Sterile neutrinos. Who cares ?

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Definition

Sterile neutrino:

- name introduced by B.Pontecorvo in 1967
- neutral lepton that does not take part in the weak interactions
- can mix with ν_e, ν_μ or ν_τ

Why do we search for sterile neutrinos ?

The Nobel Prize in Physics 2015 was awarded to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

What is the neutrino mass generation mechanism ?

Neutrino mass generation

Simplest possibility

- Neutrinos are Dirac particles
- mass generation with the same Higgs mechanism as for other leptons and quarks
- new right-handed neutrino field (fields)

- Higgs-neutrino Yukawa couplings much smaller than couplings of charged leptons with the Higgs $\Rightarrow$ no explanation of small masses of ν

Dirac-Majorana masses

- If there are no ν_R, the only possible mass term in the Lagrangian is the Majorana mass term
- If there are ν_R, there can be both Majorana and Dirac mass terms

Why do we search for sterile neutrinos ?

There are neither theoretical limits on mass nor number of sterile neutrinos.

- $m_s = \mathcal{O}(\text{eV})$ – experimental hints
- $m_s = \mathcal{O}(\text{keV})$ – Dark Matter candidate
- . . .

eV-scale neutrinos

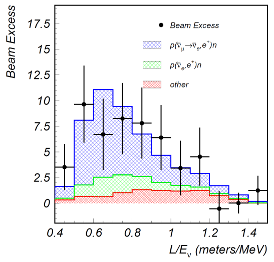
Considerable interest in search for eV-scale sterile neutrinos

- Results from MINOS, MINOS+, NOvA, IceCube, Daya Bay, NEOS (Korea), DANSS (Russia), STEREO (ILL-Grenoble)
- Dedicated future experiments: SBN (Fermilab), PROSPECT (Oak Ridge), nuPRISM (J-PARC), JSNS (J-PARC), KPipe (J-PARC), Neutrino-4 (Russia), SoLid (Belgium), CeSOX (GranSasso), BEST (Baksan), IsoDAR@KamLAND . . .

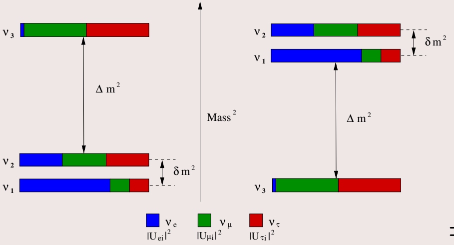
Three experimental anomalies

Hints for eV-scale neutrinos

LSND anomaly- excess of $\overline{\nu}_e$ in a beam of $\overline{\nu}_\mu$



- Consistent with oscillations for $\Delta m^2_{\mathrm{LSND}} \gtrsim 0.1\ \mathrm{eV}^2$
- Measured: $\delta m^2 \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$ $\Delta m^2 \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$

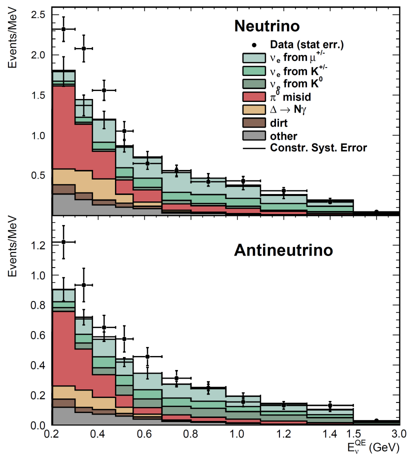


$\Rightarrow$

fourth neutrino state is needed

Hints for eV-scale neutrinos

LSND anomaly- checked by MiniBooNE

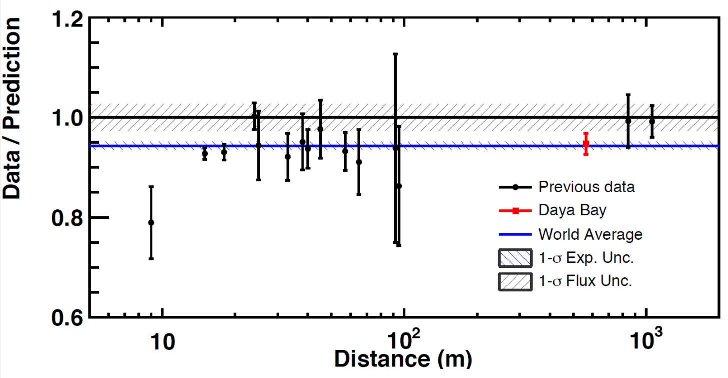


MiniBooNE constructed to confirm or refute LSND result.

Different E and L, but similar L/E ratio.

Reactor anomaly

Deficit of $\overline{\nu}_e$ flux at short distances from reactors



Deficit of reactor neutrino flux could be explained by oscillations with $\Delta m^2_{\mathrm{reactor}} \gtrsim 0.2\ \mathrm{eV}^2$.

Hints for eV-scale neutrinos

Reactor anomaly

Commercial reactors: four main isotopes participate in fissions: $^{235}\mathrm{U}$,$^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, $^{241}\mathrm{Pu}$.

