Status and Prospects of eV Sterile Neutrinos

Iván Martínez Soler

Prospects of Neutrino Physics

Based on: M. Dentler, A. Hernandez-Cabezudo, J. Kopp, P.A.N. Machado, M. Maltoni, IMS, T. Schwetz, JHEP 1808 (2018) 010 (2018-08-03)

April 11th, 2019

Fermilab

Northwestern University

Why do we need to consider a ν_s with mass around 1 eV?

- **LSND**: excess of $\overline{\nu}_e$ compatible with $E/L \sim 1\text{eV}^2$
- **MiniBooNE**: excess of the ν_e and $\overline{\nu}_e$ compatible with an oscillation with $0.1 < \Delta m^2 < 1$.
- **Gallium anomaly** can be explained by an oscillation of ν_e into ν_s with $\Delta m^2 \geq 1\text{eV}^2$
- **Reactor anomaly** can be explained as an oscillation of $\overline{\nu}_e$ with $\Delta m^2 \geq 1\text{eV}^2$

Scenario 3+1

In the 3+1ν scenario, neutrino evolution is described by the Schrödinger equation

$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E}\left[U^{\dagger} Diag(0, \Delta m^2_{21}, \Delta m^2_{31}, \Delta m^2_{41})U \pm V_{mat}\right]\vec{\nu} \qquad \vec{\nu} = (\nu_e\,\nu_\mu\,\nu_\tau)^T$$

$$V_{mat} = \sqrt{2}G_F \begin{pmatrix} N_e - N_n & 0 & 0 & 0 \\ 0 & -N_n & 0 & 0 \\ 0 & 0 & -N_n & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

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- Depends on:
  - 6 mixing angles and 3 complex phases.

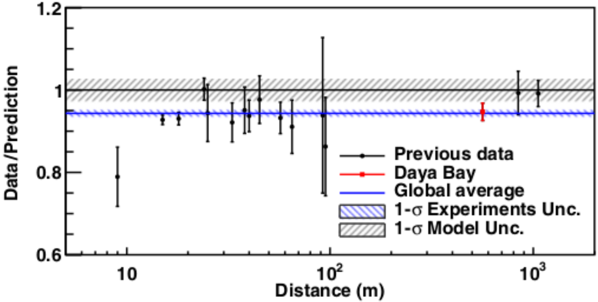
    $$U \equiv R_{34}(\theta_{34})\,R_{24}(\theta_{24},\delta_{24})\,R_{14}(\theta_{14})\,R_{23}(\theta_{23})\,R_{13}(\theta_{13},\delta_{13})\,R_{12}(\theta_{12},\delta_{12})\,,$$

  - Three mass splittings: ($\Delta m^2_{21} \sim 10^{-5}eV^2$, $\Delta m^2_{31} \sim 10^{-3}eV^2$ and Δm^2_{41})

$\overline{\nu_e}$ disappearance: Reactor anomaly

See ISHITSUKA's Talk
See Jouni's Talk

- $\overline{\nu}_e$ emitted from ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu fissions
- $E_\nu \sim 4$ MeV and $L \lesssim 1$ Km;
- The reevaluation of the $\overline{\nu}_e$ flux determined a deficit in the experimental data (reactor anomaly).
- Data/Prediction $= 0.952 \pm 0.014 \pm 0.023$ (Daya Bay), 0.918 ± 0.018 (RENO)



PRL 116, 061801 (2016)

How can be explained the reactor anomaly?

$\overline{\nu_e}$ disappearance: Reactor anomaly

Sterile neutrinos

- For $\Delta m^2_{41} \geq 0.05\text{eV}^2$

$$P_{ee} \approx 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

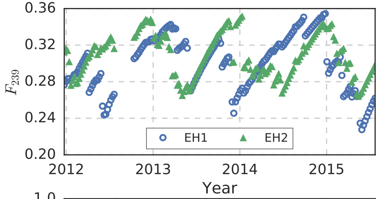
- The flux coming from all the isotopes would be equally affected

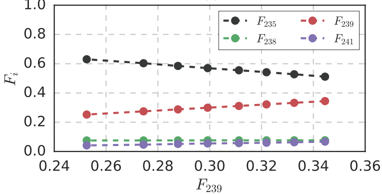
$\overline{\nu_e}$ disappearance: Reactor anomaly

