Overview of the experimental anomalies

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Abstract

The phenomenon of neutrino oscillations has been established by a number of experiments. An incomplete list includes Homestake, Gallex, Sage, Kamiokande, IMB, Soudan2, Macro, SNO and recently also Double Chooze, Reno and Daya Bay. Assuming existence of three neutrinos, one can extract neutrino mixing angles and mass differences from the data and use them to predict outcome of any other oscillation experiment. However, there is a handful of experiments, whose results are incompatible with this standard picture and hint towards the existence of an additional, sterile, neutrino. Among these are LSND, KARMEN, MiniBooNE, MINOS and many of the short-baseline reactor experiments. In this talk I will review the experimental setups and results, as well as their implications for the neutrino physics.

Outline

Conventional picture

- In the standard model neutrinos are strictly massless. Historically it is explained by the fact, that when the Standard Model was formulated, all the existing experiments were compatible with zero neutrino mass and absence of the right-handed neutrino.

- The situation was changed by the Homestake experiment, which operated from 1970 till 1994. This experiment has observed only 1/3 of the flux predicted by the Standard Solar Model. To explain this result the neutrino oscillation hypothesis was proposed. According to this hypothesis the electron neutrinos produced in the sun oscillate to the other flavors on the way to Earth. And since the detector is only capable of measuring the electron,

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

but not the muon or tau-neutrinos, this explains results of the Homestake experiment.

- A decisive confirmation of this hypothe-

- A decisive confirmation of this hypothesis was provided by the SNO experiment. It measured neutral-current interactions:

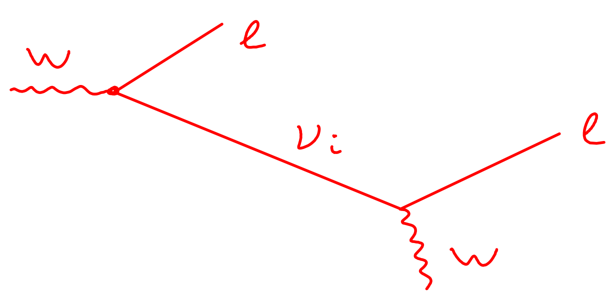
$$\nu_x + d \rightarrow p + n + \nu_x$$

which are equally sensitive to all neutrino flavors. The measured total neutrino flux was in agreement with the prediction of the standard solar model. On the other hand the flux of electron neutrinos measured via charged current interaction:

$$\nu_e + d \rightarrow p + p + e^-$$

was smaller than the total flux. This has proven that the oscillation hyposes is correct and that neutrinos have masses.

- A typicall oscillation experiment is described by the diagram:



The neutrino is produced as flavor eigenstate but propagates as a mass eigenstate. If the neutrinos are massles, then the

If the neutrinos are massles, then the mass eigenstates coincide with the flavor eigenstates and oscillations are impossible. This implies that the Standard Model should be extended, for instance in the one of the ways discussed by Lisa.

- The oscillation probability depends on the neutrino masses and mixing angles.

$$P_{\alpha\to\beta} = |\sum_i U_{\alpha i} e^{+im_i^2 L/2E} U^+_{i\beta}|^2$$

$\alpha \to i \to \beta$

We can simplify this expression to:

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\frac{\Delta m^2_{ij}L}{4E}) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\frac{\Delta m^2_{ij}L}{2E}),$$

As follows from this expression, amplitude of the oscillations depends on the mixing angles, and the oscillating behavior on the product $\Delta m^2_{ij}\,(L/E)$. This dependence is decisive for the whole following discussion. Changing the ratio (L/E) we can test different values of Δm^2_{ij}. Loosely speaking, the shorter the distance, the larger is Δm^2 one can study.

- The oscillation parameters have been measured by a number of experiments.

measured by a number of experiments.

The solar neutrino angle and the corresponding mass difference was measured by Gallex, Sage, Kamiokande, and lately by Borexino experiments.

$$\theta_{12} \approx 33^\circ, \quad \Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$$

The atmospheric parameters have been measured by Kamiokande, IMB, Soudan 2, and Macro experiments.

assuming normal hierarchy.

$$\theta_{23} \approx 40^\circ \text{ or } 50^\circ, \quad \Delta m^2_{31} = 2.47 \times 10^{-3} eV^2$$

Finally the missing reactor mixing angle has recently been measured by Double Chooz, Reno, and Daya Bay experiments.

$$\theta_{13} \approx 8.6^\circ$$

- There also CP-violating phases, one or three, but they are not known at present. But the two mass differences and the three mixing angles are sufficient to predict the outcome of pretty much every neutrino oscillation experiment. A deviation from the predicted behavior is an anomaly.

LSND, KARMEN

- Historically, one of the first anomalies was found by the LSND experiment.

- Details of the experiment:

  - used 800 MeV proton beam to create pions.

  - neutrinos were produced in the following decay chain:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu, \qquad \mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

} 95% of the decays - at rest.

π^- - absorbed in the target and the expected $\bar{\nu}_e$ flux is $\sim 8 \times 10^{-4}$ of the $\bar{\nu}_\mu$ flux.

- Primary goal - search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, where $\bar{\nu}_e$ are identified by $\bar{\nu}_e p \to e^+ n$; then $n + p \to d + \gamma$ (2.2 MeV)

Physical potential.