Fission products → beta decays → production of $\overline{\nu}_{\mathrm{e}}$.

Hints for eV-scale neutrinos

Reactor anomaly Two methods to predict the reactor neutrino flux:

Summation method

- Summing spectra of all decay branches of all fission isotopes
- Based on nuclear database
- Larger uncertainty (10-20%)

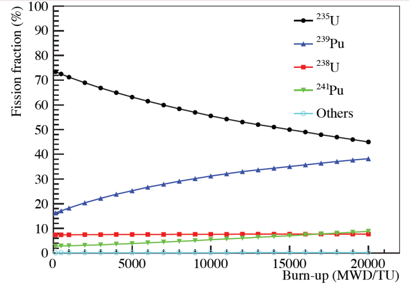
Conversion method

- Uses measured electron spectra associated with $^{235}\mathrm{U}$,$^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, $^{241}\mathrm{Pu}$.
- $\overline{\nu_\mathrm{e}}$ spectra deduced from electron spectra
- Flux recalculated with this method → reactor anomaly

Hints for eV-scale neutrinos

Reactor anomaly

Fuel composition ($^{235}\mathrm{U}$,$^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, $^{241}\mathrm{Pu}$) changes during fuel cycle

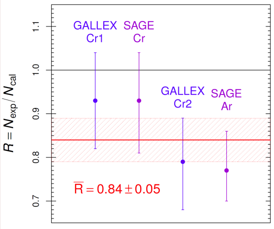


Daya Bay result – change of $\overline{\nu_e}$ flux with the fuel evolution. (Is the $^{235}\mathrm{U}$ primary contributor to the reactor anomaly ?) Phys.Rev.Lett.118, 251801 (2017) , Phys.Rev.Lett.120,022503 (2018)

Hints for eV-scale neutrinos

Gallium anomaly

- GALLEX, SAGE – solar neutrino experiments; main reaction: $\nu_{\mathrm{e}} + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + \mathrm{e}^-$
- Tests with radioactive sources ${}^{51}\mathrm{Cr}$ and ${}^{37}\mathrm{Ar}$: $\mathrm{e}^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_{\mathrm{e}}$, $\mathrm{e}^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_{\mathrm{e}}$



Deficit of ν_e interactions could be explained by oscillations with $\Delta m^2_{\mathrm{Ga}} \gtrsim 1\ \mathrm{eV}^2$.

Hints for eV-scale neutrinos

Experiment	Source	Channel	Significance
LSND	μ^+ decay at rest	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	3.8σ
MiniBooNE	accelerator	$\nu_\mu \rightarrow \nu_e$	3.4σ
MiniBooNE	accelerator	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	2.8σ
Reactors	beta-decays	$\overline{\nu}_e$ disapp.	3.0σ
GALLEX,SAGE	radioactive source, electron capture	ν_e disapp.	2.9σ

All anomalies could be explained by the existence of eV-scale neutrino

Search for neutrino oscillations

Sterile neutrinos can modify standard neutrino oscillation pattern.

Neutrino oscillations

Probability of $\nu_\alpha \to \nu_\alpha$ disappearance in model with two neutrinos

$$\mathrm{P}_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino oscillation matrix in the three-flavour model

$$|\nu_j\rangle = \sum_{\alpha=\mathrm{e},\mu,\tau} U_{\alpha j}|\nu_\alpha\rangle .$$

$$\mathrm{U} = \begin{pmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} .$$

$|U_{\alpha j}|^2$, describe the neutrino flavour-α fraction of ν_j

Neutrino oscillation matrix

Extended oscillation matrix:

$$\mathrm{U} = \begin{pmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} & U_{\mathrm{e}4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{\mathrm{s}1} & U_{\mathrm{s}2} & U_{\mathrm{s}3} & U_{\mathrm{s}4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}.$$

Active-sterile mixing must be small:

$$|U_{\alpha i}|^2 \ll 1 \qquad\qquad (\alpha = \mathrm{e}, \mu, \tau; i = 4, \ldots, N).$$

Mixing angles in 3+1 model

Mixing matrix U can be parameterized by the mixing angles θ_{34}, θ_{24}, θ_{14}, phases δ_2 and δ_3 in addition to θ_{23}, θ_{13} and θ_{12} and δ_1,

$$
\begin{aligned}
|U_{e4}|^2 &= \sin^2\theta_{14}, \\
|U_{\mu 4}|^2 &= \cos^2\theta_{14}\sin^2\theta_{24}, \\
|U_{\tau 4}|^2 &= \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}.
\end{aligned}
$$

For small angles $|U_{e4}|^2 = \sin^2\theta_{14}$, $|U_{\mu 4}|^2 \simeq \sin^2\theta_{24}$ and $|U_{\tau 4}|^2 = \sin^2\theta_{34}$.

