Beyond Standard Neutrino Oscillations at DUNE

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1. Introduction
2. First example
3. Second example
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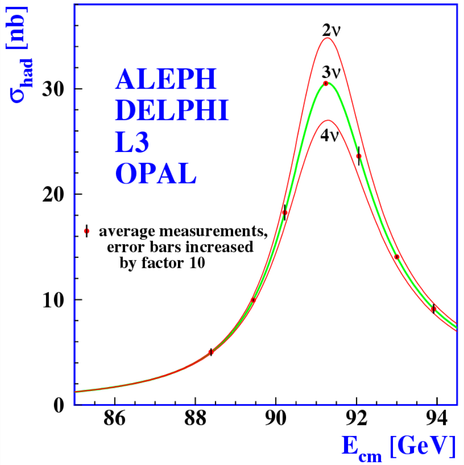
Introduction

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 can't couple to SM gauge bosons, so they have to be sterile!

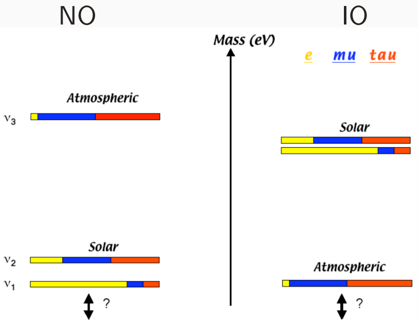
- 'Light' sterile neutrino(s) with $\Delta m^2 \sim 1\text{eV}^2$ are motivated by SBL anomalies.
  - One economical extension is to introduce one extra sterile neutrino, 3+1 framework.
- 'Heavy' sterile neutrino(s), spanning several energy-scales, are predicted in neutrino mass models (and in connection with DM).
  - If directly produced, they might be detected at beam-dump facilities or at NDs of neutrino experiments.
  - If too heavy, the lepton mixing matrix is not longer unitary and small deviation from unitarity is expected.

Three-active neutrino oscillations

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U^*_{\alpha k}|\nu_k\rangle, \; \alpha = e, \mu, \tau.$$

U, assumed to be unitary, can be parametrized in the form:

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \overbrace{\underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Reactor}}}^{\text{Atm.}-\text{Solar Interference}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}}$$



- Six oscillation parameters: $\theta_{ij}, \delta, \Delta m^2_{21}, \Delta m^2_{31}$, and two possible mass orderings: NO or IO.

Three-active neutrino oscillations

Parameter dependency

- 2-ν: $\boxed{P_{\alpha\alpha} = 1 - \sin^2(2\theta)\,\sin^2(\phi_{\rm osc})}$ with $\phi_{\rm osc} \equiv \frac{\Delta m^2\, L}{4\, E} = 1.27\,\frac{\Delta m^2[eV^2]\, L[km]}{E[GeV]}$
- $\Delta m^2_{jk} \equiv m_j^2 - m_k^2$ sensitivity range depends on L/E.
- Two mass squared differences in Nature: $\Delta m^2_{\rm sol.}$ and $\Delta m^2_{\rm atm.}$.

Three-active neutrino oscillations

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Channel	Baseline	Energy	Experiment
$\nu_e \to \nu_x$	$\sim 10^8$ km	$\sim$MeV	Solar
$\bar{\nu}_e \to \bar{\nu}_e$	~ 200 km	$\sim$MeV	Reactor: KamLAND
$\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$	$20 - 10^4$ km	0.5-10^2 GeV	Atmospheric
$\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$	295(735, 810) km	$\sim$ GeV	LBL: T2K(MINOS,NOvA)
$\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)$			
$\bar{\nu}_e \to \bar{\nu}_e$	~ 1 km	$\sim$MeV	Reactors: DC,RENO,Daya Bay

Three-active neutrino oscillations

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- $\Delta m^2_{jk} \equiv m_j^2 - m_k^2$ sensitivity range depends on L/E.
- Two mass squared differences in Nature: $\Delta m^2_{\rm sol.}$ and $\Delta m^2_{\rm atm.}$.

