DUNE sensitivities to the mixing between sterile and tau neutrinos

Based on arXiv:1707.05348

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NUFACT
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In coll. with: Pilar Coloma & Stephen Parke

Outline

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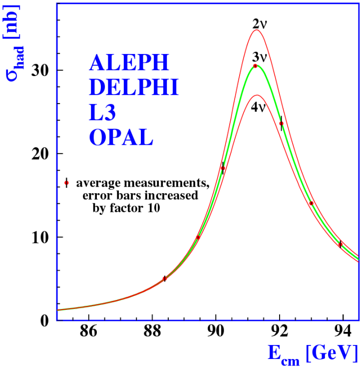
Introduction

Three and only three active neutrinos: $N_\nu = 2.984 \pm 0.008$

Phys.Rept. 427 (2006) 257-454 arxiv:hep-ex/0509008



- Extra flavor neutrino states have to be 'sterile'!
- Light sterile neutrino(s) with $\Delta m^2 \sim 1\text{eV}^2$ are motivated by SBL anomalies.
- One economical extension is to introduce one extra sterile neutrino, 3+1 framework.

Introduction

Besides SBL experiments, sterile oscillation can be tested using the ν_μ disappearance channel at the far detector (FD) of accelerator experiments:

- MINOS: P. Adamson et. al. arxiv:1104.3922 P. Adamson et. al. arxiv:1607.01176
  - For $m_4 = m_1$: Limits $\theta_{34} < 26^\circ(37^\circ)$ at the 90% C.L .
    For $m_4 \gg m_1$: Limits $\theta_{24} < 7^\circ(8^\circ)$ and $\theta_{34} < 26^\circ(37^\circ)$ at the 90% C.L
  - For $\Delta m^2_{41} = 0.5$ eV^2: Limits $\sin^2\theta_{24} < 0.016$) (assuming $|U_{e4}|^2 = 0$ [*]), also $\sin^2\theta_{34} < 0.20$ (assuming $c^2_{14} = c^2_{24} = 1$)...at the 90% C.L.
- NOvA: P. Adamson et. al. arxiv:1706.04592
  - For $\Delta m^2_{41} = 0.5$ eV^2: Limits $\theta_{24} < 20.8^\circ$ and $\theta_{34} < 31.2^\circ$ or $|U_{\mu 4}|^2 < 0.126$ and $|U_{\tau 4}|^2 < 0.268$ (assuming $c^2_{14} = 1$) at the 90% C.L.

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An important experimental constraint comes from atmospheric neutrinos at Super-Kamiokande: K. Abe et. al. arxiv:1410.2008

- No evidence of sterile oscillations is seen $\rightarrow |U_{\mu 4}|^2 < 0.041$ and $|U_{\tau 4}|^2 < 0.18$ for $\Delta m^2 > 0.1$ at the 90% C.L (Assuming $|U_{e4}|^2 = 0$).

[*] $|U_{e4}|^2 < 0.041$ at 90% C.L, from ‘solar+KamLAND’ plus ’Daya Bay+RENO’, for $\Delta m^2 \sim 1$ eV^2. A. Palazzo arxiv:1302.1102

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Can we improve our knowledge of the ν_τ fraction of a sterile state?

Outline

Generalities

3+1 sterile neutrino framework

Flavor and mass eigenstates are connected via:

$$\nu_\alpha = U^*_{\alpha i}\nu_i\,, \text{ with } \quad \alpha = e, \mu, \tau, s$$

where we have parametrized U in this arbitrary form:

$$U = O_{34}\, V_{24}\, V_{14}\, O_{23}\, V_{13}\, O_{12}\,,$$

where O_{ij} (V_{ij}) denotes a real (complex) rotation.