Potential of neutrino experiments to study U

type of measurement	sensitive to
ν_{e} or $\overline{\nu}_{\mathrm{e}}$ disappearance	$\lvert U_{\mathrm{e}i}\rvert$
ν_{μ} or $\overline{\nu}_{\mu}$ disappearance	$\lvert U_{\mu i}\rvert$
$\nu_{\alpha} \rightarrow \nu_{\beta}$ appearance	$\lvert U_{\alpha i}\rvert$ and $\lvert U_{\beta i}\rvert$

Most results (including all anomalies !)
related to $\lvert U_{\mathrm{e}4}\rvert$ or $\lvert U_{\mu 4}\rvert$.
The weakest constraints are on $\lvert U_{\tau 4}\rvert$.

Constraints on the electron-sterile mixing

Constraints on the electron-sterile mixing

Sources of data:

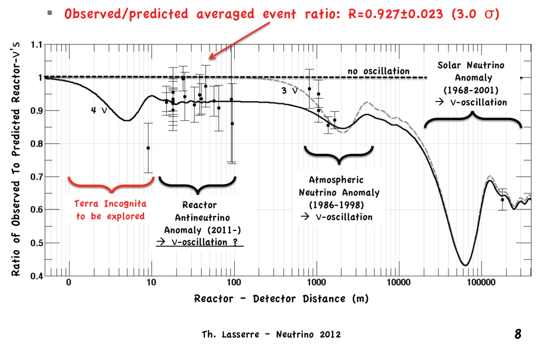
- Gallium experiments
- reactors
- solar
- atmospheric

New results from reactor experiments NEOS and DANSS. More to come.

Reactor experiments

$$P^{3\nu}_{(\overline{\nu_e}\to\overline{\nu_e})} \simeq 1 - \cos^4\theta \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2_{21} L}{E_\nu}\right) - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\left(\frac{1.27\Delta m^2_{31} L}{E_\nu}\right) + \sin^2\theta_{12}\sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right)\right)$$

Comparison of data with 3-flavour and 3+1 predictions



- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

Th. Lasserre - Neutrino 2012

8

Currently $R = 0.943 \pm 0.008(exp) \pm 0.023(model)$

NEOS and DANSS results

Very short baseline reactor experiments !
$\overline{\nu}_e$ detected with reaction $\overline{\nu}_e + p \to e^+ + n$

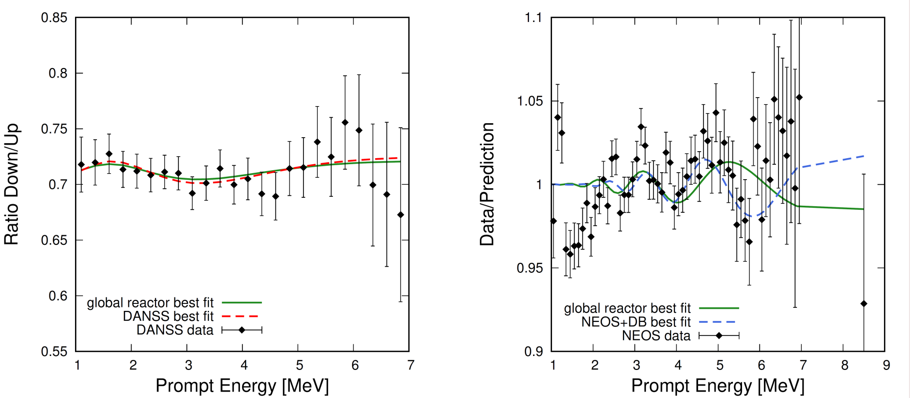
DANSS

- in Russia
- varied distance from the reactor core: 10.7 m-12.7 m.
- segmented plastic scintillator (volume 1 m^3)
- $\sim$ 5000 $\overline{\nu}_e$ per day
- ratio of prompt energy spectra at two positions

NEOS

- in Korea
- $\sim$ 24 m from the reactor core
- Gd-doped liquid scintillator
- $\sim$ 2000 $\overline{\nu}_e$ per day
- prompt energy spectrum normalized to Daya Bay spectrum

NEOS and DANSS



Results independent on flux predictions.

Constraints on the muon-sterile mixing

Constraints on the muon-sterile mixing

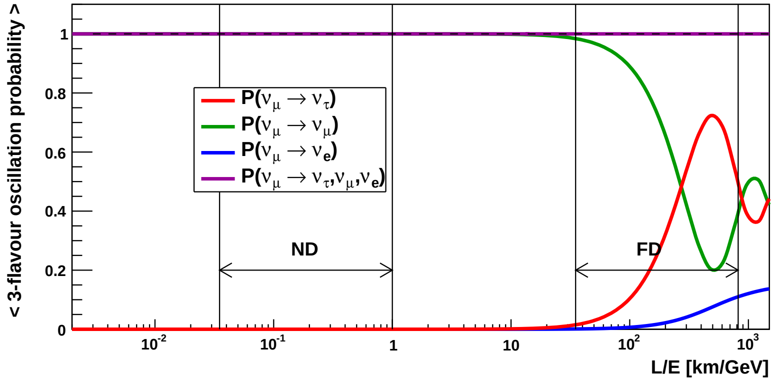
MINOS and MINOS+ - sensitive to wide range of Δm^2_{41}.