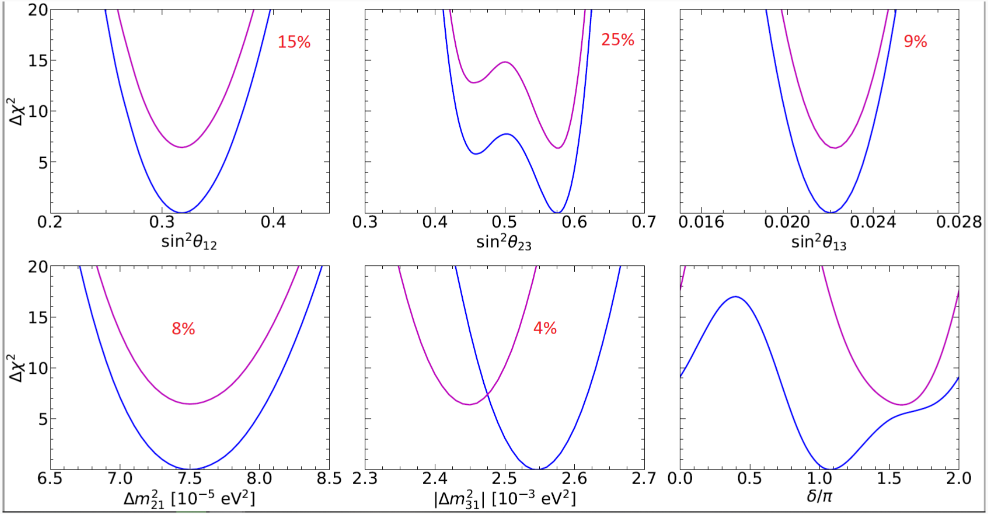
Channel	Experiment	Main	Other
$\nu_e \to \nu_x$	Solar	θ_{12}	Δm^2_{21}, θ_{13}
$\bar\nu_e \to \bar\nu_e$	Reactor: KamLAND	Δm^2_{21}	θ_{12}, θ_{13}
$\nu_\mu(\bar\nu_\mu) \to \nu_e(\bar\nu_e)$	Atmospheric	θ_{23}	Δm^2_{31}, θ_{13}, δ
$\nu_\mu(\bar\nu_\mu) \to \nu_e(\bar\nu_e)$	LBL: T2K(MINOS,NOvA)	θ_{13}	δ, θ_{23}
$\nu_\mu(\bar\nu_\mu) \to \nu_\mu(\bar\nu_\mu)$	LBL: T2K(MINOS,NOvA)	Δm^2_{31}, θ_{23}	
$\bar\nu_e \to \bar\nu_e$	Reactors: DC,RENO,Daya Bay	θ_{13}	Δm^2_{31}

3ν-Oscillation framework

Global fit

3σ

P. F. de Salas, DVF, et. al. arxiv:2006.11237



List of questions

Directly related to neutrino oscillations

Related to the standard physics program:

- Is the lepton mixing matrix a unitary matrix?
- Do leptons violate the charge-parity (CP) symmetry and to which extent?
- What is the correct neutrino mass ordering?
- Is the value of the atmospheric mixing angle maximal i.e. $(\pi/4)$? If not, is it $< \pi/4$ or $> \pi/4$?

Beyond the standard physics program:

- Are there sterile neutrinos and what is their mass-scale?
- Is it possible that neutrinos have other interactions than the ones predicted in the SM?
- Are there other sources of CP violation?

To shed light on this questions, future facilities are being built and DUNE is certainly going to play an important role. In the following, two examples of the DUNE potential to probe some BSM scenarios will be presented.

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The case of one light sterile state

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: P. Coloma, DVF & S. Parke arxiv:1707.05348

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

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

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

- 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}.

Notation: $\Delta m^2_{jk} L/(4E) \equiv \Delta_{jk}$.

The main concept

By probability conservation we know $\sum_\alpha P_{\mu\alpha} = 1$ or

$$\sum_{\alpha=e,\mu,\tau} P_{\mu\alpha} = 1 - P_{\mu s}\,,$$

So, in the presence of s the $\sum_\beta P^{3\nu}_{\mu\beta} < 1$! Which is something that is experimentally exploited (NC measurements).