Assuming we can neglect the solar contribution to the (vacuum) sterile oscillation probability, or $\Delta_{21} \ll \Delta_{31}$, one obtains:

$$\begin{aligned} P_{\mu s} \equiv P(\nu_\mu \to \nu_s) = {} & 4|U_{\mu 4}|^2|U_{s4}|^2 \sin^2\Delta_{41} + 4|U_{\mu 3}|^2|U_{s3}|^2 \sin^2\Delta_{31} \\ & + 8\,\mathrm{Re}\left[U^*_{\mu 4} U_{s4} U_{\mu 3} U^*_{s3}\right] \cos\Delta_{43} \sin\Delta_{41} \sin\Delta_{31} \\ & + 8\,\mathrm{Im}\left[U^*_{\mu 4} U_{s4} U_{\mu 3} U^*_{s3}\right] \sin\Delta_{43} \sin\Delta_{41} \sin\Delta_{31}\,, \end{aligned}$$

How many new parameters we have included to the 3-flavor case?

Generalities

Degrees of freedom, working assumptions

General degrees of freedom:

- θ_{i4} new mixing angles.
- Three new splittings $\Delta m^2_{4k} \equiv m^2_4 - m^2_k$, with $k = 1, 2, 3$.
- Two new CP-violating phases: δ_{14} and δ_{24}.

working assumptions:

- For simplicity, and without losing generality, from now on we consider $\theta_{14} = 0$.
  This assumption implies only one extra phase is physical, δ_{24}.

At the end, we are left with: θ_{34}, θ_{24}, δ_{24} and Δ_{41} extra parameters!

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From now we consider the sterile appearance channel, $P(\nu_\mu \to \nu_s)$

Limiting cases

$$P_{\mu s} \equiv P(\nu_\mu \to \nu_s) = 4|U_{\mu 4}|^2|U_{s4}|^2 \sin^2\Delta_{41} + 4|U_{\mu 3}|^2|U_{s3}|^2 \sin^2\Delta_{31}$$
$$+ 8\,\mathrm{Re}\left[U^*_{\mu 4}U_{s4}U_{\mu 3}U^*_{s3}\right] \cos\Delta_{43}\sin\Delta_{41}\sin\Delta_{31}$$
$$+ 8\,\mathrm{Im}\left[U^*_{\mu 4}U_{s4}U_{\mu 3}U^*_{s3}\right] \sin\Delta_{43}\sin\Delta_{41}\sin\Delta_{31},$$

Depending on the Δm^2_{41} value respect to Δm^2_{31}, one have three 'oscillation regimes':

- $\Delta_{41} \ll \Delta_{31}$, sterile oscillation has not developed at FD

$$P_{\mu s} = 4|U_{\mu 3}|^2|U_{s3}|^2 \sin^2\Delta_{31}$$

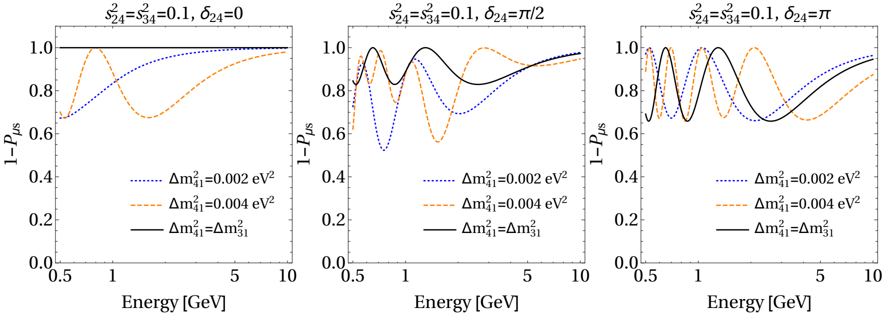
- $\Delta_{41} \approx \Delta_{31}$, sterile matches the 3-flavor oscillation phase:

$$P_{\mu s} = 4\left|U^*_{\mu 4}U_{s4} + U^*_{\mu 3}U_{s3}\right|^2 \sin^2\Delta_{31}$$