$L = 30$ m

$E_{\bar{\nu}_\mu}$ - 20 .. 60 MeV

E_{ν_μ} - 60 .. 200 MeV

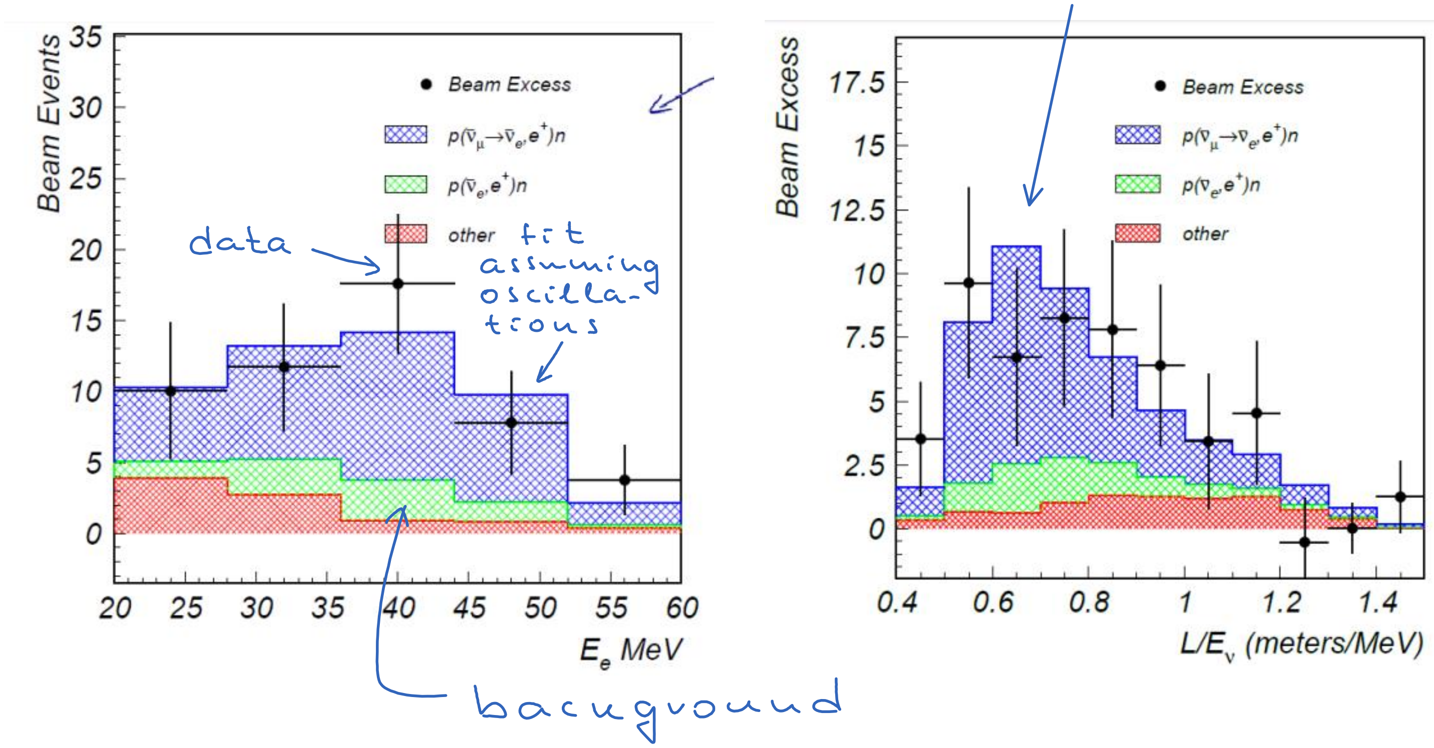
E_{ν_μ} - 60 .. 200 MeV

$$\frac{E\,(1\,\text{MeV})}{L\,(100\,\text{km})} \sim 10^{-5}\,\text{eV}^2 \;\rightarrow\; \frac{E}{L} \sim 1\,\text{eV}^2$$

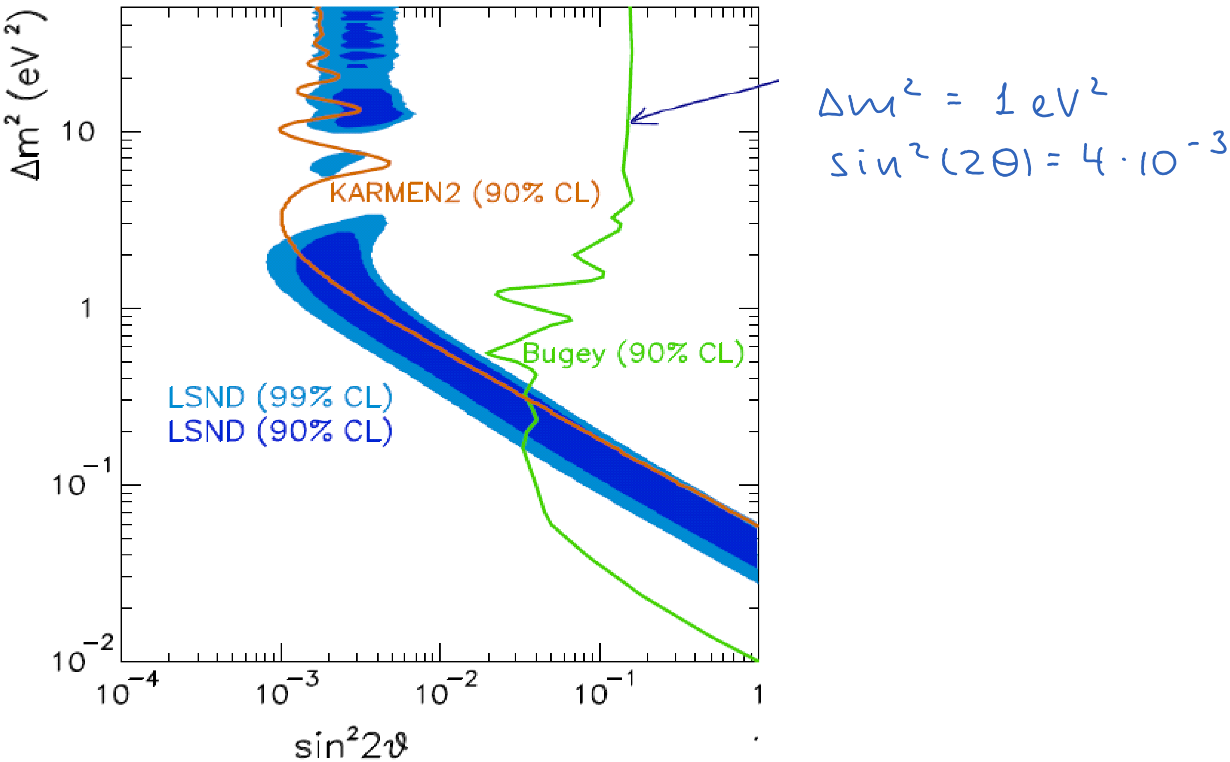
If the conventional picture is correct, neutrinos would not have time to oscillate on such a short distance.

- They have observed an excess. Energy and L/E dependence of the excess:

non-trivial L-dependence



- The data can be fit assuming existence of an additional neutrino with $\Delta m^2 \sim 1$. Larger Δm^2 are also acceptable.



- A very similar experimental setup was used in the KARMEN experiment. The main differences, as compared to LSND are:

  - smaller distance to the detector, $L \sim 18\,m$

  - clear separation of ν_μ from π^+ decay from $\bar{\nu}_\mu$ and ν_e from μ^+ decay.

The expected background was 15.8 events and the measured number was 15. In other words, KARMEN does not support the claim of LSND. To be fair, one should note that KARMEN does not exclude part of the LSND plot with $\Delta m^2 < 2\,eV^2$ and $\Delta m^2 \sim 7\,eV^2$.

MiniBooNE

- To cross-check the controversial results of LSND the same group of people has built another experiment - MiniBooNE.