Working assumptions:

- We consider the sterile appearance channel, $P(\nu_\mu \to \nu_s)$.
- For simplicity, and without losing generality, we consider $\theta_{14} = 0$ [*]. This assumption implies that 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!
[*] $|U_{e4}|^2 < 0.041$ at 90% C.L, from 'solar+KamLAND' plus 'Daya Bay+RENO', for $\Delta m^2 \sim 1\,\text{eV}^2$. A. Palazzo arxiv:1302.1102

Prior studies

Besides SBL experiments, an sterile oscillation can be tested at the FD of LBL 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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Constraints from atmospheric neutrinos: K. Abe et. al. arxiv:1410.2008

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

M. G. Aartsen et. al. arxiv:1702.05160

- No evidence of sterile oscillations is seen (IceCube) $\rightarrow |U_{\mu 4}|^2 < 0.11$ and $|U_{\tau 4}|^2 < 0.15$ for $\Delta m^2 = 1\,$eV^2 at the 90% C.L (Assuming $|U_{e4}|^2 = 0$),

Vacuum sterile app. probability

Oscillation regimes, neglecting the Δm^2_{21} contribution

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

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

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

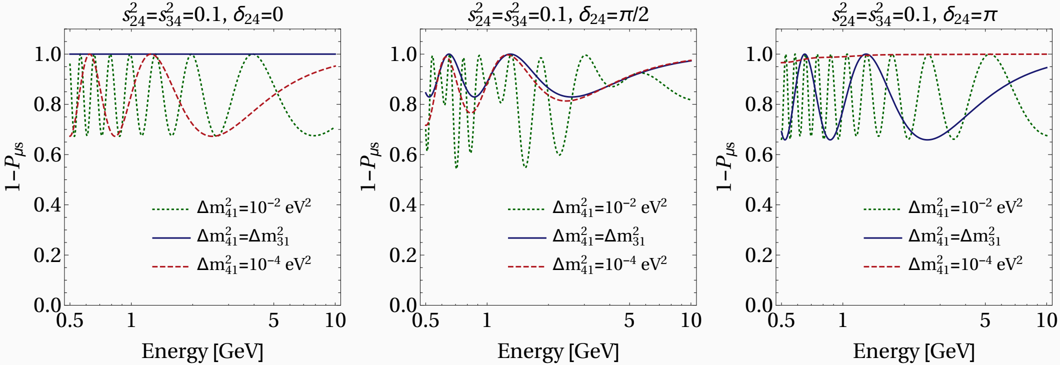
- $\Delta_{41} \approx \Delta_{31}$, sterile matches the 3-flavor oscillation phase:

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

- $\Delta_{41} \gg \Delta_{31}$, 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 amplitude happens for certain values of θ_{24} and θ_{34}: $|U_{\mu 4}^* U_{s4} + U_{\mu 3}^* U_{s3}|^2 \approx 0$ (left panel).
- When $\Delta_{41} \ll \Delta_{31}$, and for $\delta_{24} = \pi$, a cancellation of the oscillation amplitude happens for certain values of θ_{24} and θ_{34}: $|U_{s3}|^2 \approx 0$ (right panel).

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

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:

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

- 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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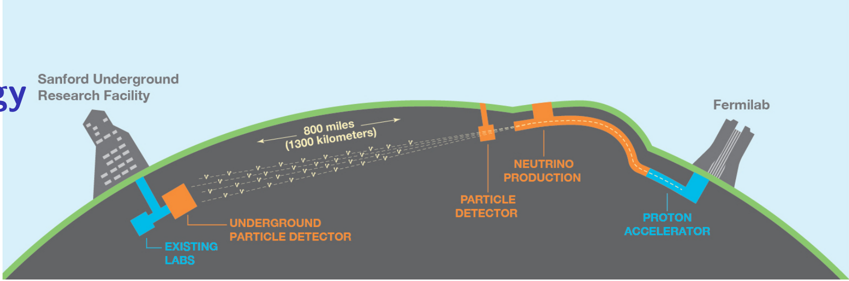
Matter effects were included in the sensitivity analysis!

Simulation and analysis strategy



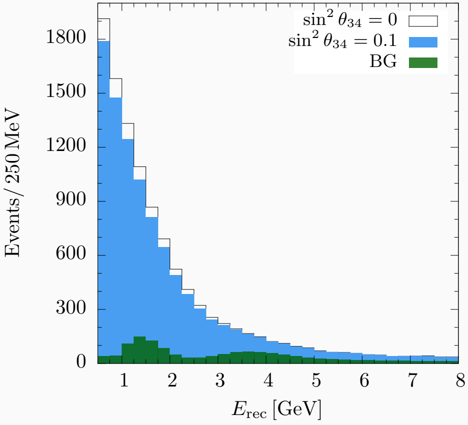
- Energy reconstruction:
  - Signal: Migration matrix accounts for the correspondence between a given incident neutrino energy and the amount of visible energy deposited in the detector. V. De Romeri et. al. arxiv:1607.00293
  - BG: Gaussian energy resolution function, following the DUNE CDR values. T. Alion et. al. arxiv:1606.09550
- Efficiencies:
  - Signal: A flat 90% efficiency was assumed as a function of $E_{\rm rec}$.
  - 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.