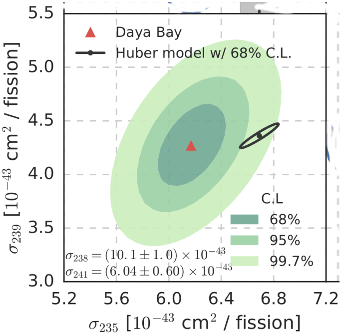
Problem with the Flux prediction

See ISHITSUKA's Talk

- Daya Bay measured the contribution of the different isotopes.
- Discrepancies between measurement/prediction:
  - 1.7σ in the overall yield.
  - 3.1σ in the dependence of the yield with the fuel composition.
- Preference for ^{235}U as a source of the anomaly







Phys. Rev. Lett. 118 (2017) 251801
[arXiv:1704.01082]

Can be excluded the existence of ν_s?

We can compare the two hypotheses:

- Free fluxes (no steriles)
  - ^{235}U and ^{239}Pu vary freely.
- Fluxes fixed + ν_s
  - Huber+Muller flux prediction.
  - $\Delta m^2_{41} > 0.05\text{eV}^2$
- Preference of Daya Bay for the free fluxes hypothesis (2.7σ)
- Sterile neutrino hypothesis provides an acceptable gof

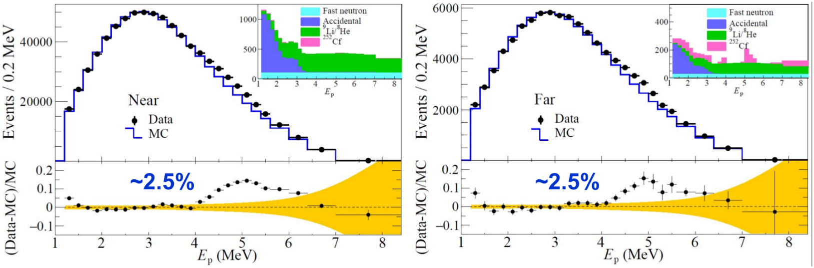
	PG
Free fluxes	0.7
Fluxes fixed + ν_s	0.18

M. Dentler, A. Hernandez-Cabezudo, J. Kopp, M. Maltoni, T. Schwetz, JHEP 1711 (2017) 099

Flux excess at 5 MeV

See Jouni's Talk

- The ratio of measured over the predicted flux shows an excess at 5 MeV.
- The excess is present in all experiments.
- The "bump" is time independent and it is correlated with the reactor power.

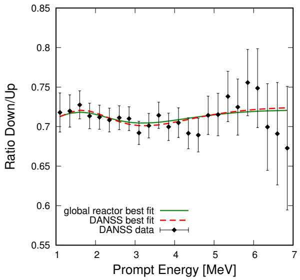


I. Tu (RENO), NEUTRINO 2018

$\overline{\nu_e}$ disappearance: Reactor neutrinos

DANSS

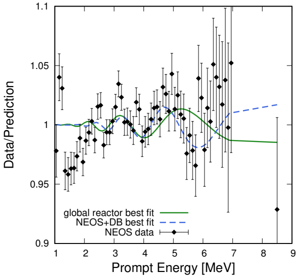
- Measurement at two locations (10.7 m and 12.7 m)



Phys.Lett. B787 (2018) 56-63
[1804.04046]

NEOS

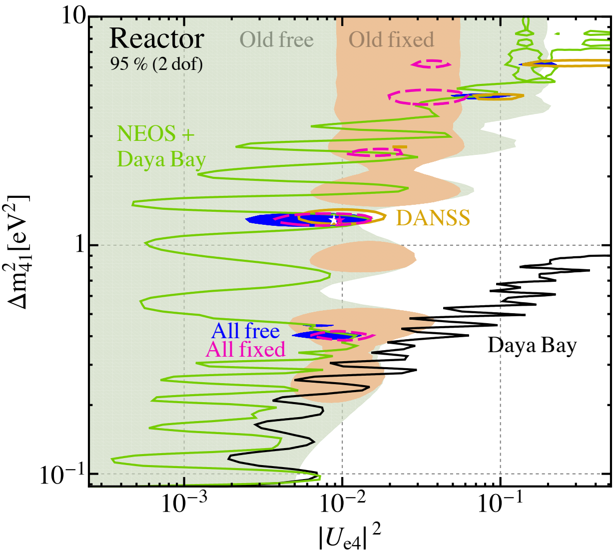
- Baseline $\sim$ 23.7 m.
- Use Daya Bay as a prediction of non-oscillation



PRL 118 (2017) 121802
[arXiv:1610.05134]

The combined analysis between NEOS and DANSS excluded the non-oscillation hypthesis to 3.3σ.