Details of the experiment:

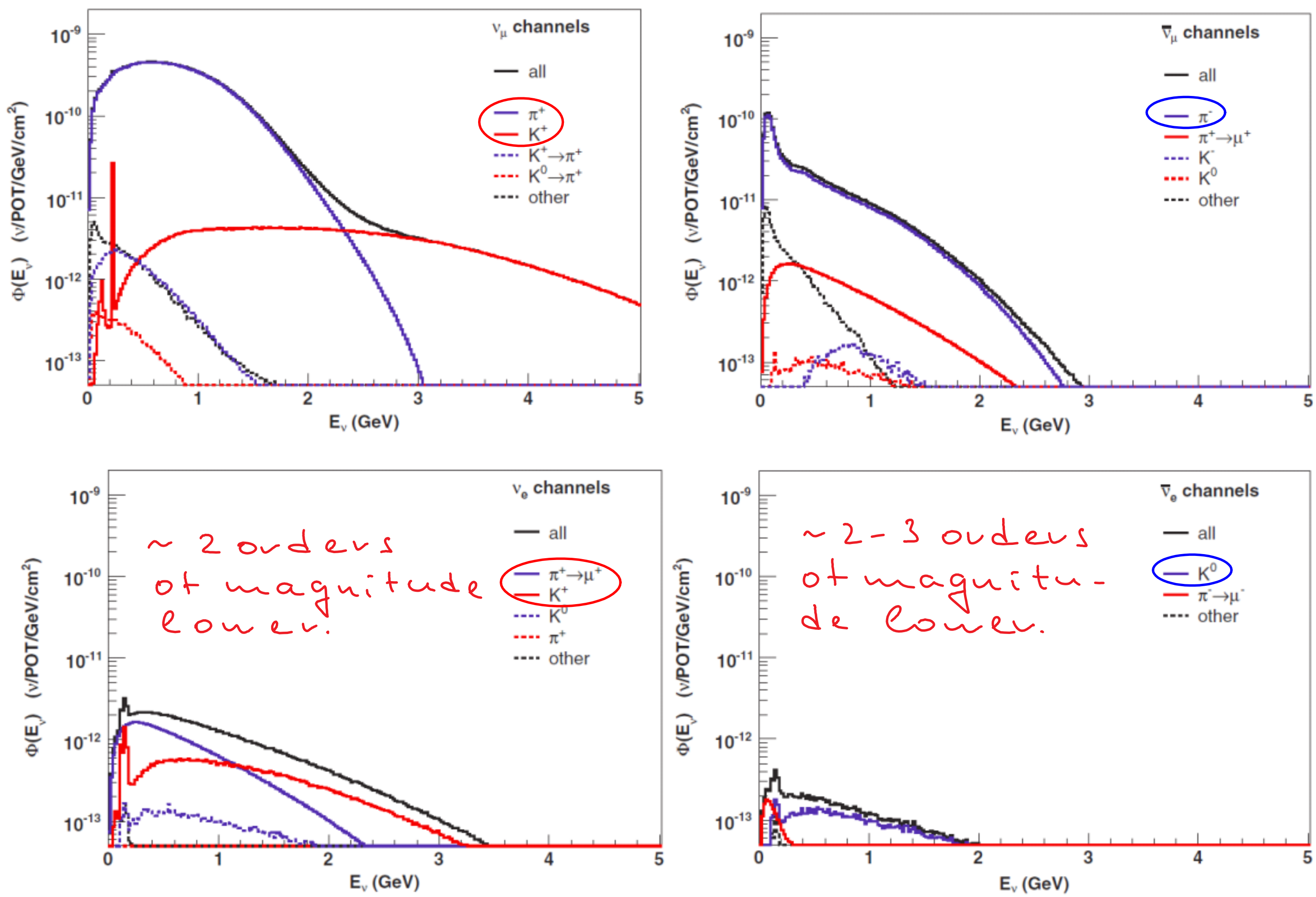
- used 8 GeV proton beam to create pions and caons.

- magnetic field was used to form either a π^+, K^+ or π^-, K^- beam.

- neutrino / antineutrino modes

Particle	Lifetime (ns)	Decay mode	Branching ratio (%)
π^+	26.03	$\mu^+ + \nu_\mu$	99.9877
		$e^+ + \nu_e$	0.0123
K^+	12.385	$\mu^+ + \nu_\mu$	63.44
		$\pi^0 + e^+ + \nu_e$	4.98
		$\pi^0 + \mu^+ + \nu_\mu$	3.32
K_L^0	51.6	$\pi^- + e^+ + \nu_e$	20.333
		$\pi^+ + e^- + \bar{\nu}_e$	20.197
		$\pi^- + \mu^+ + \nu_\mu$	13.551
		$\pi^+ + \mu^- + \bar{\nu}_\mu$	13.469
μ^+	2197.03	$e^+ + \nu_e + \bar{\nu}_\mu$	100.0

- neutrino and antineutrino fluxes:



- Primary goal: study of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. Thus, it can cross-check the LSND result.

- detection process - CC quasi-elastic scattering: $\nu_e C \to e^- X$ and $\bar{\nu}_e C \to e^+ X$

- the detector cannot distinguish between ν_e and $\bar{\nu}_e$ candidates

• Physical potential:

- the detector is located 541 m away from the decay pipe.

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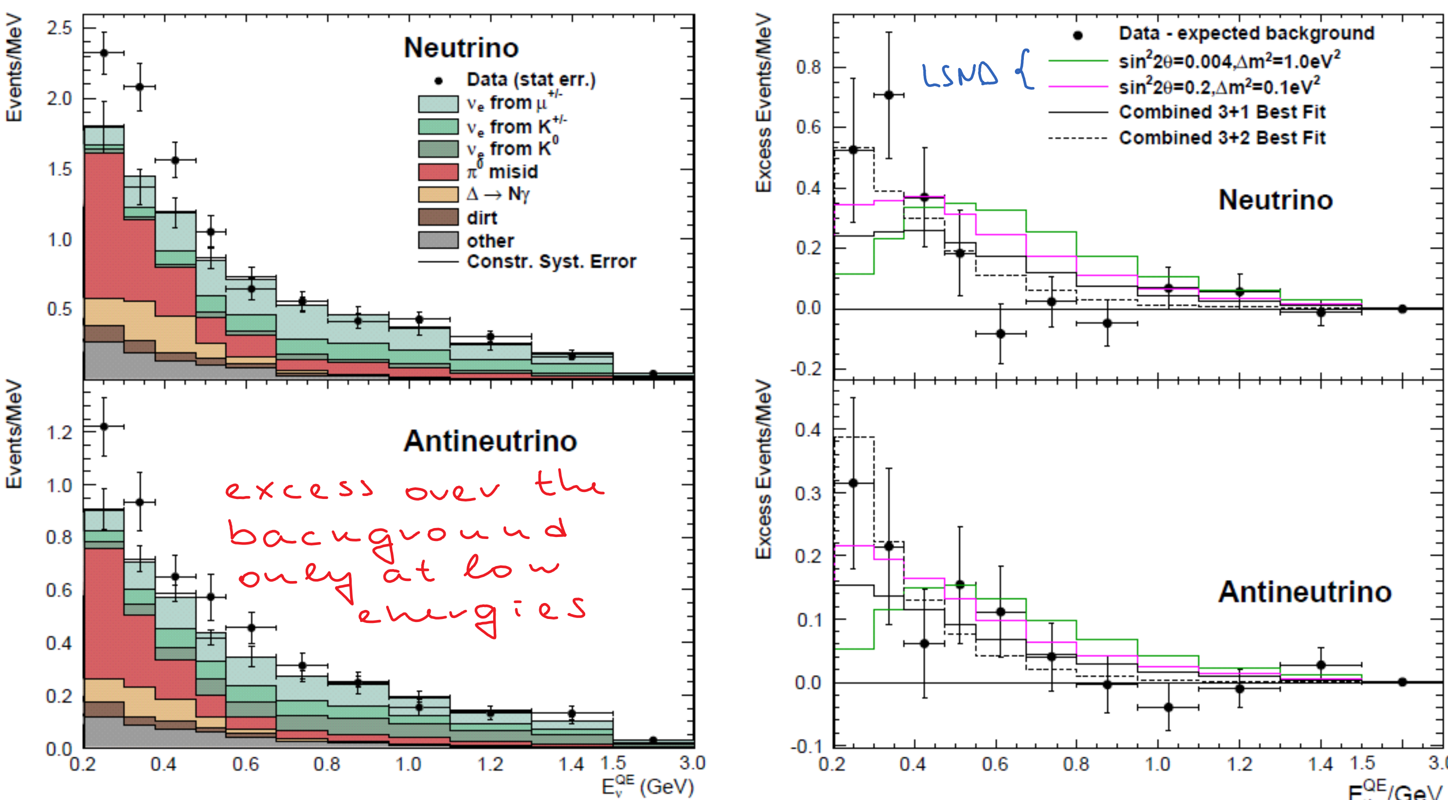
- taking average neutrino energy $E_\nu \sim 2$ GeV we find for E/L:

$$\frac{2\times10^3 \times 1\,\text{MeV}}{0.5\times10^{-2}\times 100\,\text{km}} = 4\times10^5\times10^{-5}\,\text{eV}^2 \sim 4\,\text{eV}^2$$

i.e. MiniBooNE is sensitive to the same range of Δm^2 as LSND, but the different range of energies allows to obtain an independent cross-check of the LSND results.

- Results:



in both neutrino and antineutrino modes

- At high energies no excess observed. At low

- At high energies no excess observed. At low energies there is an excess, but on the other hand, this is the region where the theoretical estimates are not particularly reliable.

- in the antineutrino mode the low-energy excess seems to be consistent with the LSND fit. But if we look more carefully, its shape is not consistent with simple 2-neutrino oscillation picture.

- in the neutrino mode the excess is larger and is worse compatable with the expectations based on the LSND results.

- interpretation of the neutrino and antineutrino results.

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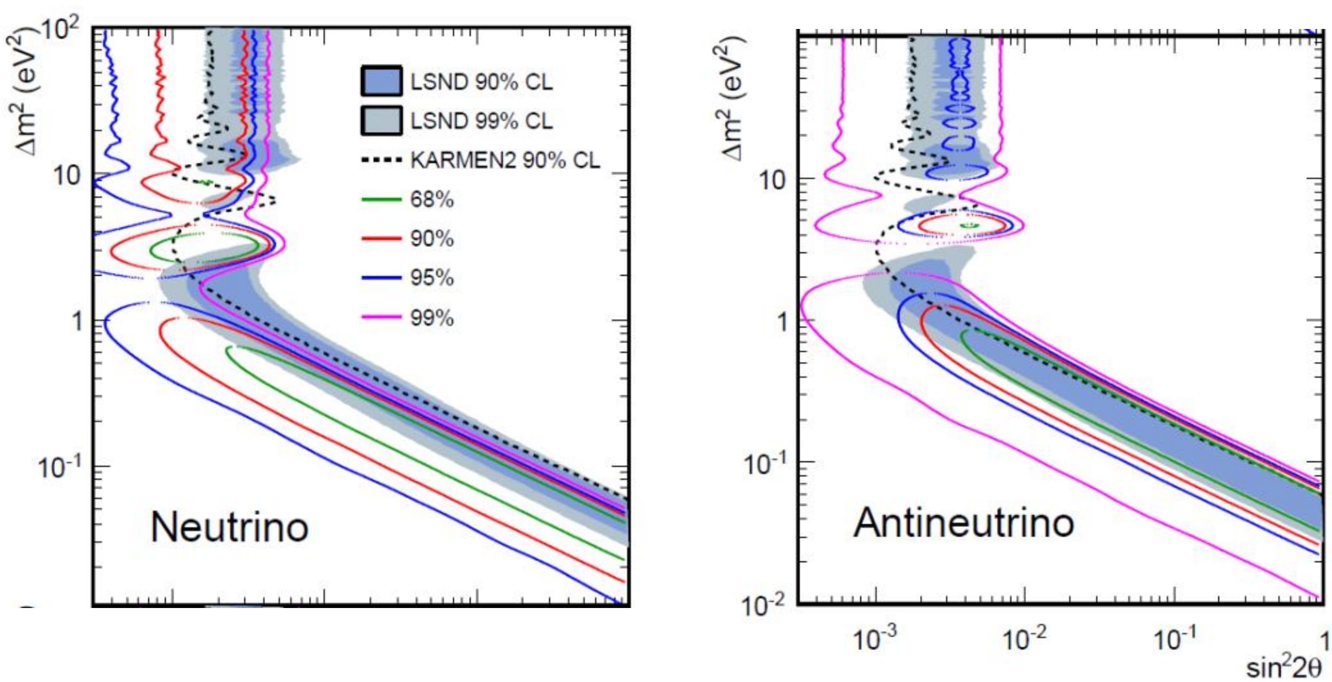


The antineutrino mode seems to be compatible with the results of LNSD, whereas in the neutrino mode the agreement is rather poor.

- This inconsistency can in principle be explained in 3+2 scheme, which introduces CP-violation and thus different properties of neutrinos and antineutrinos.

Gallium anomaly

- Gallex and SAGE studied solar neutrinos using reaction $\nu_e + {}^{71}Ga \to {}^{71}Ge + e^-$.

- To calibrate the experiments two calibrations have been performed with ${}^{51}Cr$ and ${}^{37}Ar$ sources.

- They both have observed lack of events from the source, which cannot be explained by solar-type oscillations (orders of magnitude smaller distance).