- $\Delta_{41} \gg \Delta_{31}$, sterile oscillations already averaged-out at the FD:

$$P_{\mu s} = 2|U_{\mu 4}|^2|U_{s4}|^2 + 4\left\{|U_{\mu 3}|^2|U_{s3}|^2 + \mathrm{Re}[U^*_{\mu 4}U_{s4}U_{\mu 3}U^*_{s3}]\right\}\sin^2\Delta_{31}$$
$$+ 2\,\mathrm{Im}[U^*_{\mu 4}U_{s4}U_{\mu 3}U^*_{s3}]\sin 2\Delta_{31}$$

δ_{24} effect at the probability level



- When $\Delta_{41} \approx \Delta_{31}$, and for $\delta_{24} = 0$, a cancellation of the oscillation amplitud happens for certain values of θ_{24} and θ_{34}:
  $|U^*_{\mu 4} U_{s4} + U^*_{\mu 3} U_{s3}|^2 \approx 0$
- When $\Delta_{41} \ll \Delta_{31}$, and for $\delta_{24} = \pi$, a cancellation of the oscillation amplitud happens for certain values of θ_{24} and θ_{34}:
  $|U_{s3}|^2 \approx 0$

Cancellations will impact our analysis results, as it will be shown later.

Outline

Simulation and analysis strategy

- We assume that no sterile oscillations have taken place at the ND.
- Then one should look for a depletion in the number of NC events at the FD with respect to the (3-flavor) prediction.

- Signal:

$$\begin{aligned} N_{NC} &= N_{NC}^{e} + N_{NC}^{\mu} + N_{NC}^{\tau} \\ &= \phi_{\nu_\mu}\, \sigma_{\nu}^{NC} \left\{ P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau) \right\} \\ &= \phi_{\nu_\mu}\, \sigma_{\nu}^{NC} \left\{ 1 - P(\nu_\mu \to \nu_s) \right\} , \end{aligned}$$

- Background:
  $\nu_{e,\mu,\tau}$-CC events potentially misidentified as NC events.

Therefore, ‘good’ discrimination power between neutral-current and charged-current events is required!

DUNE neutrino oscillation experiment is therefore a good place to look for the ‘depletion‘ of NC events at FD.

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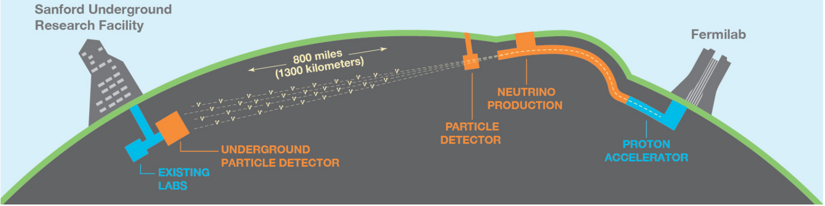
Matter effects were included in the sensitivity analysis!

Simulation and analysis strategy



- Energy reconstruction:
  - Signal: Migration matrix accounts for the correspondence between a given incident neutrino energy and the amount of visible energy deposited in the detector. V. De Romeri et. al. arxiv:1607.00293
  - BG: Gaussian energy resolution function, following the DUNE CDR values. T. Alion et. al. arxiv:1606.09550
- Efficiencies:
  - Signal: A flat 90% efficiency was assumed as a function of E_{rec}.
  - BG: Rejection efficiency at the level of 90%, except for taus (irreducible bg).
- Systematical errors (implemented as nuisance parameters ζ):
  - Signal: Total normalization (norm) and shape uncertainty.
  - BG: Total normalization.

ζ parameters are taken to be uncorrelated between ν and $\bar{\nu}$ channels as well as between the different contributions to the signal and/or background events.

Outline

First analysis, constraining the tau-sterile mixing

Let us consider the simpler case of having only a non-trivial tau-sterile mixing:

$$P_{\mu s}(\theta_{24} \to 0) = c_{13}^4 \sin^2 2\theta_{23} s_{34}^2 \sin^2 \Delta_{31} .$$

$\theta_{24} \to 0$ case: $P_{\mu s}$ is Δm_{41}^2-independent $\to$ no effect on the ND.

