Exploring Light sterile $\nu$ with LBL experiments

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Outline

Introduction

Interference effects mediated by sterile neutrinos

LBL constraints on new CP phases: present

LBL constraints on new CP phases: future

Conclusions
Introduction
It is timely to pose a new question

Can sterile neutrinos generate observable CP violating effects at LBL experiments?

Question basically ignored in the past!


LBL experiments start to be sensitive to the CP violating phase $\delta$
Most probably, the discovery of sterile $\nu_s$ can come only from SBL experiments by observing the characteristic oscillation pattern and we have already some hints…
from accelerators

(unexplained $\nu_e$ appearance in a $\nu_\mu$ beam)
from reactor rates and solar calibration

(unexplained $\nu_e$ disappearance)


SAGE coll., PRC 73 (2006) 045805
...and recently also from reactor spectra

**NEOS** arXiv:1610:05134

\[ \chi^2_{4\nu} - \chi^2_{3\nu} = -6.5 \]

**DANSS** arXiv:1804:04046

\[ \chi^2_{4\nu} - \chi^2_{3\nu} = -13.1 \]

Best fit points very similar: \((\sin^2 2\theta, \Delta m^2) \approx (0.05, 1.4\text{eV}^2)\)
However, SBL have an intrinsic limitation

At SBL atm/sol oscillations are negligible

\[
\frac{L}{E} \sim \frac{m}{\text{MeV}} \quad \Delta_{12} \simeq 0 \quad \Delta_{13} \simeq 0
\]

Impossible to observe phenomena of interference between the new frequency (\(\Delta_{14} \sim 1\)) and atm/sol ones

\[
\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}
\]

This limitation can be overcome at LBL’s…
Interference effects mediated by sterile $\nu_s$

How to enlarge the 3-flavor scheme

At LBL the effective 2-flavor SBL description is no more valid and calculations should be done in the 3+1 (or 3+N_s) scheme.

\[ \Delta m_{atm}^2 \]
\[ \Delta m_{sol}^2 \]

3ν scheme

3+1 scheme

\[ |U_{s4}| \sim 1 \]
\[ \Delta m_{14}^2 \sim 1 \text{ eV}^2 \]
Mixing Matrix in the 3+1 scheme

\[ U = \tilde{R}_{34} \ R_{24} \ \tilde{R}_{14} \ R_{23} \ \tilde{R}_{13} \ R_{12} \]

\[ R_{ij} = \begin{bmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{bmatrix} \quad \tilde{R}_{ij} = \begin{bmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}_{ij}^* & c_{ij} \end{bmatrix} \quad s_{ij} = \sin \theta_{ij} \]

\[ c_{ij} = \cos \theta_{ij} \quad \tilde{s}_{ij} = s_{ij} e^{-i \delta_{ij}} \]

3\nu \left\{ \begin{array}{l} 3 \text{ mixing angles} \\ 1 \text{ Dirac phase} \\ 2 \text{ Majorana phases} \end{array} \right. \quad 3+1 \left\{ \begin{array}{l} 6 \\ 3 \end{array} \right. \quad 3+N \left\{ \begin{array}{l} 3+3N \\ 1+2N \\ 2+N \end{array} \right.

In general, we have additional sources of CPV
\[ P^{3\nu}_{\nu_{\mu}\rightarrow\nu_e} = P^{\text{ATM}} + P^{\text{SOL}} + P^{\text{INT}}. \]

**In vacuum:**

\( P^{\text{ATM}} = 4s_{23}^2 s_{13}^2 \sin^2 \Delta \)

\( P^{\text{SOL}} = 4c_{12}^2 c_{23}^2 s_{12}^2 (\alpha \Delta)^2 \)

\( P^{\text{INT}} = 8s_{23}s_{13}c_{12}c_{23}s_{12}(\alpha \Delta) \sin \Delta \cos(\Delta + \delta_{CP}) \)

\[ \Delta = \frac{\Delta m_{31}^2 L}{4E}, \quad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \]

\[ \Delta \sim \pi/2 \]

\[ \alpha \sim 0.03 \]

- **\( P^{\text{ATM}} \)** leading \( \Rightarrow \theta_{13} > 0 \)
- **\( P^{\text{INT}} \)** subleading \( \Rightarrow \) dependency on \( \delta \)
- **\( P^{\text{SOL}} \)** negligible