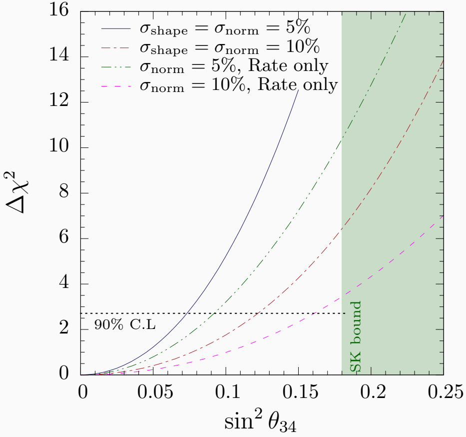
ζ parameters are taken to be uncorrelated between ν and $\bar{\nu}$ channels as well as between the different contributions to the signal and/or background events.

First analysis, constraining the tau-sterile mixing

Only a non-trivial tau-sterile mixing

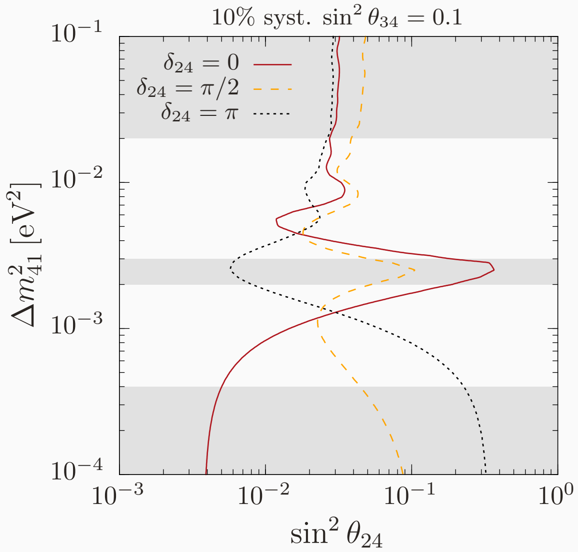
$P_{\mu s}(\theta_{24} \to 0) = c_{13}^4 \sin^2(2\theta_{23}) s_{34}^2 \sin^2 \Delta_{31}$, so Δm_{41}^2-independent $\Rightarrow$ no effect on the ND.





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: $\left|U^*_{\mu 4}U_{s4} + U^*_{\mu 3}U_{s3}\right|^2 \approx 0$ when $\delta_{24} = 0$,