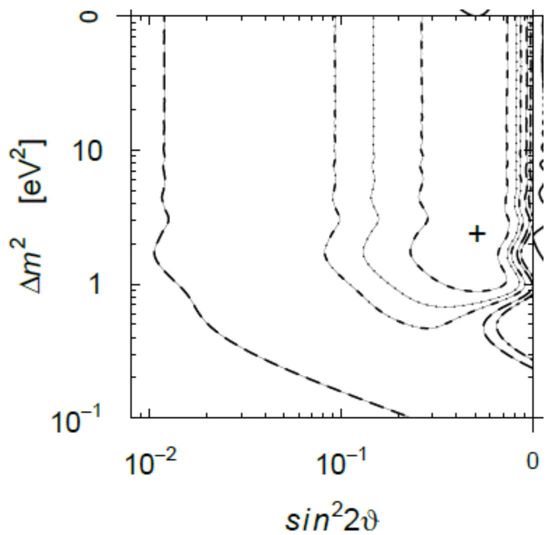
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R^k_B (Bahcall)	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm ^{+0.084}_{-0.078}$
R^k_H (Haxton)	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm ^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

- For Gallex the same detector, source and distance were used for the callibration and two different results were obtained.

  - It is not quite clear, which numbers for the cross-sections are more reliable, but in any case the second measurement shows a deviation from the expected numin any case the second measurement shows a deviation from the expected number of events.

- Interpretation.

Like for any other short-baseline experiment this result can be explained by the existence of an additional sterile neutrino. Implied parameters:

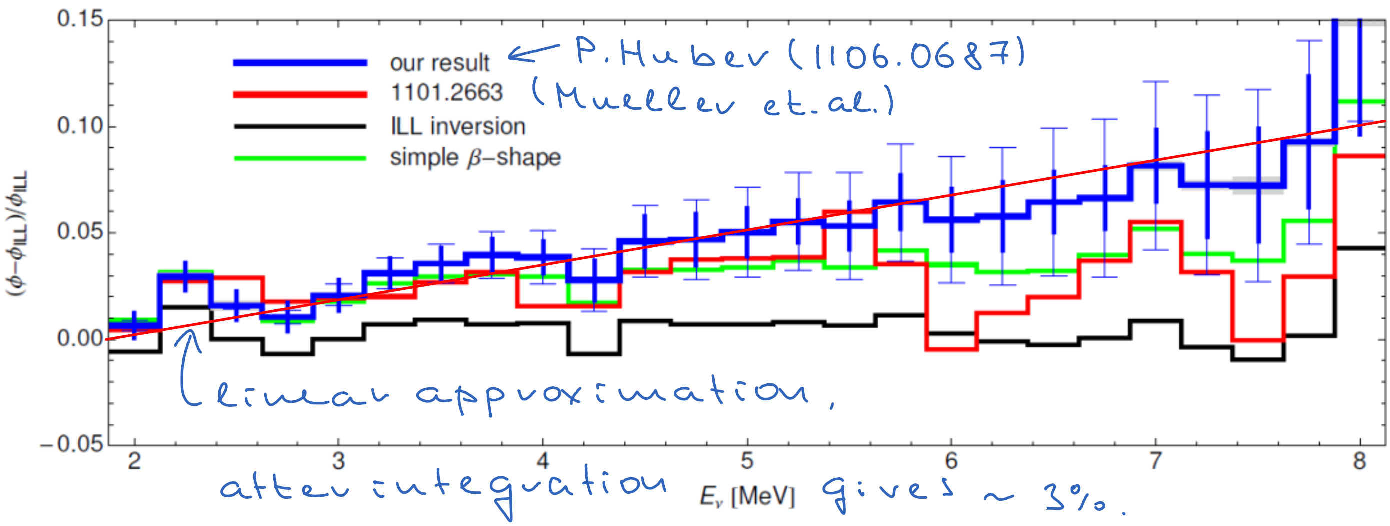


$\sin^2 2\Theta \gtrsim 0,07$
$\Delta m^2 \gtrsim 0,35\ eV^2$

- Note that solar neutrino parameters have been measured by a number of experiment. Since the solar parameters obtained by Gallex and Sage are compatible with the others, we can consider the solar measurement as calibration and the source experiments as short-baseline sterile neutrino experiment.

Reactor anomaly

- Reactor experiments belong to the ones most commonly used in the neutrino physics.
- Reactors produce a pure $\bar{\nu}_e$ beam with typical energy $E_\nu \sim$ a few MeV. This energy is two low to produce muons or taus. Therefore, a reactor experiment can only be a disappearence experiment.
- There is a new estimate of the antineutrino flux that predicts ~ 3% higher flux. The difference comes from higher energies.

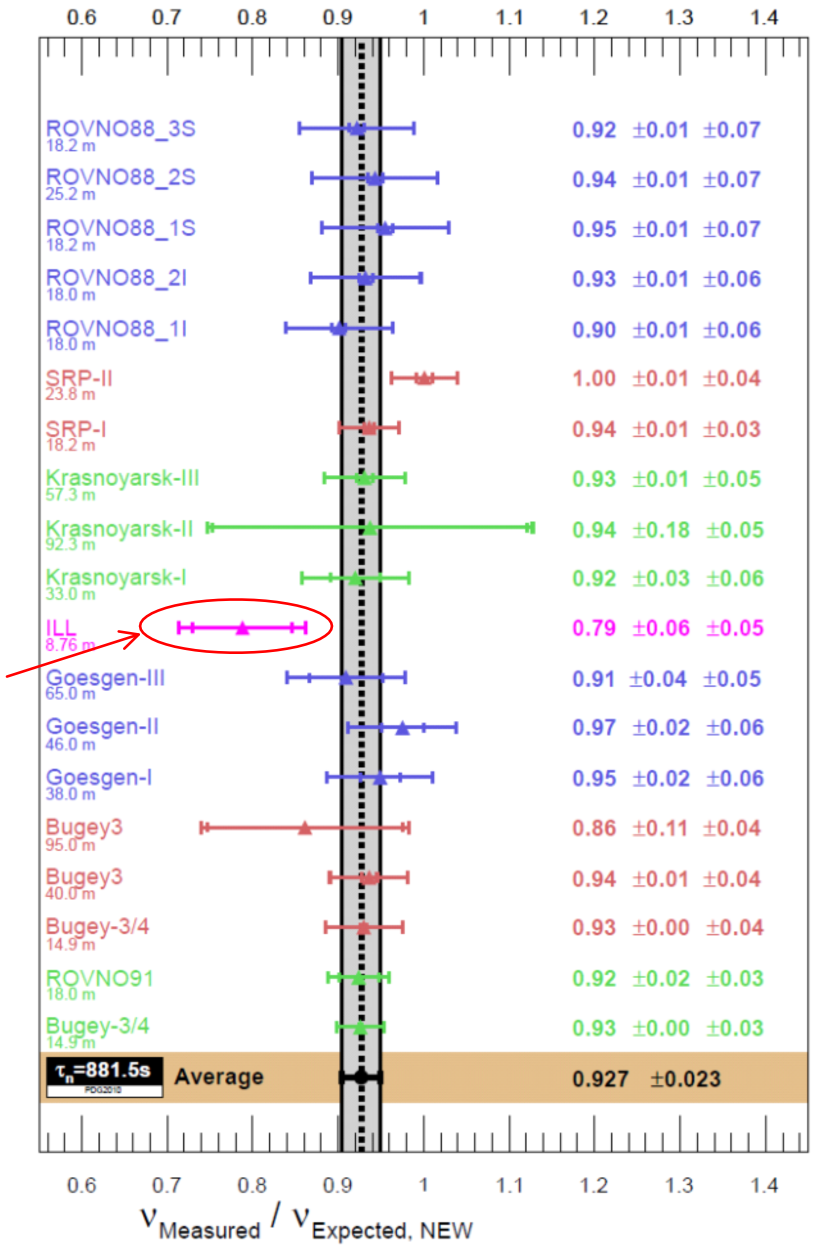


Note that a reliable estimate of the high-energy part of the spectrum is difficult. Therefore, even though there is no doubt that the new analysis improves the old results, it is unclear if the error-bars that the new analysis improves the old results, it is unclear if the error-bars are reliably estimated.