**T2K osc. maximum** \( E = 0.6 \text{ GeV} \)

\[ \sin 2\theta_{13} \]

- best \( \theta_{13} \) estimate
A new interference term in the 3+1 scheme


- $\Delta_{14} \gg 1$ : fast oscillations are averaged out

- But interference of $\Delta_{14}$ & $\Delta_{13}$ survives and is observable

$$P_{\mu e}^{4\nu} \simeq P_{\text{ATM}} + P_{\text{INT}}^I + P_{\text{INT}}^II$$

$$P_{\text{ATM}} \simeq 4s_{23}^2 s_{13}^2 \sin^2 \Delta$$

$$P_{\text{INT}}^I \simeq 8s_{13}s_{23}c_{23}s_{12}c_{12}(\alpha \Delta) \sin \Delta \cos(\Delta + \delta_{13})$$

$$P_{\text{INT}}^II \simeq 4s_{14}s_{24}s_{13}s_{23} \sin \Delta \sin(\Delta + \delta_{13} - \delta_{14})$$

$S_{13} \sim S_{14} \sim S_{24} \sim 0.15 \sim \varepsilon$

$\alpha = \frac{\delta m^2}{\Delta m^2} \sim 0.03 \sim \varepsilon^2$

Sensitivity to the new CP-phase $\delta_{14}$

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Amplitude of the new interference term

\[
\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2
\]

T2K
\[\theta_{13} = 9^\circ\]
E = 0.6 GeV

Numerical examples of 4ν probability

The fast oscillations get averaged out due to the finite energy resolution

The modifications induced by $\delta_{14}$ are almost as large as those induced by the standard CP-phase $\delta_{13}$

Consequences...
LBL constraints on sterile vs: present

arXiv:1503.03966

A.P., PLB 757, 142 (2016)
arXiv:1509.03148

Capozzi, Giunti, Laveder & A.P.,
PRD 95 (2017)
arXiv:1612.07764
LBL constraints change in the 3+1 scheme

- The level of (dis-)agreement of LBL & Rea. depends on $\delta_{14}$

- In this analysis $\theta_{14}$ and $\theta_{24}$ are fixed at the SBL best fit values

- These results call for a more refined analysis …
Joint SBL and LBL constraints on $[\theta_{14}, \theta_{24}, \delta_{14}]$

- $[\theta_{14}, \theta_{24}]$ determined by SBL experiments
- $\delta_{14}$ constrained by LBL experiments
Constraints on the two CP-phases

- $\delta_{13}$ is more constrained than $\delta_{14}$
- **Best fit values**: $\delta_{13} \sim \delta_{14} \sim -\pi/2$
- This information cannot be extracted from SBL alone!

PRD (2017)

SBL + LBL

![Graph showing constraints on two CP-phases](image-url)
Impact of sterile neutrinos on $\theta_{23}$

**Indication for non-maximal $\theta_{23}$ persists in 3+1 scheme**

**Preference for $\theta_{23}$ octant disappears in 3+1 scheme**

**Octant fragility seems to be a general feature (see later)**
Looking to the future


arXiv: 1607.01745 (PLB 2016)
arXiv: 1801.04855 (JHEP 2018)
- Sensitivity to CPV induced by $\delta_{13}$ reduced in 3+1 scheme
- Potential sensitivity also to the new CP-phases $\delta_{14}$ e $\delta_{34}$
- Clear hierarchy in the sensitivity: $\delta_{13} > \delta_{14} > \delta_{34}$ for $\theta_{14} = \theta_{24} = \theta_{34} = 9^0$
Reconstruction of the CP phases in DUNE

\[ \delta_{13} \text{ (test) [degree]} \]

\[ \delta_{14} \text{ (test) [degree]} \]

\[ \theta_{34} \text{ true} = \frac{\pi}{2}, \frac{3\pi}{2} \] and \[ \frac{\pi}{2}, \frac{\pi}{2} \] cases. The two confidence levels correspond to \( 2\sigma \) and \( 3\sigma \). We see that in all cases we obtain a unique reconstructed region at the \( 3\sigma \) level. The typical \( \pm \sigma \) level uncertainty on the reconstructed CP phases is approximately \( \pm \delta \). The regions in Fig. 8 should be compared with the analogous ones. Note that this is true also in the second panel, because the four corners of the square form a connected region due to the cyclic nature of the two CP-phases.
Reconstruction of the CP phases in T2HK

JHEP 2018

Figure 7: Reconstructed regions for the two CP phases $\delta_{13}$ and $\delta_{14}$ for the four benchmark pairs of their true values indicated in each panel. We have taken the NH as the true hierarchy and we have marginalized over the two possible hierarchies in the test model. The contours refer to $2\sigma$ and $3\sigma$ level.