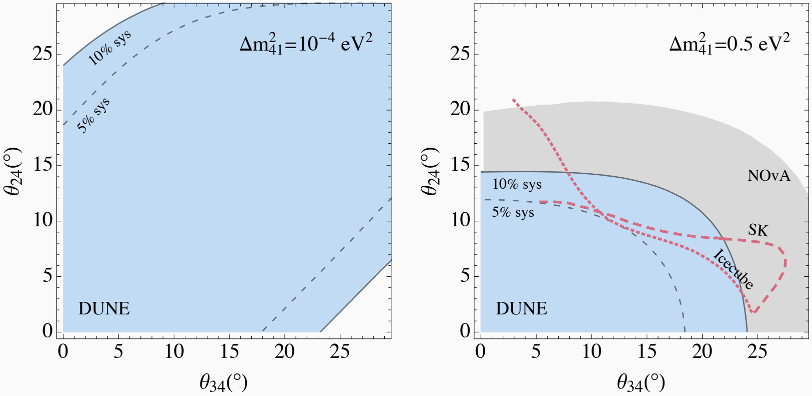
- $\Delta_{41} \ll \Delta_{31}$

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

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

Third analysis, testing the 4-flavor hypothesis

Minimizing over δ_{24}

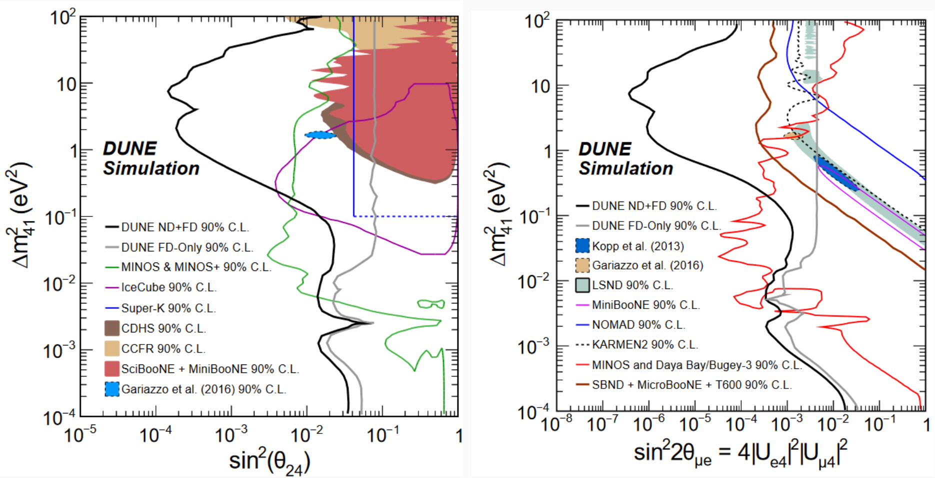


- Left panel: In the $\Delta_{41} \ll \Delta_{31}$ regime, $P_{\mu s} = 4|U_{\mu 3}|^2|U_{s3}|^2 \sin^2 \Delta_{31}$
  Cancellations: For $\delta_{24} = \pi$, when $|U_{s3}|^2 \approx 0$
- Right panel: In the $\Delta_{41} \gg \Delta_{31}$ regime, almost no δ_{24} impact, and therefore no cancellations.

Other efforts

Includding CC information

DUNE TDR arxiv:2002.03005



A. Sousa, E. Fernandez-M, M. Blennow & S. Rosauro, as part of the DUNE BSM Physics WG

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 performed 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.
  - 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.

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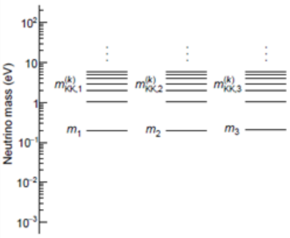
Motivation

- From the model point of view:
  - Extra space-time dimensions were originally introduced to "alleviate" the so called hierarchy problem, i.e. the large difference between the electroweak and the GUT (or even the Planck) energy scales.
  - Models with large extradimensions can also accommodate non-zero neutrino masses, specifically, of the Dirac type which are naturally small.
- From the phenomenological point of view:
  - The LED model (Davoudiasl et. al. 2002) turns out to be pretty testable at neutrino oscillation experiments (Machado et. al. 2011).
  - MINOS (2016) experiment set a constrain to the LED compactification radius to $R < 0.45\,\mu m$ at 90% of C.L. when the lightest neutrino mass $m_0 \to 0$.

Main consequences

LED model (Davoudiasl et. al 2002) :

- In this model, three bulk right-handed neutrinos coupled (via Yukawas's) to the three active brane neutrinos.
- After compactification of the effective extra dimension, from the four dimensional (brane) point of view, the right-handed neutrino appears as an infinite tower of sterile neutrinos or Kaluza-Klein modes.



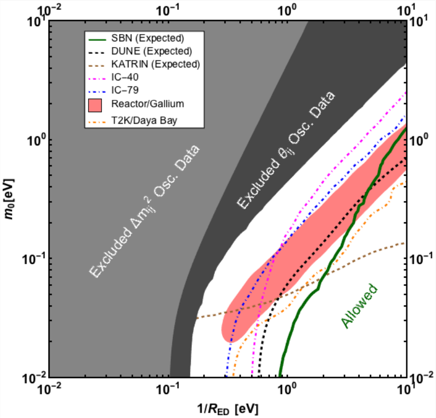
Phenomenological consequences:

- The sterile-active mixings and the new oscillation frequencies modify the active 3ν-oscillations therefore distorting the neutrino event energy spectrum.
- Departures from the standard oscillations due to the existence of LED can then be probed at neutrino oscillation experiments (Long & Short baselines).

Prior studies

At neutrino oscillation experiments

- SBN program: G. Stenico, DVF & O.L.G Peres arxiv:1808.05450



- DUNE FD-only: Berryman et. al. arxiv:1603.00018
- IceCUBE: A. Esmaili et. al. arxiv:1409.3502
- Daya Bay & T2K data: Di Lura et. al. arxiv:1411.5330
- Reactor anomaly: P.A.M Machado et. al. arxiv:1107.2400

So far, MINOS is the only experimental collaboration that has constrained R with data. Thus, MINOS sensitivity will be our reference.