Sources of data:

- accelerator: MINOS, MINOS+, also CDHS
- atmospheric: IceCube, Deep Core, SuperKamiokande
- MiniBooNE disappearance data

Long-baseline accelerator experiments

Neutrino oscillation probabilities in the 3-flavour model

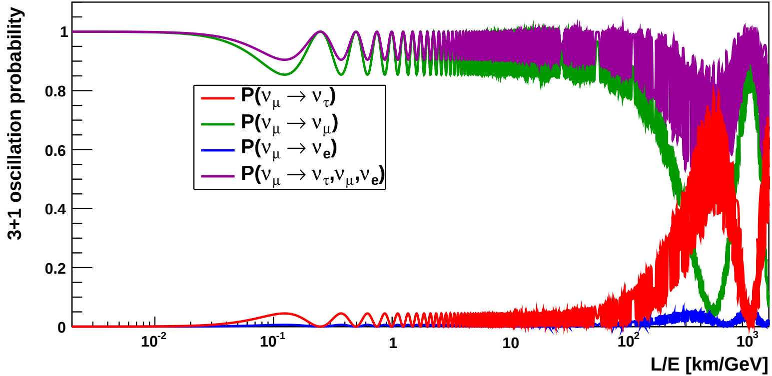


ND – MINOS+ Near Detector (1 km from the neutrino source)
FD – MINOS+ Far Detector (735 km from the neutrino source)

Long-baseline accelerator experiments

Monoenergetic beam, $\Delta m^2_{41} = \mathbf{10}\ \mathrm{eV}^2$

Neutrino oscillation probabilities in the model with one sterile ν

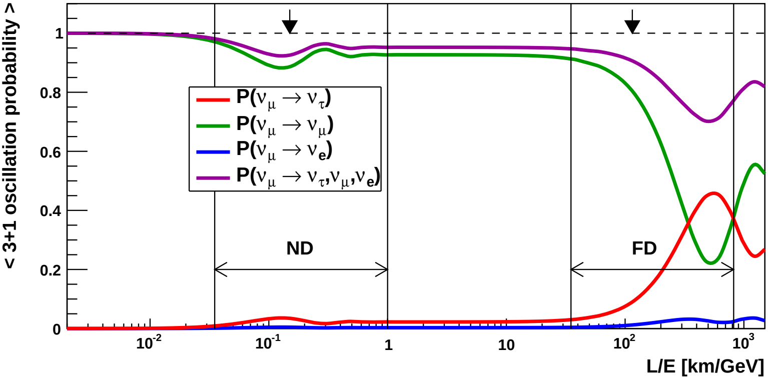


$\Delta m^2_{41} = \mathbf{10}\ \mathrm{eV}^2$, $\theta_{14} = 0.2$, $\theta_{24} = 0.2$, $\theta_{34} = 0.6$ and $\delta_i = 0$.

Long-baseline accelerator experiments

Non-monoenergetic beam, $\Delta m^2_{41} = \mathbf{10}\ \mathrm{eV}^2$

Neutrino oscillation probabilities in the model with one sterile ν

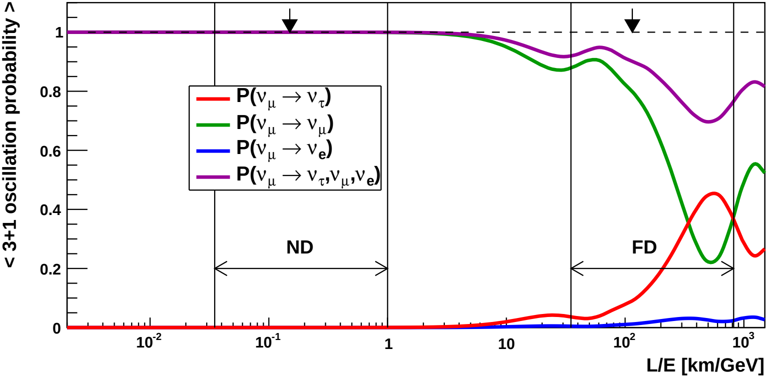


$\Delta m^2_{41} = \mathbf{10}\ \mathrm{eV}^2$, $\theta_{14} = 0.2$, $\theta_{24} = 0.2$, $\theta_{34} = 0.6$ and $\delta_i = 0$.