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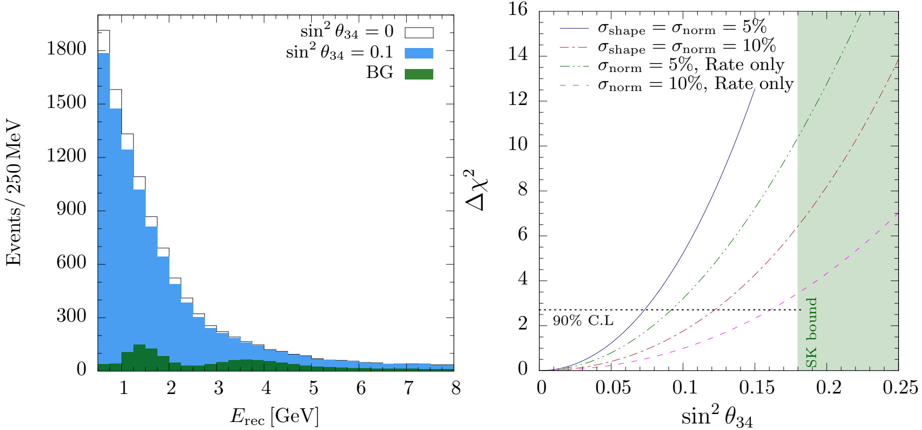

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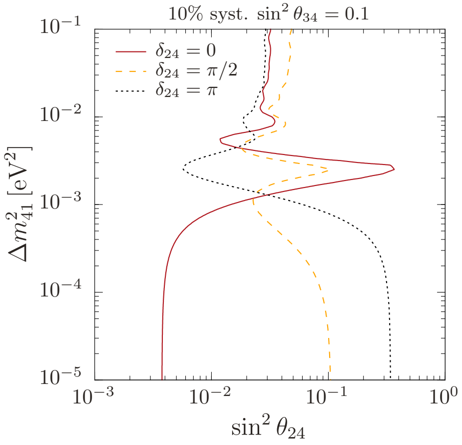
At FD the oscillation is driven by the atmospheric scale. So, a clean constraint on θ_{34} can be obtained!

Second analysis, rejecting the three-family hypothesis



Three oscillation regimes:

- $\Delta_{41} \gg \Delta_{31}$
- $\Delta_{41} \approx \Delta_{31}$

  $$P_{\mu s} = 4\left|U^*_{\mu 4}U_{s4} + U^*_{\mu 3}U_{s3}\right|^2 \sin^2\Delta_{31}$$

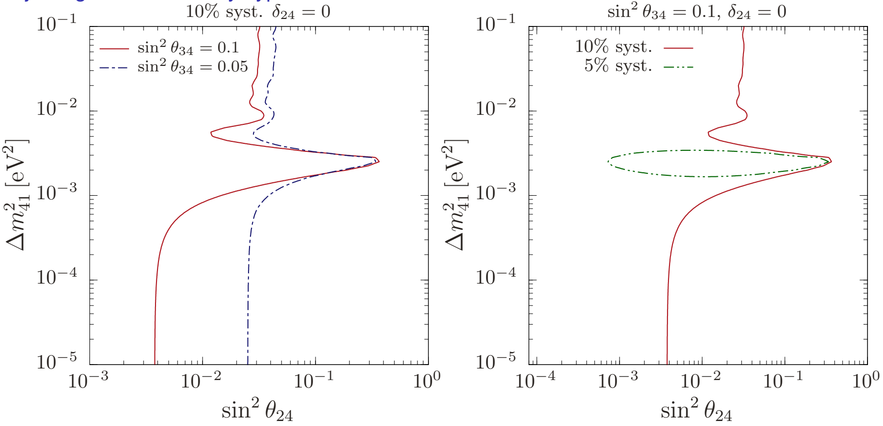
  Cancellations: For $\delta_{24} = 0$, when $\left|U^*_{\mu 4}U_{s4} + U^*_{\mu 3}U_{s3}\right|^2 \approx 0$
- $\Delta_{41} \ll \Delta_{31}$