$\overline{\nu_e}$ disappearance: global analysis of reactor experiments

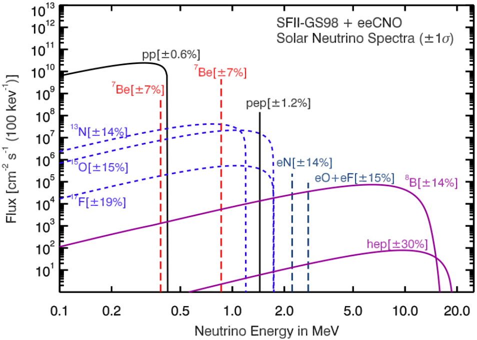


Preference of $\sim 3\sigma$ ($\sim 3.5\sigma$) for ν_s for free (fixed) fluxes.

ν_e disappearance: Solar neutrino measurement

- ν_e is produced by two different nuclear fusion reactions: pp chains and CNO cycles.
- The flux is composed by ν_e with a characteristic energy (^7Be,pep) or spectrum (pp, CNO, ^8B, hep).
- Sensitivity to:
  - ν_e disappearance channel.

Phys. Rev. D 98, 030001 (2018)

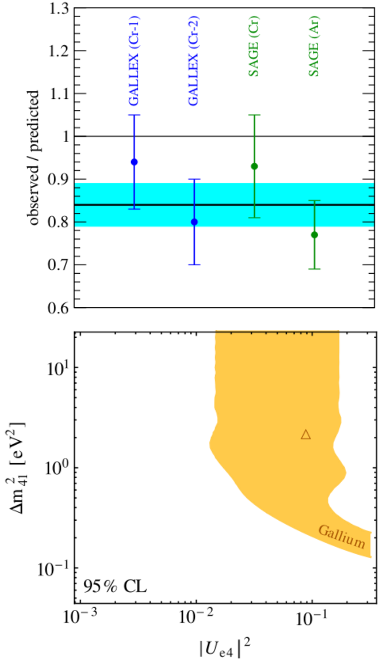


Gallium anomaly

- GALLEX and SAGE (solar Gallium experiments) has been tested by a radioactive source (^{51}Cr, ^{37}Ar)
- Ratio measured/predited shows a $\sim 3\sigma$ deficit [1]

$$R = 0.84 \pm 0.05$$

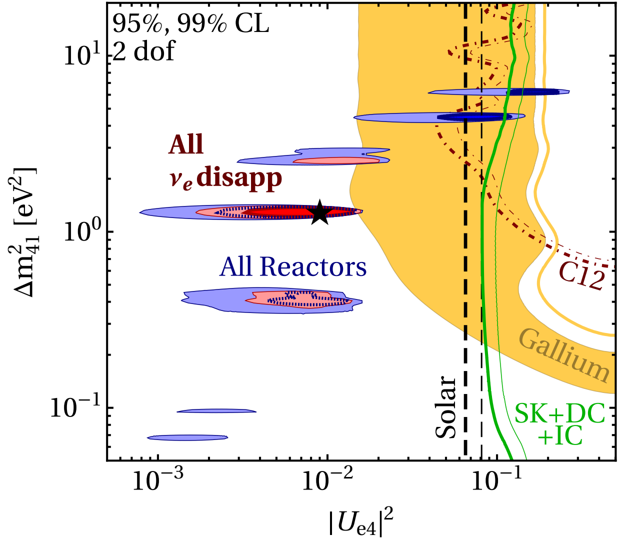
- The anomaly can be explained by $\Delta m^2_{41} \geq 1\text{eV}^2$