Long-baseline accelerator experiments

Non-monoenergetic beam, $\Delta m^2_{41} = \mathbf{0.05}\ \mathrm{eV}^2$

Neutrino oscillation probabilities in the model with one sterile ν

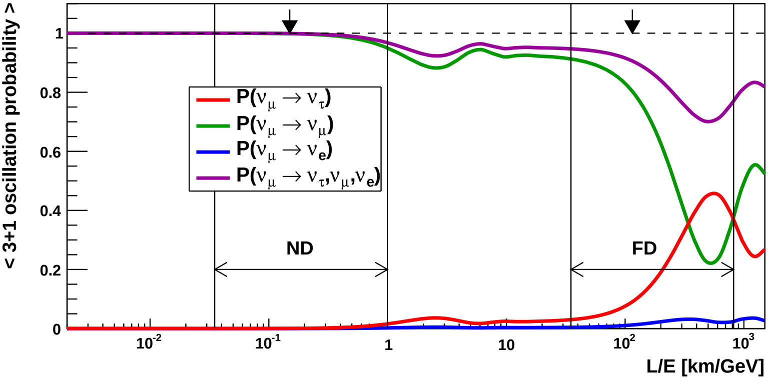


$\Delta m^2_{41} = \mathbf{0.05}\ \mathrm{eV}^2$, $\theta_{14} = 0.2$, $\theta_{24} = 0.2$, $\theta_{34} = 0.6$ and $\delta_i = 0$.

Long-baseline accelerator experiments

Non-monoenergetic beam, $\Delta m^2_{41} = \mathbf{0.5}\ \mathrm{eV}^2$

Neutrino oscillation probabilities in the model with one sterile ν

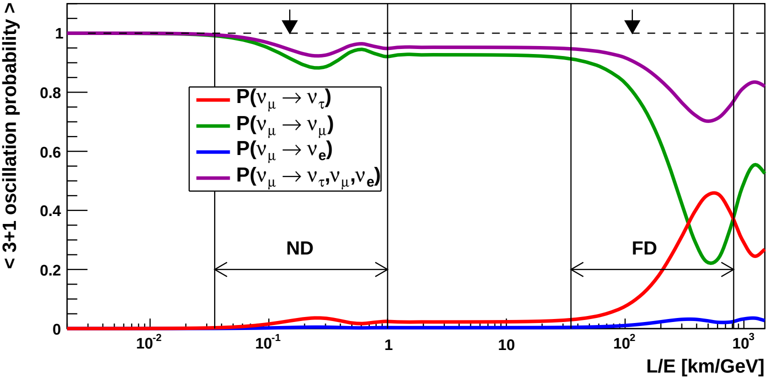


$\Delta m^2_{41} = \mathbf{0.5}\ \mathrm{eV}^2$, $\theta_{14} = 0.2$, $\theta_{24} = 0.2$, $\theta_{34} = 0.6$ and $\delta_i = 0$.

Long-baseline accelerator experiments

Non-monoenergetic beam, $\Delta m^2_{41} = \mathbf{5}\ \mathrm{eV}^2$

Neutrino oscillation probabilities in the model with one sterile ν

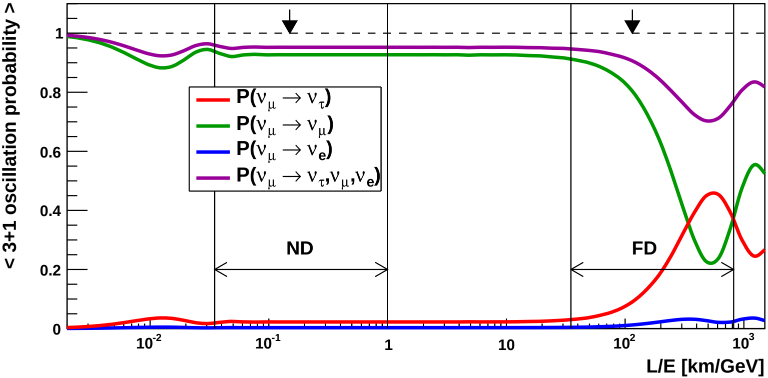


$$\Delta m^2_{41} = \mathbf{5}\ \mathrm{eV}^2,\ \theta_{14} = 0.2,\ \theta_{24} = 0.2,\ \theta_{34} = 0.6 \text{ and } \delta_i = 0.$$

Long-baseline accelerator experiments

Non-monoenergetic beam, $\Delta m^2_{41} = \mathbf{100}\ \mathrm{eV}^2$

Neutrino oscillation probabilities in the model with one sterile ν



$\Delta m^2_{41} = \mathbf{100}\ \mathrm{eV}^2$, $\theta_{14} = 0.2$, $\theta_{24} = 0.2$, $\theta_{34} = 0.6$ and $\delta_i = 0$.

MINOS and MINOS+ ν_μ disappearance

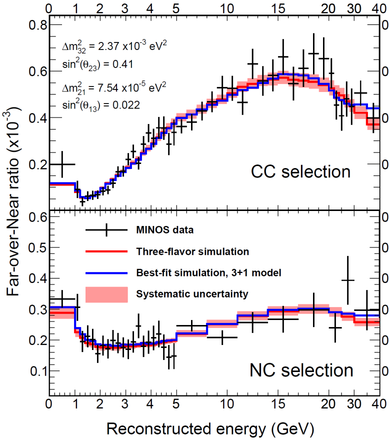
Oscillations can be present in both detectors

