependence on $\epsilon$ with the same flavor indeces
The **future**: signals at the DUNE Near Detector

- **Source and detection NSI**
  
  - overall systematic normalization uncertainty of 10% for the $\nu_\mu$ disappearance, $\nu_e$ disappearance and $\nu_e$ appearance channels signals
  
  - 25% for the $\nu_\tau$ appearance signal
  
  - for the NC background we considered a 15% uncertainty

Investigation of parameter space complementary to Far Detector studies

\[ |\varepsilon^{s/d}_{\mu e}| < 0.0046 \quad |\varepsilon^{s/d}_{\mu \tau}| < 0.0018 \]
Conclusions

- On-going and planned neutrino experiments will probe the PMNS with huge precision
- Good chance to investigate New Physics effects in Neutrino oscillations:
  several “Beyond the Standard Model” scenarios, including Neutrino Decay and Non-Standard Interactions
- For the latter, interesting synergy between FD and ND