M. Maltoni, NEUTRINO 2018

[1] JHEP 1305 (2013) 050

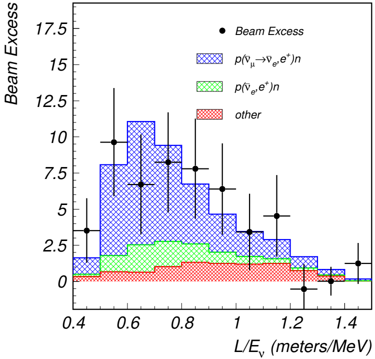
Results: ν_e and $\overline{\nu_e}$ diappearance



ν_e apperance

LSND

- The first channel that pointed to ν_s with masses in the eV scale.
- Excess of $\overline{\nu}_e$ in a $\overline{\nu}_\mu$ beam ($E_\nu \sim 30$ MeV, $L \sim 35$ m);
- $\pi^+ \to \mu^+\nu_\mu$, $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$
- Including the contribution from DaR and DiF;

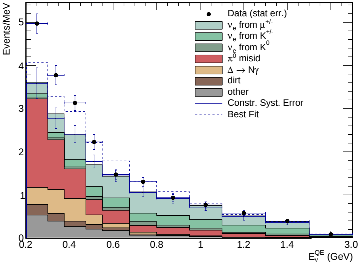


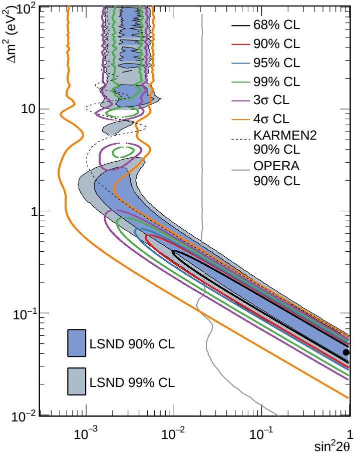
A. Aguilar-Arevalo et al. [LSND collab], Phys.Rev. D64 (2001) 112007

ν_e apperance

MiniBooNE

- Designed to search for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ at the same L/E as LSND;
- observe an excess at low energy in the $\overset{(-)}{\nu}_e$ $(200 \leq E_\nu \leq 1250$ MeV).
- Combine analysis with LSND has a preference for ν_s of 6σ





Phys.Rev.Lett. 121 (2018) no.22, 221801

ν_e apperance

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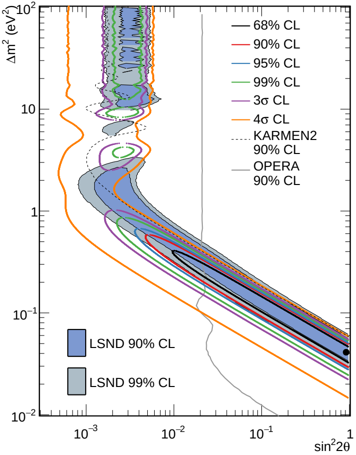
- Combine analysis with LSND has a preference for ν_s of 6σ

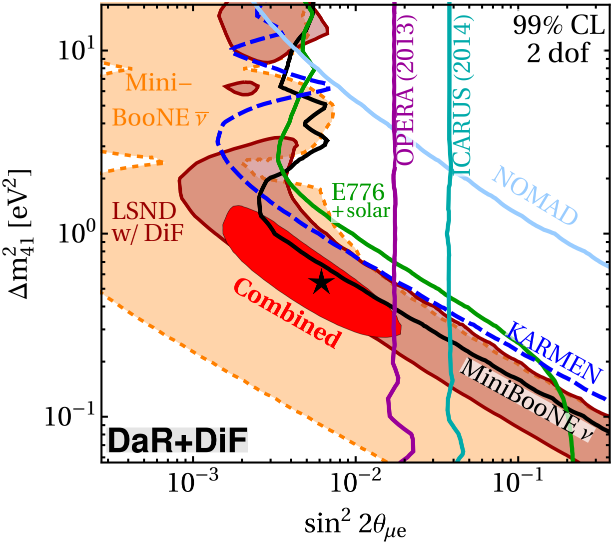
KARMEN, NOMAD, E776, ICARUS and OPERA couldn't confirm/reject the oscillation.