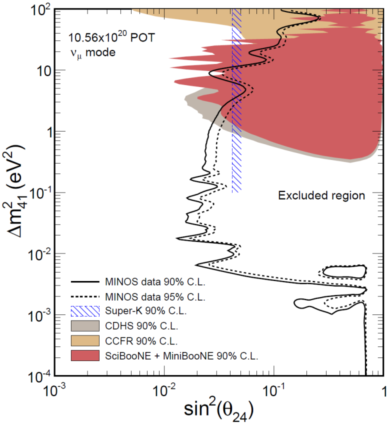
Two approaches. Three-flavour and 3+1 oscillations models fitted to:

1. ratios of Far/Near energy spectra
2. energy spectra in Near Detector and Far Detector (simultaneous fit)
3. in both cases fit to CC (charged-current) ν_μ and NC (neutral current) samples

MINOS and MINOS+ ν_μ disappearance

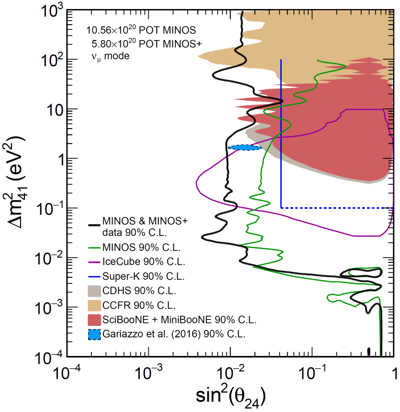
Far/Near analysis





MINOS and MINOS+ ν_μ disappearance

Two-detector simultaneous analysis



Constraints on the tau-sterile mixing

Constraints on the tau-sterile mixing

Not many sources of data. No beams of ν_τ.

τ appearance experimentally challenging.

Possibilities to study tau-sterile mixing:

- via matter effects
- Neutral Current interactions
- ν_τ appearance

ν_τ appearance in MINOS+

Neutrino oscillation probabilities at short-distances in the 3+1 model

ν_τ appearance in Near Detector not present in the three-flavour model !

$$\mathrm{P}_{\nu_\mu\to\nu_\tau}(L,E) \simeq 4|U_{\mu 4}|^2|U_{\tau 4}|^2 \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$= \sin^2 2\theta_{\mu\tau} \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$\mathrm{P}_{\nu_\mu\to\nu_\mu}(L,E) \simeq 1-4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2) \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$= \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

Motivation

ν_τ appearance in MINOS+

- Unique signature of sterile neutrinos in Near Detector
- Unlike in NOvA and T2K – most of the energy spectrum above the threshold for τ production
- High statistics of collected events in Near Detector
- It is possible to select channel with smallest systematics
- Detector of low-granularity – hardly reducible background

MINOS+ ν_τ appearance

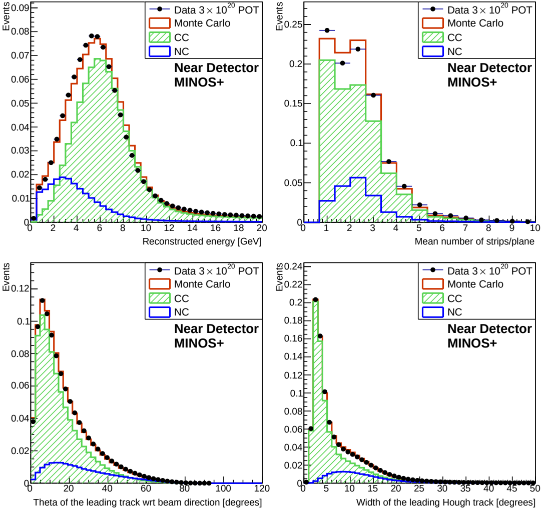
CC ν_τ, $\tau \to \mu$ selection

Main steps of the analysis

- Preselection 1 - track with vertex in the fiducial volume
- Preselection 2 - to remove neutral current (NC) events
- kNN, multivariate selection to reduce the dominant background from CCν_μ
- $>$99.5% of NC background is removed
- $>$92% of charged-current (CC) ν_μ background is removed
- Fit to energy spectrum in the Near Detector
- Grid of points in the $(\sin^2 2\theta_{\mu\tau}, \Delta m^2_{41})$ plane
- Minimization of χ^2 with nuisance parameter $\sin^2 2\theta_{\mu\mu}$
- Profile likelihood method

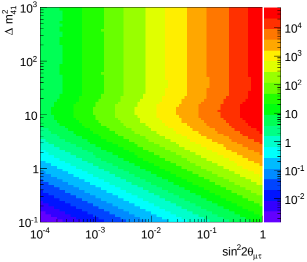
MINOS+ ν_τ appearance – CC ν_τ, $\tau \to \mu$ selection

Variables used as inputs to kNN after preselection

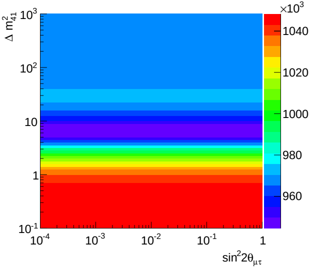


CC ν_τ, $\tau \rightarrow \mu$ selection

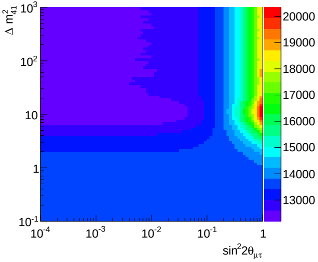
Numbers for 3×10^{20} POT
Dominant background from CC ν_μ