- Before the new estimate of the reactor spectrum, results of the old short-baseline oscillation experiments were compatible with the standard picture. But with the new theoretical fluxes they all have seen 3% too few events.

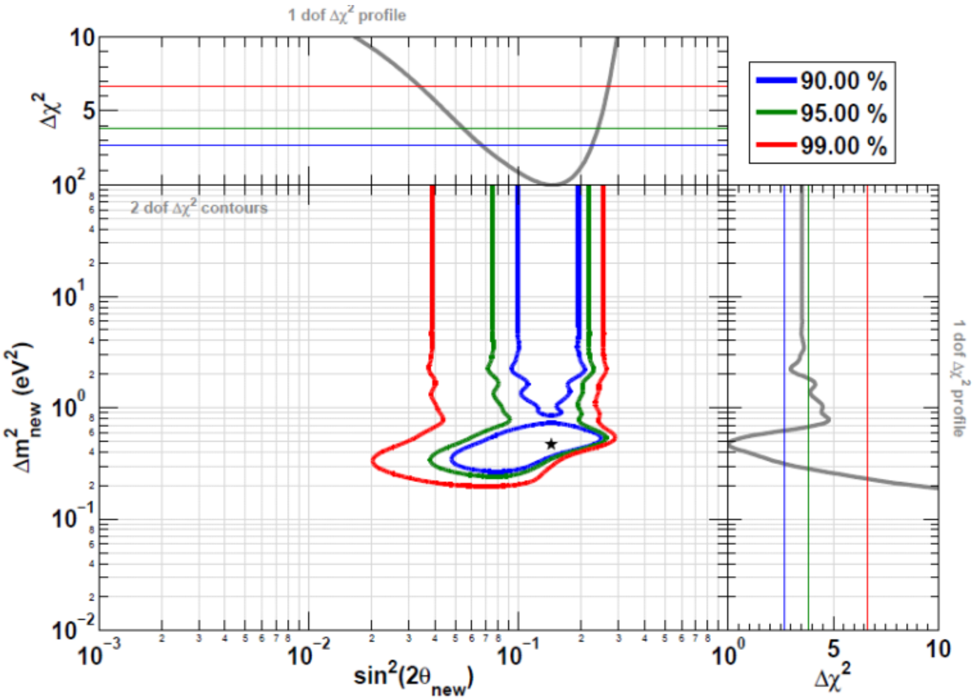
- Since typical distance from the reactor to the detector was below 100 m, they were insensitive to Δm^2_{31} driven oscillations. Therefore, if we take the new prediction for the fluxes seriously, we can interpret the experimental results as a hint towards the existence of a new sterile neutrino.

- Reanalysis of the existing experimental data.



most of the experiments are consistent with each other.

• Results of rate-only analysis:

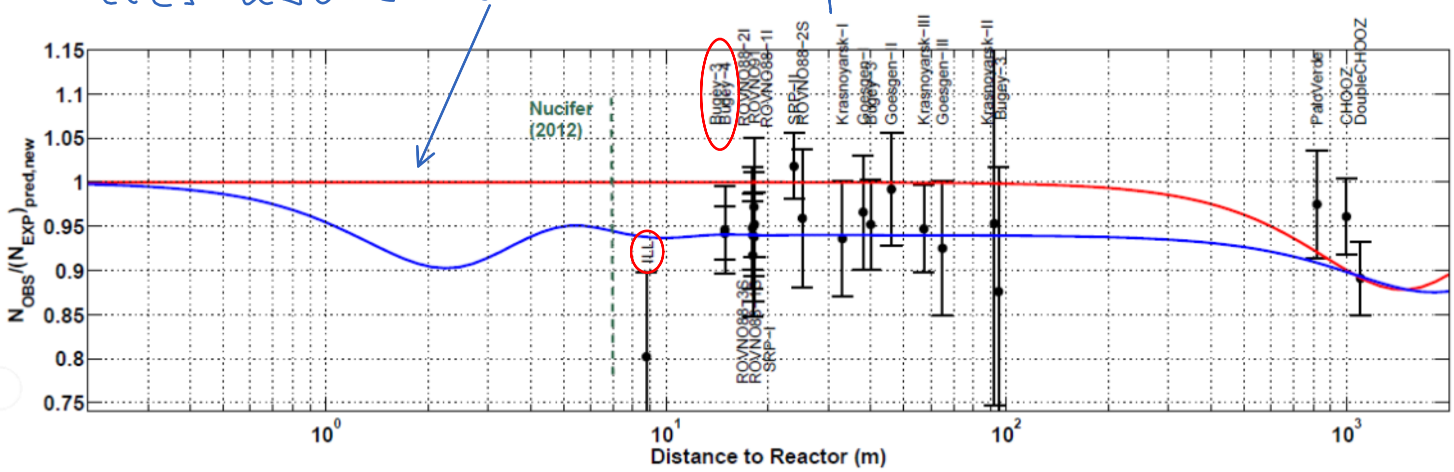


rate-only:
$\Delta m^2 \approx 0.5\, eV^2$
$\sin^2(2\theta) =$
$= 0.15$

- The analysis based on the total flux alone strongly depends on the uncertanties in the flux calculation. It would be more interesting to observe L-dependence. This will probably be done by Nucifer experiment.