Phys.Rev.Lett. 121 (2018) no.22, 221801

ν_e apperance

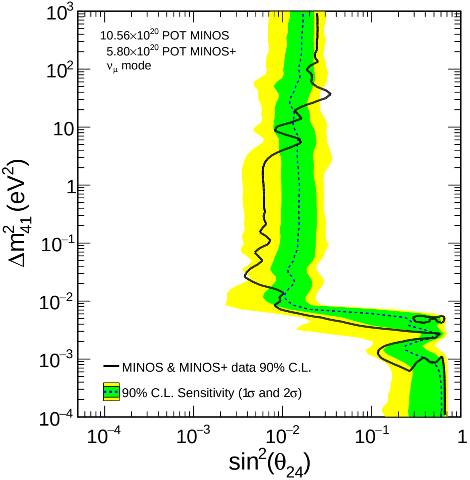
$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$



ν_μ disappearance

LBL experiments:

- NOνA searches based on NC
  - Narrow energy beam $\rightarrow \Delta m^2_{41} \in [0.05, 0.5]\mathrm{eV}^2$
- MINOS/MINOS+ combined analysis
  - For $\Delta m^2_{41} \in [10^{-3}, 10^{-1}]\mathrm{eV}^2$ oscillation in the **FAR** detector.
  - For $\Delta m^2_{41} \in [1, 100]\mathrm{eV}^2$ oscillation in the **NEAR** detector.

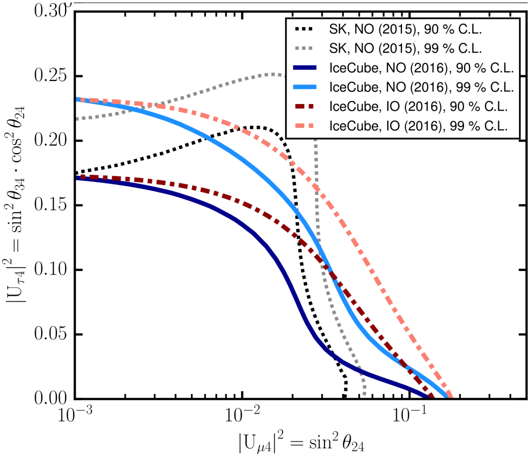


Phys.Rev.Lett. 122 (2019) no.9, 091803

ν_μ disappearance

Low energy Atmospheric neutrinos:

- DeepCore, SK
- Cannot resolve the oscillations for $\Delta m^2_{41} \sim 1\text{eV}^2$.
- $U_{\mu 4}$ modify the overall normalization.
- $U_{\tau 4}$ modify the energy of the neutrino oscillation.



Phys. Rev. D91 (2015), no. 7 072004, [1410.7227]

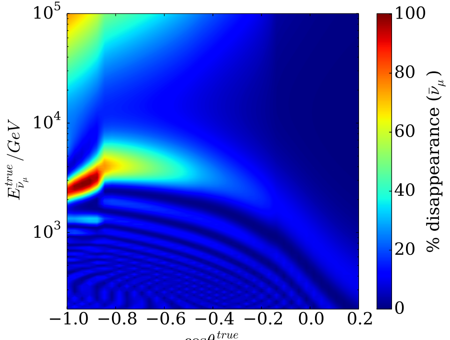
ν_μ disappearance

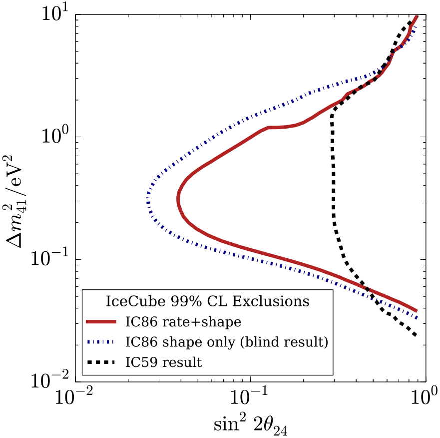
High-energy atmospheric neutrinos:

- IceCube
- Resonance for neutrinos crossing the Earth at TeV scale

$$E_{res} = 5.73\text{TeV}\left(\frac{5\text{g/cm}^3}{\rho_\oplus}\right)\left(\frac{\Delta m^2_{41}}{1\text{eV}^2}\right)$$

- The resonance take place for $\bar{\nu}$.