CC ν_τ

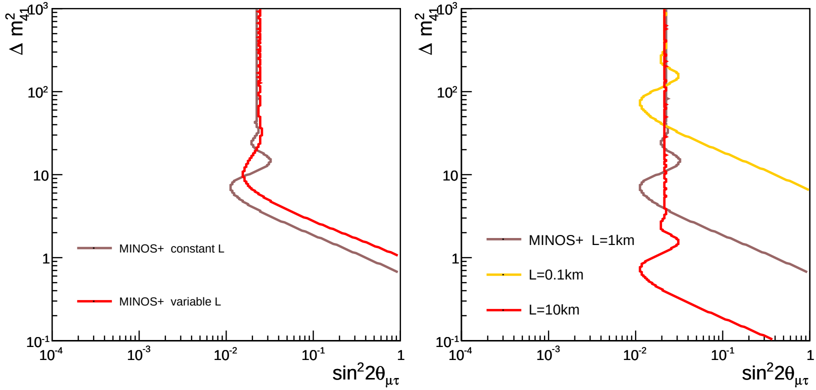


CC ν_μ



NC

MINOS+ ν_τ appearance – statistics only sensitivities

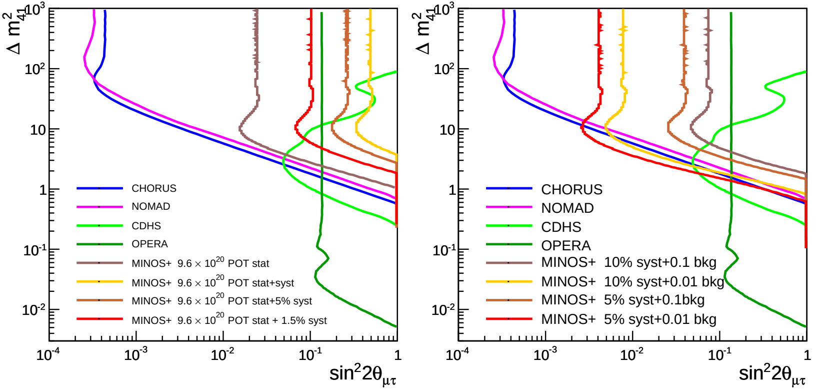


90% CL sensitivity contours

Left: Constant (1.04 km) vs variable baseline.

Right: Comparison of sensitivities for different baselines

MINOS+ ν_τ appearance



Comparison of 90% CL MINOS+ sensitivities with 90% CL limits from CHORUS, NOMAD, OPERA i CDHS.

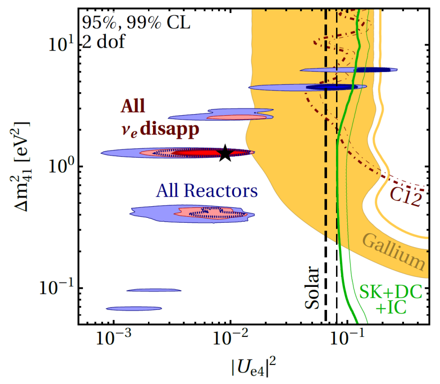
Recent global analyses of neutrino data

- Gariazzo2017 – S. Gariazzo, C. Giunti, M. Laveder, Y.F. Li, Updated global 3+1 analysis of short-baseline neutrino oscillations,

  J. High Energy Phys **1705**, 135 (2017)
- Dentler2018 – M. Dentler, A. Hernandez-Cabezudo, J. Kopp, P. Machado, M. Maltoni, I. Martinez-Soler, T. Schwetz, Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos,

  arXiv:1803.10661, 28 March, 2018

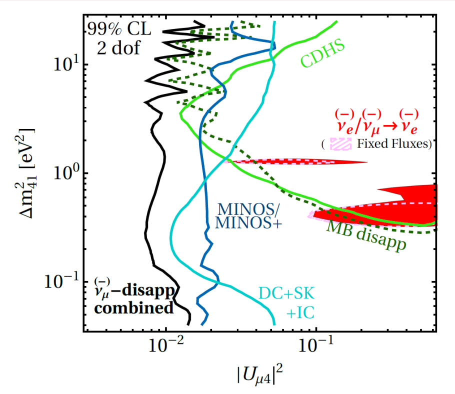
Global ν_e disappearance analysis



Reactor neutrino data (mainly DANSS and NEOS) – preference for sterile oscillations with $\Delta m^2_{41} \sim 1.3\ \mathrm{eV}^2$, $U_{e4} \sim 0.1$. Result independent from predicted neutrino fluxes.