- Fit to data in 3 and 3+1 schemes.

lies above most of the experiments



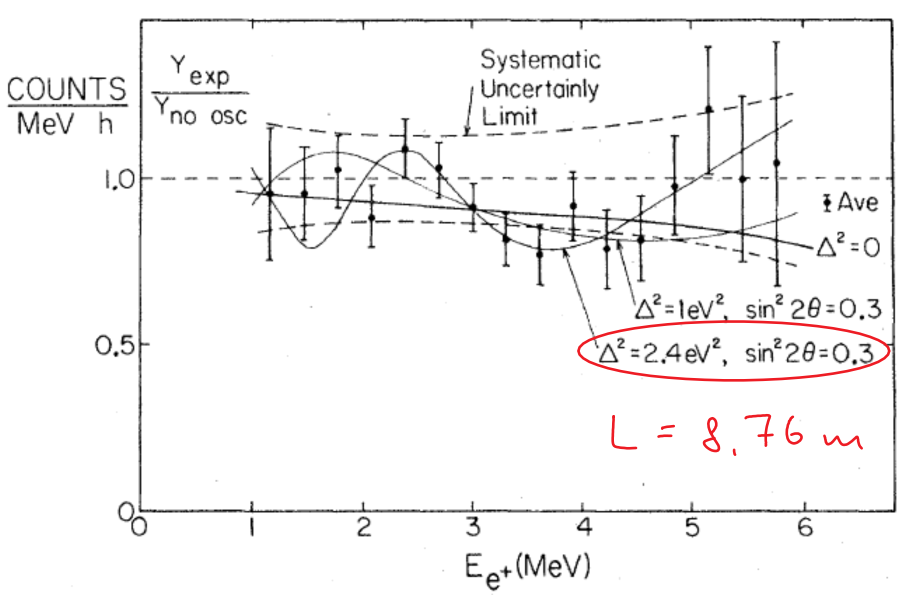
– red line assumes 3 neutrinos

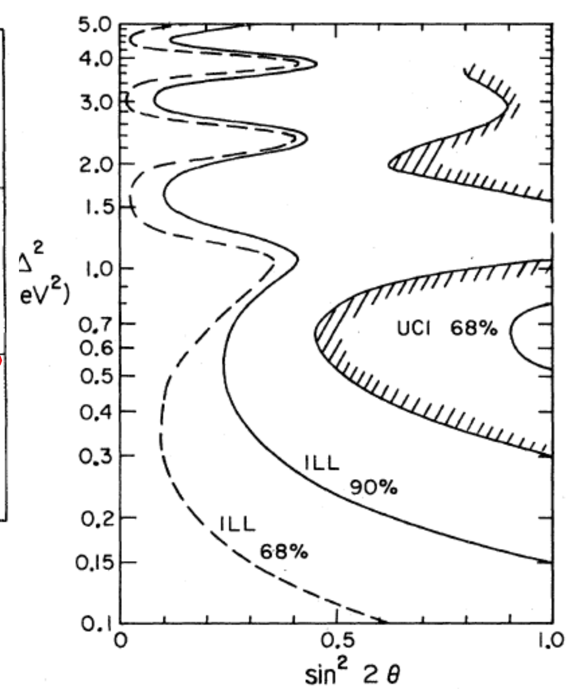
- blue line assumes $\sin^2(2\Theta_{13}) \approx 0.085$ and a new neutrino with $\Delta m^2 \gg 2\,eV^2$ and $\sin^2(2\Theta_{new}) = 0.12$.

- Out of the past experiments only ILL and Bugey were close enough to the core to see the L-dependence.

  - Bugey didn't observe any distortion of the spectrum and therefore the new neutrino should be heavier than approximately $1\,eV^2$.

  - On the other hand, there is an indication of the spectrum distortion in the ILL data. PRD 24, 1097 (1981)





MINOS

- MINOS probes oscillation into sterile neutrino by measuring NC events at two locations. NC interactions are identical for the active neutrinos. On the other hand, since sterile neutrinos do not interact via NC, oscillation into the steriles would result in an energy-dependent depletion of the flux. That is, MINOS is a disappearence experiment.

- Physical potential:

far detector, near detector

$L = 735$ km , $L = 1.04$ km

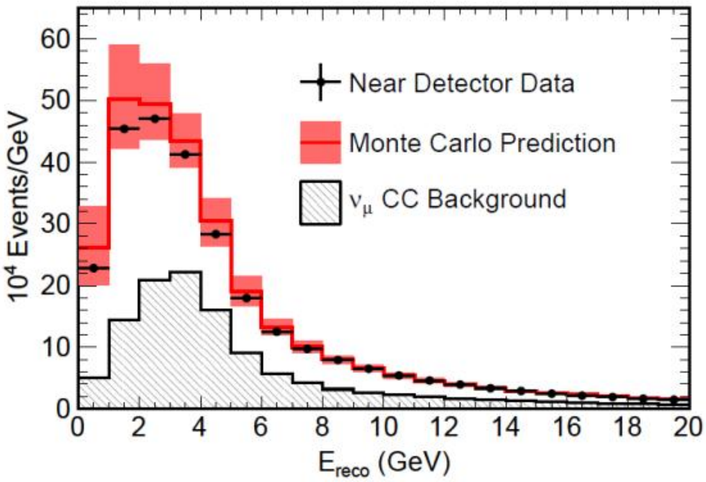
$E_\nu \simeq 3.3$ GeV

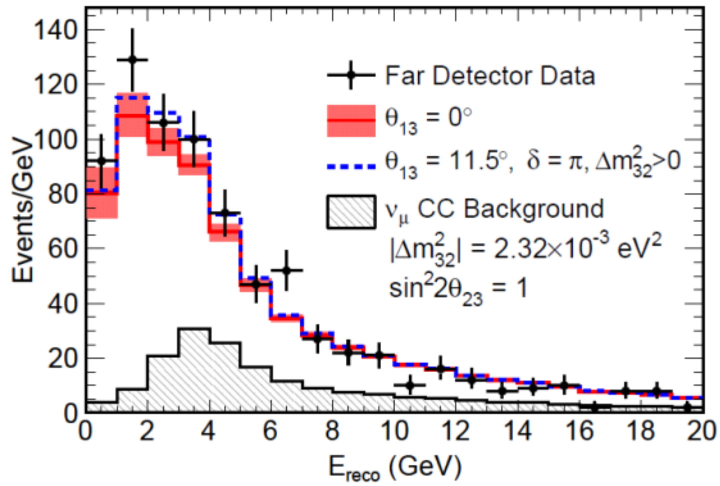
$$\frac{E}{L_{far}} \simeq \frac{3.3 \times 10^3 \times 1\,\text{MeV}}{7.3 \times 100\,\text{km}} \simeq 5 \times 10^{-3}\ \text{eV}^2$$

$$\frac{E}{L_{near}} \simeq \frac{3.3 \times 10^3 \times 1\,\text{MeV}}{10^{-2} \times 100\,\text{km}} \simeq 3\ \text{eV}^2$$

- the near detector makes it sensitive to the steriles.