Vacuum probabilities

Three-active neutrino oscillation probability:

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_{k=1}^{3} U_{\alpha k}^{*} U_{\beta k} \exp\left(-i \frac{m_k^2}{2E}\right) \right|^2$$

LED oscillation probability, n-KK modes:

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_{k=1}^{3} \sum_{n=0}^{\infty} U_{\alpha k}^{*} U_{\beta k} \left(L_k^{0n}\right)^2 \exp\left(-i \frac{\left(\lambda_k^{(n)}\right)^2}{2ER^2}\right) \right|^2$$

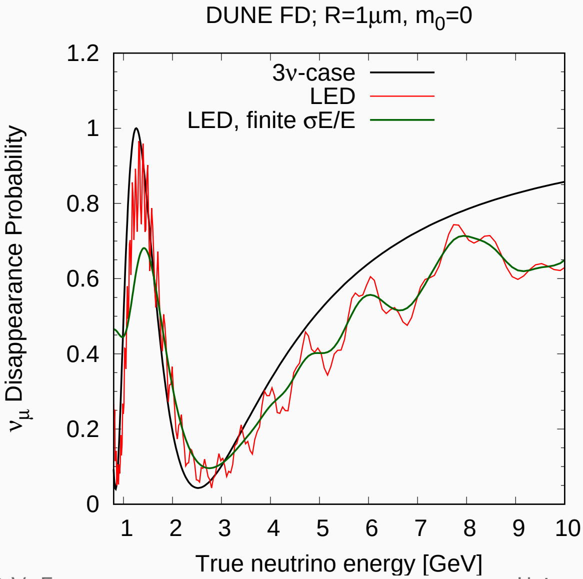
& $\lambda_k^{(n)}$ is obtained from $\boxed{\lambda_k^{(n)} - \pi (m_k^D R)^2 \cot(\pi \lambda_k^{(n)}) = 0}$ with $\boxed{\lambda_k^{(n)} \in [n, n+1/2]}$. We can then make the identification:

$$\boxed{m_k^{(n)} = \frac{\lambda_k^{(n)}}{R} \overset{n \gg 1}{\to} \frac{n}{R}}, \text{ and for the 'modified' mixing } \boxed{U_{\alpha k} L_k^{0n}}$$

Four free parameters m_1^D, m_2^D, m_3^D and R in the theory.

For '$n = 0$' and '$m^D R \ll 1$', 3ν-flavor phenomenology must be satisfied.

Main features



Most active (sterile) case corresponds to $n = 0$ ($n \ll 1$). The standard 3ν-neutrino oscillations are recovered in the limit $R \to 0$.

- Global reduction of survival probabilities, which is typically noticeable at high energies (Machado et. al 2011).
- Appearance of modulations and fast oscillations to Kaluza-Klein states.
- These shape-like features can be exploited at the analysis level. This have been done in MINOS (2016).
- Sensitivity analyses for several osc. Exps (Machado et. al 2011), IceCube (Esmaili et. al. 2014), DUNE (Berryman et. al 2016... "revamped" for DUNE FD TDR & ND CDR), and SBN (Stenico 2018).

DUNE setup

$40kt \times (3.5yr(\nu) + 3.5yr(\bar{\nu})) \times 1.07MW = 300\ kt\ MW\ years$ of exposure

Information considered in the analysis:

- Signal: CC, ν and $\bar{\nu}$, appearance and disappearance oscillation channels included in the analysis.
- Only FD information is considered, but ND fixes the flux normalization.