Dentler 2018

Global ν_μ disappearance analysis



Strong exclusion limits driven by MINOS and MINOS+ in the wide range of Δm^2_{41}

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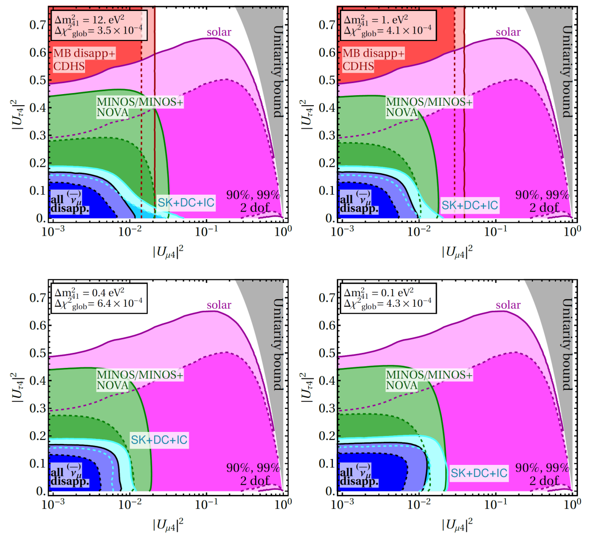
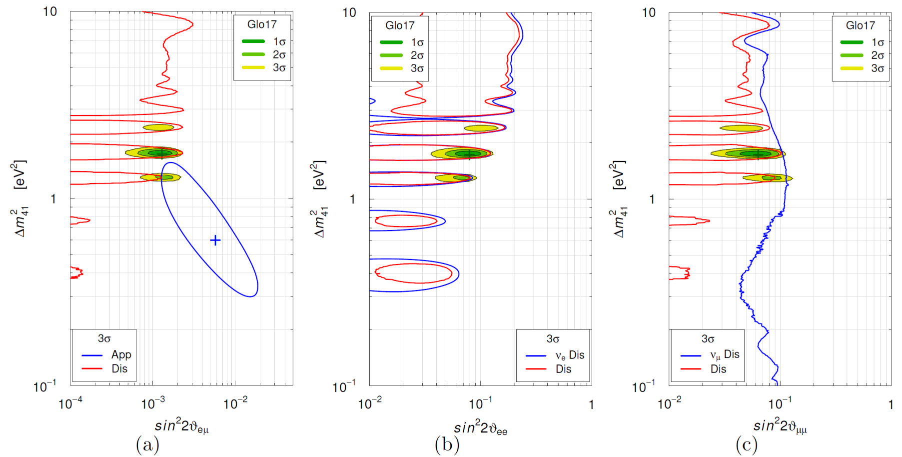
Constraints on tau-sterile and muon-sterile mixings



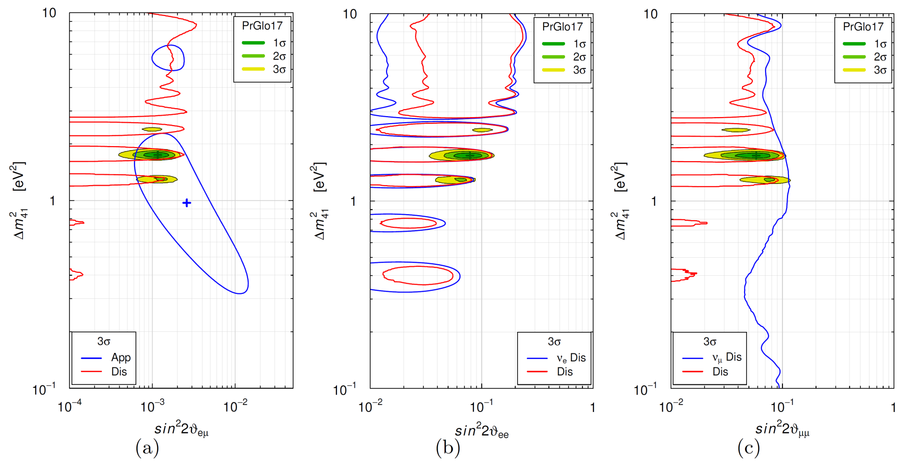
Dentler 2018

Constraints on the LSND result



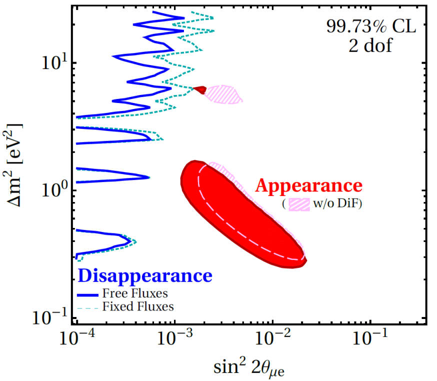
Gariazzo 2017, strong tension between appearance and disapperance data

Constraints on the LSND result



Gariazzo 2017, in pragmatic scenario (low-energy MiniBooNE data removed) tension is reduced

Constraints on the LSND result



Anomalies in $\overline{\nu}_e$ appearance(LSND) in strong tension with results from ν_μ disappearance. Explanation of LSND anomaly in model with one sterile neutrino is excluded at the 4.7σ level.

Dentler 2018

Conclusions

Possible exclusion of LSND effect does not mean the hypothesis of sterile neutrinos is excluded.