This misreconstruction is imputable to the well-known degeneracy between $\delta_{13}$ and $\Delta m^2_{23}$. The combination of phases chosen for the third panel seems to be the most favorable one, with no misreconstructed island. This happens because in such a case the difference in the number of events for NH and IH is more pronounced and therefore there is a better discrimination of the MH (see the discussion in [1]). We have explicitly checked that if the MH is supposed to be known a priori, it is fixed and not marginalized in the fit. Therefore, our results show that in T2HK in order to have good reconstruction capabilities of the two CP phases, one needs the prior knowledge of the mass hierarchy.

We close this section by performing a comparison of the CP phase reconstruction potential of three different experimental setups: T2K, NO$\nu$A, DUNE, and T2HK. In Fig. 8, for a detailed discussion of the CP-phase reconstruction potential of T2K+NO$\nu$A and DUNE, see [2].
Discovery potential of mass hierarchy

Degradation of sensitivity but $4\sigma$ level preserved
Octant of $\theta_{23}$ in danger with a sterile neutrino

Distinct ellipses ($3\nu$) become overlapping blobs ($3+1$)

For unfavorable combinations of $\delta_{13}$ & $\delta_{14}$ sensitivity is lost
Conclusions

- Sterile neutrinos are sources of additional CPV

- Consequences for the LBL estimates of the standard parameters (MH, CP-phase $\delta$, octant of $\theta_{23}$)

- Full exploration of new CP-phase ($\delta_{14}, \delta_{34}$) possible only with LBL’s

- LBL experiments complementary to the SBL ones
Thank you for your attention!
Back up slides
CPV and averaged oscillations

\[
A_{\alpha\beta}^{\text{CP}} \equiv P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)
\]

\[
A_{\alpha\beta}^{\text{CP}} = -16J_{\alpha\beta}^{12} \sin \Delta_{21} \sin \Delta_{13} \sin \Delta_{32}
\]

if

\[
\Delta \equiv \Delta_{13} \simeq \Delta_{23} \gg 1
\]

osc. averaged out by finite E resol.

\[
\langle \sin^2 \Delta \rangle = 1/2
\]

It can be:

\[
A_{\alpha\beta}^{\text{CP}} \neq 0
\]

(if \(\sin \delta = 0\))

The bottom line is that if one of the three \(\nu_i\) is \(\infty\) far from the other two ones this does not erase CPV
(relevant for the 4\(\nu\) case)
No anomaly in $\nu_\mu$ disappearance

SBL & MINOS (NC)

IceCube

$\Delta m^2$

$3+1$ best fit

Excluded region

$\sin^2\theta_{\mu\mu}$

$\sin^22\theta_{\mu\mu}$

IceCube 99% CL Exclusions

- IC86 rate+shape
- IC86 shape only (blind result)
- IC59 result
Global SBL data fit in the 3+1 scheme

There is strong internal tension
Tension in all $\nu_s$ models

\[ \nu_\mu \rightarrow \nu_e \quad \text{positive} \]
\[ \nu_e \rightarrow \nu_e \quad \text{positive} \]
\[ \nu_\mu \rightarrow \nu_\mu \quad \text{negative} \]

\[ |U_{e4}| |U_{\mu4}| > 0 \]
\[ |U_{e4}| > 0 \]
\[ |U_{\mu4}| \sim 0 \]

\[ \sin^2 2\theta_{e\mu} \sim \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu} \sim 4|U_{e4}|^2|U_{\mu4}|^2 \]
Impact on the standard parameters $[\theta_{13}, \delta_{13}]$

- Allowed range for $\theta_{13}$ from LBL alone gets enlarged
- Values preferred for $\delta_{13} \equiv \delta$ basically unaltered
- Mismatch (in IH) of LBL and Reactors decreases in 3+1