Systematics

T. Alion et. al. arxiv:1606.09550 $\rightarrow$ Same level in most recent 'glb' GLoBES file.

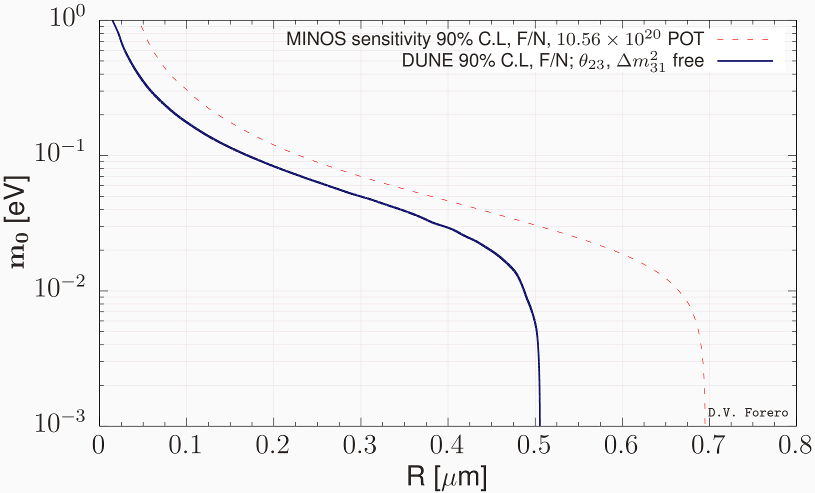
- Signal normalization systematical errors:
  $\sigma(\nu_e) = 0.02$, $\sigma(\bar{\nu}_e) = 0.02$, $\sigma(\nu_\mu) = 0.05$, $\sigma(\bar{\nu}_\mu) = 0.05$.
- Background normalization systematical errors:
  $\sigma(\nu_\mu) = 0.05$, $\sigma(\nu_e) = 0.05$, $\sigma(\nu_\tau) = 0.2$, $\sigma(\bar{\nu}_e) = 0.05$ & $\sigma(NC_{dis}) = 0.1$.

Fluxes

- The "Optimized Engineered Nov2017".

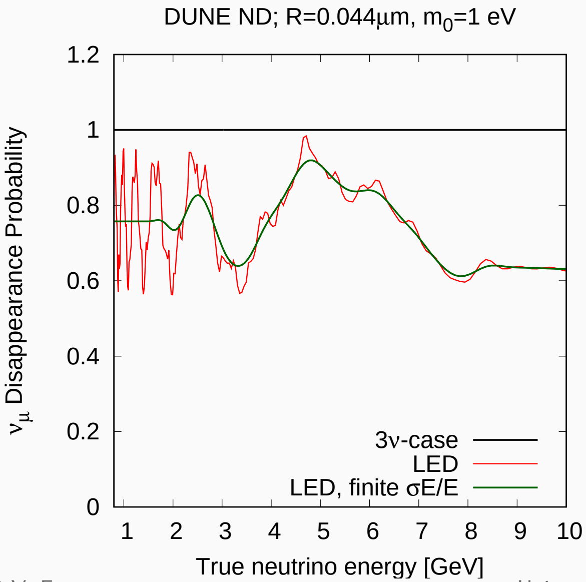
DUNE Sensitivity to LED; 300 kt MW years of exposure

DUNE TDR arxiv:2002.03005



Thanks to S. De Rijck we can show MINOS sensitivity result (Asimov data).

How sensitive is the ND?



- Reduction of survival probability, noticeable departure from 1.
- Appearance of modulations and fast oscillations to Kaluza-Klein states.
- These shape-like features can be exploited at the analysis level.

Using ND information

mass=67.2Tons; baseline=575m

Information considered in the analysis:

- Signal: CC, ν and $\bar{\nu}$, appearance and disappearance oscillation channels included in the analysis.
- Only ND information is considered.

Systematics See sterile section in TDR

Type of error	Value	affects	ND/FD correlated?
ND fiducial vol.	0.01	all ND events	no
FD fiducial vol.	0.01	all FD events	no
flux signal component	0.08	all events from signal comp.	yes
flux background component	0.15	all events from bckg comp.	yes
flux signal component n/f	0.004	all events from signal comp. in ND	no
flux background component n/f	0.02	all events from bckg comp. in ND	no
CC cross section (each flav.)	0.15	all events of that flavour	yes
NC cross section	0.25	all NC events	yes
CC cross section (each flav.) n/f	0.02	all events of that flavour in ND	no
NC cross section n/f	0.02	all NC events in ND	no

Table I. List of systematic errors assumed in the analysis.

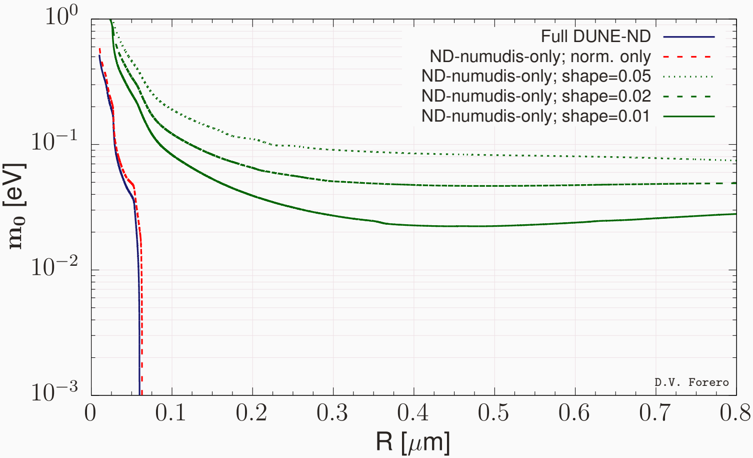
Fluxes

- The "Optimized Engineered Nov2017" for ND.