  $$P_{\mu s} = 4|U_{\mu 3}|^2|U_{s3}|^2 \sin^2\Delta_{31}$$

  Cancellations: For $\delta_{24} = \pi$, when $|U_{s3}|^2 \approx 0$

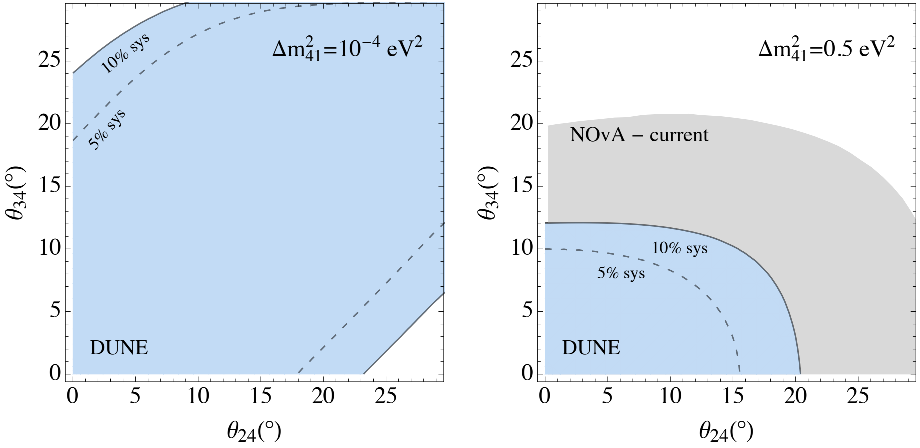
Second analysis

Rejecting the three-family hypothesis



- Left panel: In the region where $\Delta m^2_{41} \ll \Delta m^2_{31}$ there is a strong dependence of the results with the true value of θ_{34}.
- Right panel: For 5% syst. a successful rejection of the three-family hypothesis in practically all the parameter space (except in the region $\Delta_{41} \approx \Delta_{31}$) is obtained.

Third analysis, testing the 4-flavor hypothesis



- Left panel: In the $\Delta_{41} \ll \Delta_{31}$ regime, $P_{\mu s} = 4|U_{\mu 3}|^2|U_{s3}|^2 \sin^2 \Delta_{31}$
  Cancellations: For $\delta_{24} = \pi$, when $|U_{s3}|^2 \approx 0$
- Right panel: In the $\Delta_{41} \gg \Delta_{31}$ regime, almost no δ_{24} impact, and therefore no cancellations.

Outline

Conclusions

- We have derived the ν_s app. oscillation prob in vacuum and studied it in different regimes focusing in CP-violating effects due to the new phases, and we found that for some of its values, and in a given oscillation regime, cancellations in the osc. amplitude can be produced.
- Taking advantage of the excellent capabilities of liquid Argon to discriminate between CC and NC events, we have perform three different studies considering sterile neutrino oscillations (in the 3+1 scheme) at the DUNE FD by the use NC events.

- Given the current and future limits on the θ_{14}, θ_{24} sterile-active mixing angles, the case $\theta_{24} = \theta_{14} = 0$ becomes relevant by the time DUNE will be running.
  - In this case, the ν_s app. prob. is independent of Δm^2_{41} and δ_{24}, providing a unique sensitivity to the tau-sterile mixing angle.
  - Assuming 10% systematics, DUNE will be sensitive to values of $\sin^2\theta_{34} \sim 0.12$ (at 90% CL) improving the current constraints. If systematic errors could be reduced down to 5%, the experimental sensitivity would reach $\sin^2\theta_{34} \sim 0.07$ (at 90% CL).

