LBL experiments: a new window on light sterile neutrinos

Antonio Palazzo
University of Bari & INFN
Outline

Introduction

Interference effects mediated by sterile neutrinos

LBL constraints on sterile vs: present

LBL constraints on sterile vs: future

Conclusions
Introduction
It is timely to pose a new question

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

Question basically ignored in the past

Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, A.P, PRD 95, 096014 (2017)
A discovery can come only at SBL experiments

SOX experiment @ LNGS

Observing the oscillation pattern (in energy and/or space)

However …
SBL have an intrinsic limitation

At SBL atm/sol oscillations are negligible

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

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

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

But we have LBL, which are sensitive interferometers
Interference effects mediated by sterile $\nu_s$

arXiv: 1412.7524
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
Mixing Matrix in the 3+1 scheme

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

\[ R_{ij} = \begin{bmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{bmatrix} \]

\[ \tilde{R}_{ij} = \begin{bmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}_{ij} & c_{ij} \end{bmatrix} \]

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

In general, we have additional sources of CPV
LBL transition probability in 3-flavor

\[ P^{3\nu}_{\nu_{\mu} \rightarrow \nu_e} = P^{\text{ATM}} + P^{\text{SOL}} + P^{\text{INT}}. \]

in vacuum:

\[
\begin{align*}
P^{\text{ATM}} &= 4s_{23}^2 s_{13}^2 \sin^2 \Delta \\
P^{\text{SOL}} &= 4c_{12}^2 c_{23}^2 s_{12}^2 (\alpha \Delta)^2 \\
P^{\text{INT}} &= 8s_{23} s_{13} c_{12} c_{23} s_{12} (\alpha \Delta) \sin \Delta \cos(\Delta + \delta_{CP}).
\end{align*}
\]

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

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

\[ \alpha \sim 0.03 \]

**\( P^{\text{ATM}} \)** leading \( \Rightarrow \theta_{13} > 0 \)

**\( P^{\text{INT}} \)** subleading \( \Rightarrow \) dependency on \( \delta \)

**\( P^{\text{SOL}} \)** negligible

Matter effects break NH-IH degeneracy
A new interference term in the 3+1 scheme

\[ \Delta_{14} \gg 1 : \text{fast oscillations are averaged out} \]

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

\[
P_{4\nu}^{\mu e} \simeq P_{\text{ATM}} + P_I^{\text{INT}} + P_{II}^{\text{INT}}
\]

\[
P_{\text{ATM}}^{\mu e} \simeq 4s_{23}^2s_{13}^2 \sin^2 \Delta
\]

\[
P_{I}^{\text{INT}} \simeq 8s_{13}s_{23}c_{23}s_{12}c_{12}(\alpha \Delta) \sin \Delta \cos(\Delta + \delta_{13}) \sim \epsilon^3
\]

\[
P_{II}^{\text{INT}} \simeq 4s_{14}s_{24}s_{13}s_{23} \sin \Delta \sin(\Delta + \delta_{13} - \delta_{14}) \sim \epsilon^3
\]

\[
S_{13} \sim S_{14} \sim S_{24} \sim 0.15 \sim \epsilon
\]

\[
\alpha = \frac{\delta m^2}{\Delta m^2} \sim 0.03 \sim \epsilon^2
\]

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


7/7/2017

Antonio Palazzo, UNIBA & INFN
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 $4\nu$ 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 $\nu$: 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

**SBL (all available data)**
(Icecube and NEOS not included in this analysis)

**LBL ≡ T2K + NO$\nu$A**
(Neutrino 2016 data)
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!**
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
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)**

---

7/7/2017  Antonio Palazzo, UNIBA & INFN
Looking to the future

Agarwalla, Chatterjee, Dasgupta, A.P.,
arXiv: 1601.05995 (JHEP 2016)

Agarwalla, Chatterjee, A.P.,
arXiv: 1603.03759 (JHEP 2016)

Agarwalla, Chatterjee, A.P.,
arXiv: 1607.01745 (PLB 2016)

Agarwalla, Chatterjee, A.P.,
Degradation of sensitivity but $4\sigma$ level preserved
- Sensitivity to CPV induced by $\delta_{13}$ reduced in 3+1 scheme
- Potential sensitivity also to the new CP-phases $\delta_{14}$ and $\delta_{34}$
- 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

JHEP 2016

Figure 8: Reconstructed regions for the two CP phases $\delta_{13}$ and $\delta_{14}$ for the four choices of their true values indicated in each panel. The NH is taken as the true hierarchy while we have marginalized over the two possible hierarchies in the test model. The contours refer to 2σ and 3σ levels. We have fixed the values $\theta_{34}^{rttrue} = 0\pi$ violating cases $[-\pi/2, -\pi/2]$ and $[\pi/2, \pi/2]$. The two confidence levels correspond to 2σ and 3σ regions. We see that in all cases we obtain a unique reconstructed region at the 3σ level. The typical –σ level uncertainty on the reconstructed CP phases is approximately $2\pi/3\pi$ for $\delta_{13}$ and $\delta_{14}$. The regions in Figure 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

Preliminary plot realized by S.S. Chatterjee
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

• Full exploration of new CPV possible only with LBL

• LBL experiments complementary to the SBL ones
Thank you for your attention!