Phys. Rev. Lett. 117 (2016), no. 7 071801, [1605.01990].

ν_μ disappearance

Oscillation channels are not independent

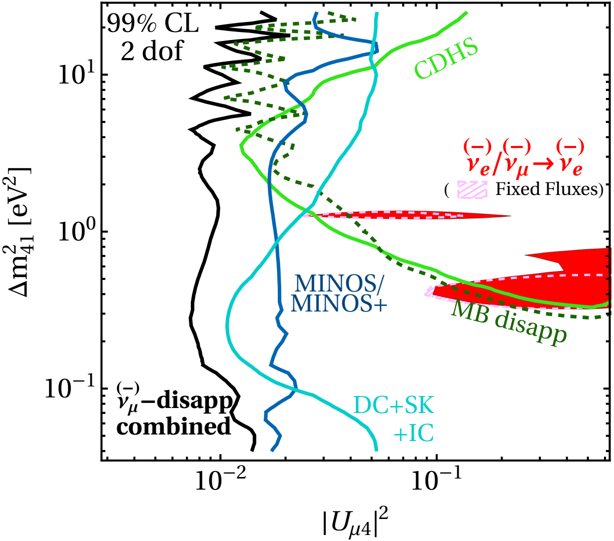
In the short-baseline limit ($\Delta m^2_{21} L/4E << 1$ and $\Delta m^2_{31} L/4E << 1$)

$$
\begin{aligned}
P_{ee}^{SBL} &= 1 - 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \\
P_{\mu e}^{SBL} &= 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \\
P_{\mu\mu}^{SBL} &= 1 - 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)
\end{aligned}
$$

Are the different channels compatible?

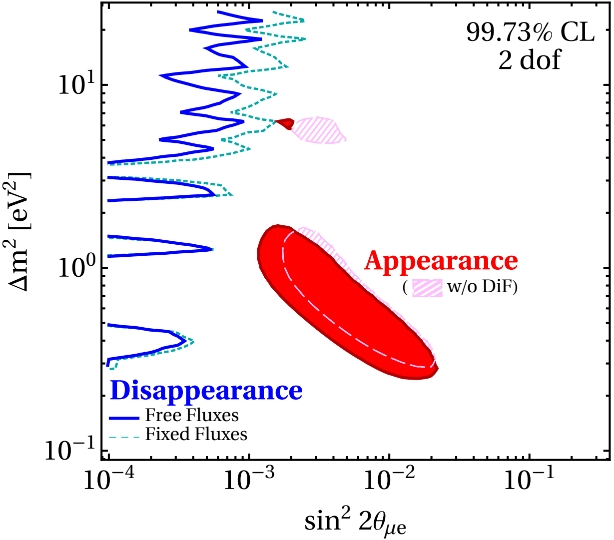
$$
P_{e\mu} > 0 \quad \rightarrow \quad \begin{array}{l} P_{ee} > 0 \\ P_{\mu\mu} > 0 \end{array}
$$

Results: ν_μ disappearance channel



Appearance/disappearance tension

Strong tension between apperance and disapperance channels
$PG = 3.7 \times 10^{-7}$



Appearance/disappearance tension

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	$\chi^2_{\text{PG}}/\text{dof}$	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

Conclusion

- There are several anomalies in the ν_e disappearance and ν_e appearance.
- Most of these anomalies can be explained in the 3+1ν scenario.
- Strong tensions between the appearance and the disappearance data.

Thank you!

Backup:

Daya-Bay studied the number of IBD yield as a function of F_{239}

$$\sigma_f(F_{239}) = \overline{\sigma_f} + \frac{d\sigma_f}{dF_{239}}(F_{239} - \overline{F}_{239})$$

- Incompatible with a constant $\overline{\nu}_e$ flux ($d\sigma_f/dF_{239} = 0$) by 10σ
- Discrepancie of 1.7σ between prediction/measurement of σ_f
- Tension of 3.1σ between prediction/measurement of $d\sigma_f/dF_{239}$
  - Different contribution to $d\sigma_f/dF_{239}$ from different isotopes.
  - Disagreemnet between prediction/measurement of 2.6σ.