Conclusions

- Rejection of the three family hypothesis:
  - For $\theta_{24} \neq 0$, strong cancellations in the probability can take place for certain values of δ_{24} and Δm^2_{41}. We found that the sensitivity of the experiment to the presence of a sterile neutrino depends heavily on the value of the new CP phase.
- Testing the 4-flavor hypothesis:
  - For $\Delta m^2_{41} \gg \Delta m^2_{31}$ we find that DUNE would be able to improve over NOvA constraints in this place by a factor of two or more (depending on assumed systematics).
  - In the case of $\Delta m^2_{41} \ll \Delta m^2_{31}$ the experimental results would allow values of θ_{24} and θ_{34} to be as large as 30°. The reason is, again, the possibility of having a strong cancellation in the oscillation probability.

THANK YOU

Back up

- $\Delta_{41} \ll \Delta_{31}$:

$$P_{\mu s} = 4|U_{\mu 3}|^2|U_{s3}|^2 \sin^2 \Delta_{31}$$

$$= 2c_{13}^4 s_{23}^2 c_{24}^2 \left[2c_{23}^2 s_{34}^2 + \sin 2\theta_{23} \sin 2\theta_{34} s_{24} \cos \delta_{24} + 2s_{23}^2 s_{24}^2 c_{34}^2\right] \sin^2 \Delta_{31} .$$

- $\Delta_{41} \approx \Delta_{31}$:

$$P_{\mu s} = 4\left|U_{\mu 4}^* U_{s4} + U_{\mu 3}^* U_{s3}\right|^2 \sin^2 \Delta_{31}$$

$$= 4\left\{|U_{\mu 4}|^2|U_{s4}|^2 + |U_{\mu 3}|^2|U_{s3}|^2 + 2\,\mathrm{Re}[U_{\mu 4}^* U_{s4} U_{\mu 3} U_{s3}^*]\right\} \sin^2 \Delta_{31}$$

$$= \Big\{c_{13}^4 \sin^2 2\theta_{23} c_{24}^2 s_{34}^2 + c_{34}^2 \sin^2 2\theta_{24}(1 - c_{13}^2 s_{23}^2)^2$$
$$- c_{13}^2 c_{24} \sin 2\theta_{23} \sin 2\theta_{24} \sin 2\theta_{34}(1 - c_{13}^2 s_{23}^2) \cos \delta_{24}\Big\} \sin^2 \Delta_{31} .$$

- $\Delta_{41} \gg \Delta_{31}$:

$$
\begin{aligned}
P_{\mu s} &= 2\,|U_{\mu 4}|^2 |U_{s4}|^2 + 4\left\{|U_{\mu 3}|^2|U_{s3}|^2 + \mathrm{Re}[U_{\mu 4}^* U_{s4} U_{\mu 3} U_{s3}^*]\right\} \sin^2\Delta_{31} \\
&\qquad + 2\,\mathrm{Im}[U_{\mu 4}^* U_{s4} U_{\mu 3} U_{s3}^*] \sin 2\Delta_{31} \\
&= \frac{1}{2} c_{34}^2 \sin^2 2\theta_{24} \\
&\qquad + \Big[c_{13}^4 \sin^2 2\theta_{23} c_{24}^2 s_{34}^2 - c_{13}^2 s_{23}^2 (1 - c_{13}^2 s_{23}^2) c_{34}^2 \sin^2 2\theta_{24} \\
&\qquad - c_{13}^2 c_{23} \sin 2\theta_{23} \sin 2\theta_{24} \sin 2\theta_{34} \left(\frac{1}{2} - c_{13}^2 s_{23}^2\right) \cos\delta_{24} \Big] \sin^2\Delta_{31} \\
&\qquad - \frac{1}{4} c_{13}^2 c_{24} \sin 2\theta_{23} \sin 2\theta_{24} \sin 2\theta_{34} \sin\delta_{24} \sin 2\Delta_{31} .
\end{aligned}
$$