Looking ahead to the next mooring!
Back up slides
CPV and averaged oscillations

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

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

If
\[ \Delta \equiv \Delta_{13} \sim \Delta_{23} \gg 1 \]
osc. averaged out by finite E resol.

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

It can be:
\[ A_{\alpha\beta}^{CP} \neq 0 \] (if \( \sin \delta = \emptyset \))

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)
The SBL accelerator anomalies
(unexplained $\nu_e$ appearance in a $\nu_\mu$ beam)

**MiniBooNE**

**LSND**

**Sample Graphs and Diagrams**

---

7/7/2017

Antonio Palazzo, UNIBA & INFN
The reactor and gallium anomalies

(unexplained $\nu_e$ disappearance)


SAGE coll., PRC 73 (2006) 045805

Warning: both are mere normalization issues

The culprit may be hidden in unknown systematics
New-generation detectors confirm deficit

However, the same detectors give us a warning ...
Understanding of reactor spectrum is incomplete

Bump/shoulder at 5 MeV observed in all the three experiments

Found both a near & far sites: not imputable to new osc. physics

$\theta_{13}$ extraction is unaffected (based on near/far comparison)

7/7/2017

Antonio Palazzo, UNIBA & INFN
5 MeV bump is under active investigation

- Systematics in reactor spectra not entirely under control
- Dissimilar results with two different nuclear databases
- Normalization & spectral shape issues not necessarily related
- New SBL experiments needed to shed light on both issues
Hanbit Nuclear Power Complex, Korea

Detector: 1 ton Gd-loaded liquid scintillator 24 m from the reactor core

Daya-Bay absolute spectrum used as a normalization

Oscillating pattern visible after normalization

NEOS arXiv:1610:05134
Two different perspectives

negative view

positive view

NEOS, arXiv:1610:05134

Gariazzo et al., arXiv: 1703.00860

Best fit: $\Delta m^2 = 1.73 \text{ eV} \quad \sin^2 2\theta = 0.05$

$\chi^2_{\text{no osc}} - \chi^2_{\text{min}} = 6.5 \quad > 95\% \text{ CL indication!}$
No anomaly in $\nu_\mu$ disappearance

SBL & MINOS (NC)

IceCube

$\Delta m^2$

$3+1$ best fit

Excluded region

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

$\sin^2 2\theta_{\mu\mu}$
Tension in all $\nu_s$ models

$$\nu_\mu \rightarrow \nu_e \quad \text{positive}$$

$$\nu_e \rightarrow \nu_e \quad \text{positive}$$

$$\nu_\mu \rightarrow \nu_\mu \quad \text{negative}$$

$$|U_{e4}| |U_{\mu4}| > 0$$

$$|U_{e4}| > 0$$

$$|U_{\mu4}| \sim 0$$

$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu} \simeq 4|U_{e4}|^2 |U_{\mu4}|^2$$
An “undecidable” problem

Figure from Giunti & Zavanin, arXiv:1508:03172
(tension slightly increased after NEOS, MINOS, IceCube)
If one accepts to live with the tension

Both analyses include IceCube data

Similar best fit points around $\Delta m^2 \sim 1.7 \text{ eV}^2$
Impact of the latest measurements

Figure 9

\( \sin^2 2\theta_{e\mu} - \Delta m^2_{41} \) planes obtained in the 331 global fit "Glo16B" of all 2016 SBL data. There is a comparison with the 3\( \sigma \) allowed regions obtained from \( (\nu_\mu \rightarrow \nu_e) \) SBL appearance data and the 3\( \sigma \) constraints obtained from \( (\nu_e \rightarrow \nu_e) \) SBL disappearance data and \( (\nu_\mu \rightarrow \nu_\mu) \) SBL disappearance data. The best-fit points of the Glo16B and App fits are indicated by crosses.

\[
\begin{align*}
\Delta m^2_{41} &\quad [\text{eV}^2] \\
\sin^2 2\theta_{e\mu} &\quad 10^{-3}
\end{align*}
\]

Figure 10

Comparison of the 3\( \sigma \) allowed regions in the \( \sin^2 2\theta_{e\mu} - \Delta m^2_{41} \) plane and the 2\( \sigma \) allowed regions in the \( |U_{\tau 4}|^2 - \Delta m^2_{41} \) plane obtained by adding to the data set of the Glo16A fit the MINOS and IceCube data separately and together and by adding also the NEOS data.

Gariazzo et al. arXiv:1703.00860

NEOS selects a subregion of the region allowed by all the other data: very intriguing!
The SBL race for the light sterile neutrino

Gariazzo et al., arXiv: 1703.00860

![Graph showing the SBL race for the light sterile neutrino]