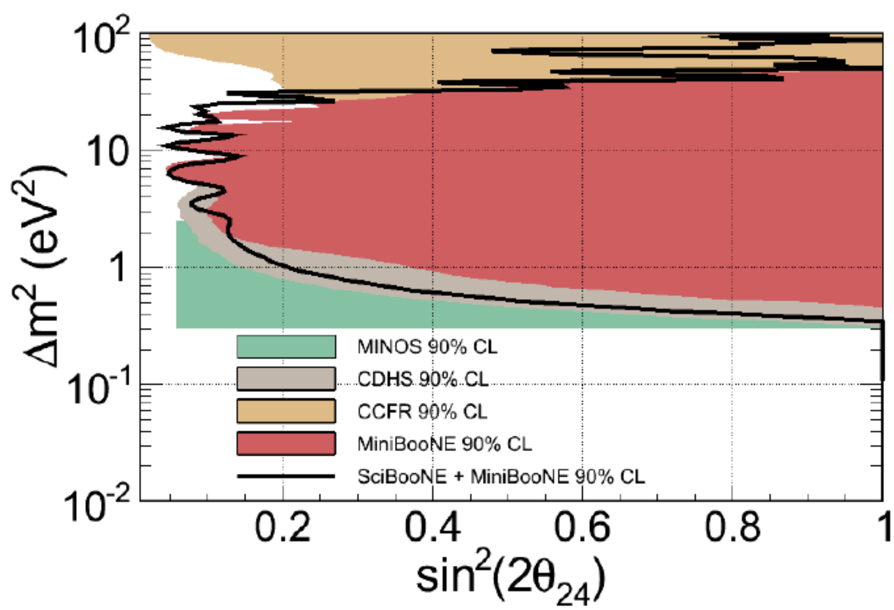
- Results: experimental results are compatible with 3ν picture





- If we insist on the existence of the sterile neutrinos, then MINOS provides us with constraints on its parameters.

3+1 scheme



- note that since the initial beam consists mainly of ν_μ, MINOS measures a different mixing angle as compared to the reactor experiments.

Global fits

- To combine all the available data we need to specify a model. Data inconsistent within one model can be consistent within another.

- The anomalies are inconsistent with 3ν model. A possible minimal extension is a 3+1 model.

- In this framework appearence and disapearence oscillation probabilities for short baseline experiments:

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

$$P_{\alpha\to\alpha} = 1 - \sin^2(2\theta_{\alpha\alpha})\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

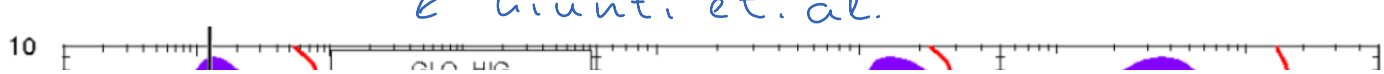
where

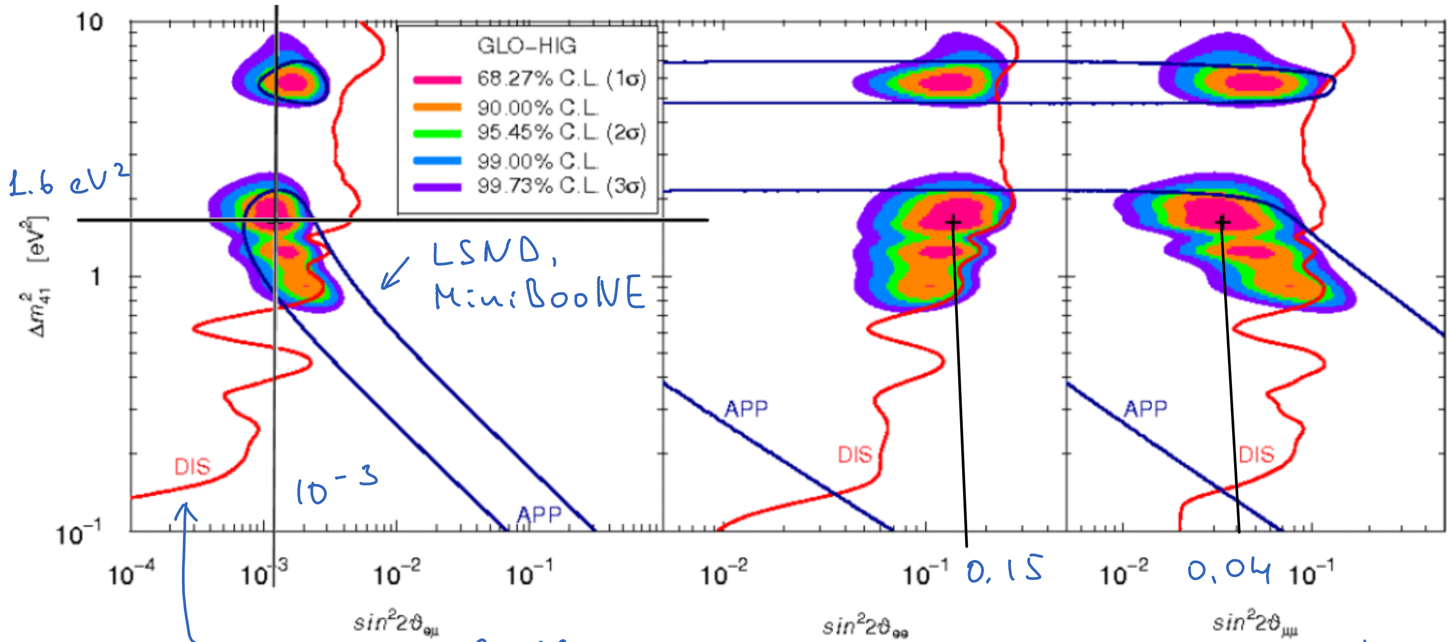
$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$$

$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

- Theoretically, combining appearence and disappearence experiments we can measure the elements of the mixing matrix.

↙ Giunti et. al.





- since the low-energy data of MiniBooNE is somewhat controversial, I only show results of a global fit that does not include the low-energy data.

- There is a tension between the appearence and disappearence experiments. Especially for eμ mixing they are barely compatible.

- For comparison let me also show results of the global fit obtained by Thomas and Joachim:

disappearence experiments

SBL only:

similar to the fit of Giunti.

	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$	χ^2/dof
3+1	1.78	0.151			50.1/67
3+2	0.46	0.108	0.89	0.124	46.5/65

appearence experiments

LSND and MiniBooNE data are in tension

appearance experiments

LSND and MiniBooNE data are in tension with the SBL data, as is evident from the next fit:

almost factor of four change.

	$\|\Delta m^2_{41}\|$	$\|U_{e4}\|$	$\|U_{\mu 4}\|$	$\|\Delta m^2_{51}\|$	$\|U_{e5}\|$	$\|U_{\mu 5}\|$	δ/π	χ^2/dof
(3+1)	(0.48)	(0.14)	(0.23)					(255.5/252)
3+2	1.10	0.14	0.11	0.82	0.13	0.12	-0.31	245.2/247
1+3+1	0.48	0.13	0.12	0.90	0.15	0.15	0.62	241.6/247

Summary

- To summarize: the experimental data are very inconclusive.

  - On one hand, there is a number of experiments which have observed a deviation from the standard picture.

  - On the other hand even experiments with very similar setups deliver different results. This makes one wonder if these results should be taken seriously

  - Finally, results of the different experiments do not fit particularly well within simple theoretical frameworks. But this, of course, may be the problem of the theoretical frameworks themselves.