DUNE Sensitivity to LED

ND-only

DUNE ND CDR

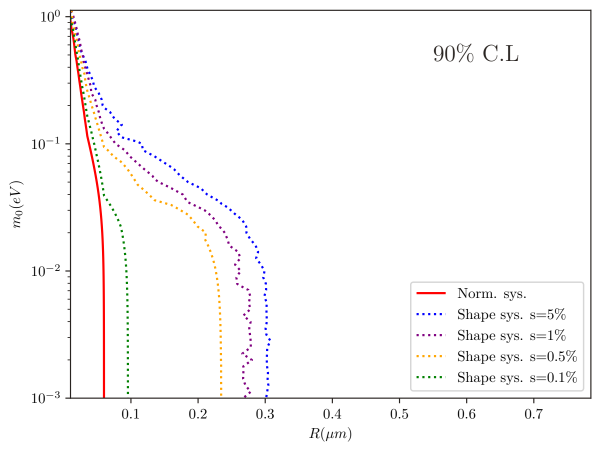


In coll. with A. Sousa, E. Fernandez-M, M. Blennow & S. Rosauro, as part of the DUNE BSM Physics WG

Towards a two-detector fit

Preliminary results for $n = 2$

Includding a shape-like systematic error in the signal (uncorrelated between detectors) in the ND.



In coll. with A. Sousa, E. Fernandez-M, M. Blennow & S. Rosauro, as part of the DUNE BSM Physics WG

Summary

- The LED model (Davoudiasl et. al 2002) turns out to be pretty testable at neutrino oscillation experiments.
- Neutrino oscillations within this LED model provide unique features that can be explored in parallel to the search for a sterile neutrino oscillation at the eV energy-scale in the economical '3+1' scenario.
- Long-baseline experiments detecting neutrinos at high energies, and with a percent-level energy resolution, are good candidates for LED probes.
- In particular, combining information from near and far detectors allows to probe lighter and heavier KK modes simultaneously. Therefore, a two-detector analysis with realistic systematics is very promising for future LED searches.
- Neutrino oscillation experiments provide a competitive, model independent constrain to R, which is complementary to other searches, for instance in neutrinoless double beta decay experiments, in core collapse supernovae, at colliders like the LHC, and in kinematical tests (Basto et. al 2012).

Outline

1 Introduction

2 First example

3 Second example

4 Final remarks

Final remarks

- Other BSM searches, not included in this talk, and carried out in the DUNE BSM working group can be found at DUNE TDR arxiv:2002.03005, Arguelles et. al. arxiv:1907.08311:
  - Non-standard Neutrino Interactions
  - BSM physics with tau neutrinos
  - Non-unitarity
  - Lorentz violation
  - Neutrino decay
  - Dark Matter searches.
- In the precision era, future neutrino experiments will be a powerfull tool to probe some BSM scenarios, as has been shown in the case of DUNE.
- We need to include all systematics, as realistic as possible, in the analysis to obtain valid conclusions.
- Theorist/phenomenologist and experimentalist should continue working together, finding common tools to accomplist the physics goals.

Thank you for your attention!

Back up

A comment on the degrees of freedom

Possible approaches

MINOS Approach:

- m_1^D, m_2^D, m_3^D and R are free parameters.
- Do not assume Δm^2_{j1} to be known, so they are free.
- This is the correct approach for a single experiment without considering external measurements.

Alternative approach from Basto et. al. (PLB 718(2013)) arxiv:1205.6212:

(Also followed in Berryman et. al. (PRD 94(2016)) arxiv:1603.00018)

- For a given hierarchy, one can use the 'known Δm^2_{j1}' to reduce the d.o.f from 4 to 2: $m_0 \equiv m_1^D(m_3^D)$ for NO(IO) and R.
- This assume Δm^2_{j1} to be known or within some small range, for instance 1σ range from global fits or PDG.
- External measurements, added as penalties to the χ^2, can be included.

Both approaches produce the same sensitivity when Δm^2_{j1} are free in the fit, as discussed with J. Coelho & S. De Rijck from MINOS. We followed the 2^{nd} approach but the atmospheric parameters are considered free.