Status of Light Sterile Neutrinos

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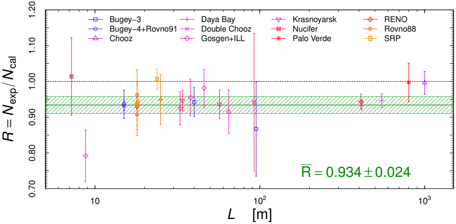
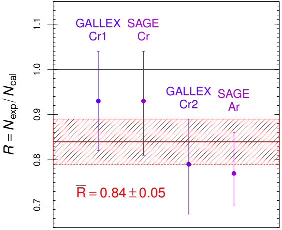
Short-Baseline Neutrino Oscillation Anomalies

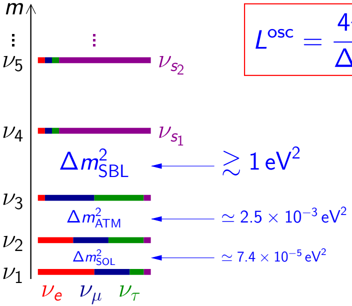
Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ $(\sim 3\sigma)$



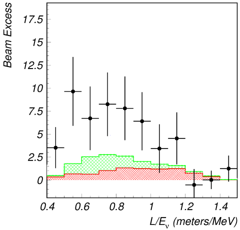
Gallium Anomaly: $\nu_e \to \nu_x$ $(\sim 3\sigma)$



$$L^{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2}$$



LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ $(\sim 4\sigma)$



Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

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

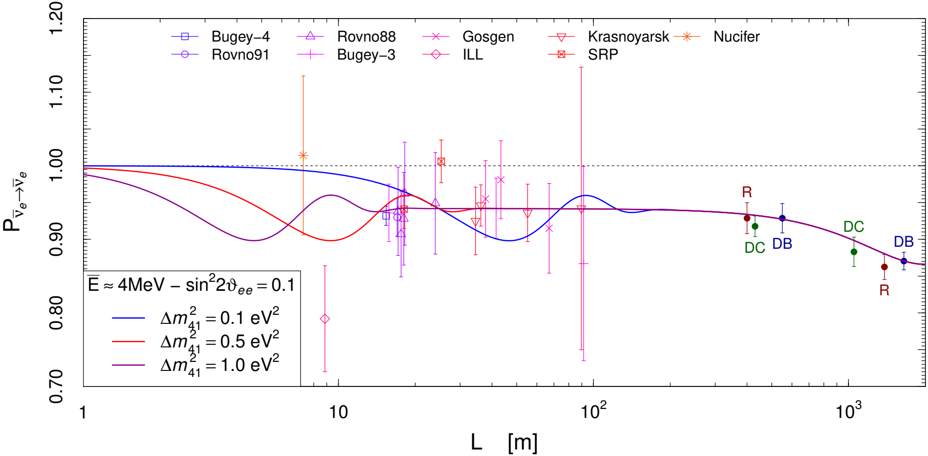
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- $\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

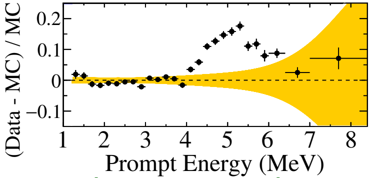
Short-Baseline Reactor Neutrino Oscillations



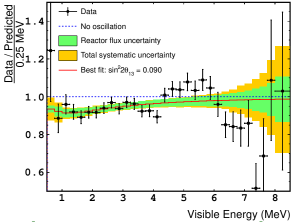
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion

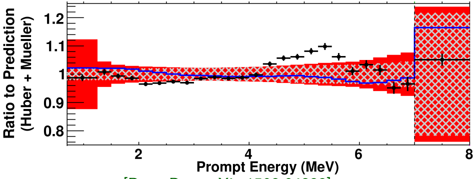
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in RENO, DC, DB).
- It is likely due to a theoretical miscalculation of the spectrum.
- Heretic solution: detector energy nonlinearity. [Mention et al, PLB 773 (2017) 307]

- $\sim 3\%$ effect on total flux, but if it is an excess it increases the anomaly!
- No post-bump complete calculation of the neutrino fluxes.
- Nominal Huber-Mueller flux calculation uncertainty: $\sim 2.7\%$.
- Post-bump estimate of the flux uncertainty due to unknown forbidden decays: $\sim 5\%$.

[Hayes and Vogel, ARNPS 66 (2016) 219]

Reactor Fuel Evolution

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of

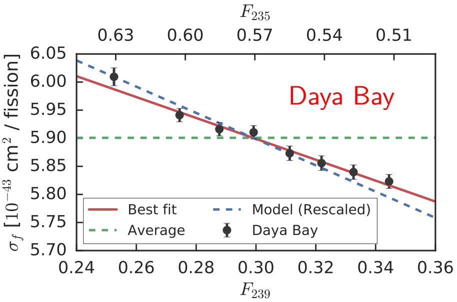
  $^{235}U \quad ^{238}U \quad ^{239}Pu \quad ^{241}Pu$

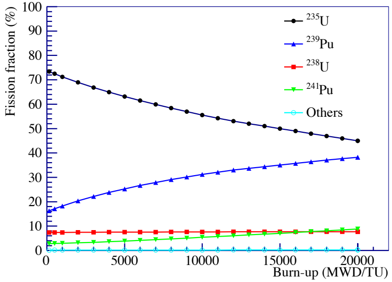
- Effective fission fractions:

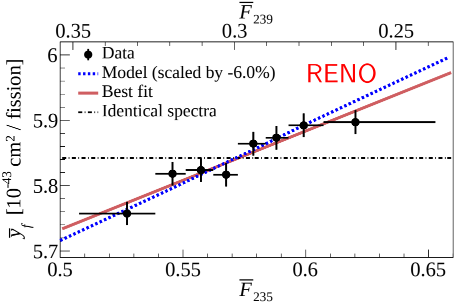
  $F_{235} \quad F_{238} \quad F_{239} \quad F_{241}$

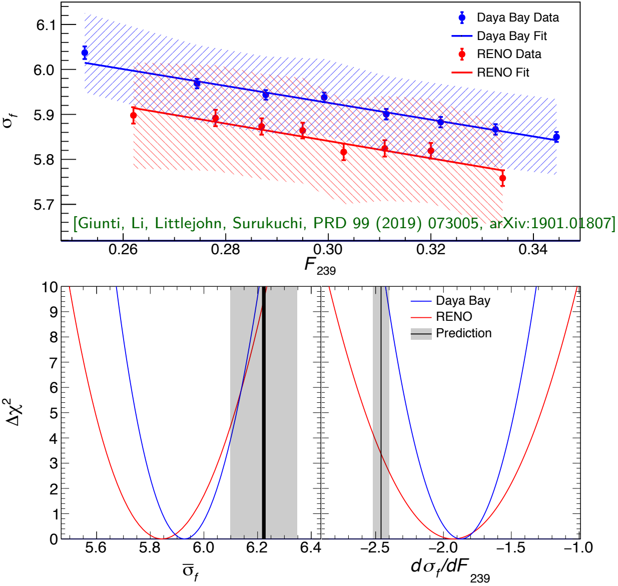
- Cross section per fission (IBD yield):

$$\sigma_f = \sum_{k=235,238,239,241} F_k \, \sigma_{f,k}$$

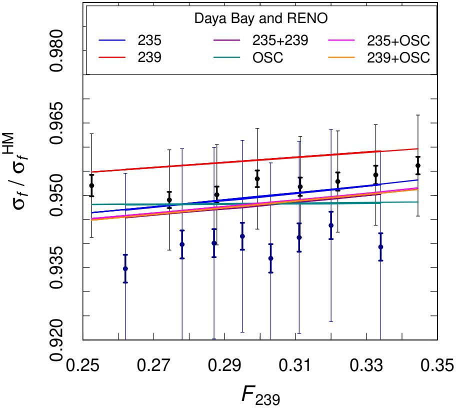


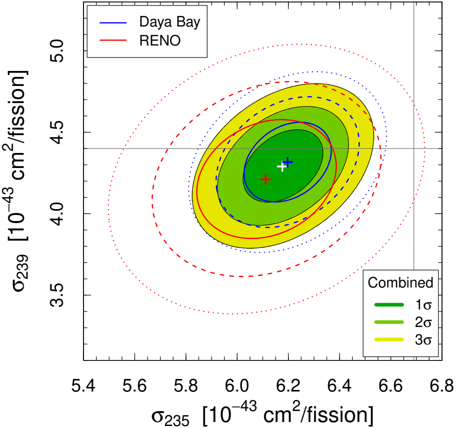






$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}} \left(F_{239} - \overline{F}_{239}\right)$$





235: $r_{235} = 0.985 \pm 0.015$

$\chi^2/\text{NDF} = 9.0/15 \quad \text{GoF} = 88\%$

OSC: $P_{\bar{\nu}_e \to \bar{\nu}_e} = 0.939 \pm 0.024$

$\chi^2/\text{NDF} = 16.3/15 \quad \text{GoF} = 37\%$

235+239: $\begin{cases} r_{235} = 0.923 \pm 0.015 \\ r_{239} = 0.975 \pm 0.032 \end{cases}$

$\chi^2/\text{NDF} = 8.7/14 \quad \text{GoF} = 85\%$

235+OSC: $\begin{cases} r_{235} = 0.938 \pm 0.029 \\ P_{\bar{\nu}_e \to \bar{\nu}_e} = 0.986 \pm 0.022 \end{cases}$

$\chi^2/\text{NDF} = 8.8/14 \quad \text{GoF} = 85\%$

[Giunti, Li, Littlejohn, Surukuchi, arXiv:1901.01807]

- Daya Bay and RENO favor a suppression of the ^{235}U flux (235) over oscillations (OSC).
- However, a better fit is obtained with the hybrid model 235+OSC.
- Moreover, the addition of other reactor data favors oscillations or, better, ^{235}U and/or ^{239}U flux suppression plus oscillations.

[Giunti, Ji, Laveder, Li, Littlejohn, JHEP 1710 (2017) 143, arXiv:1708.01133]

- Even if there are short-baseline neutrino oscillations, it is likely that the reactor antineutrino flux calculations must be corrected (most likely the ^{235}U flux) to fit:
  1. The 5 MeV bump
  2. The fuel evolution data
- The search for short-baseline neutrino oscillations needs

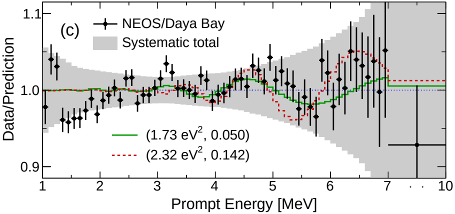
model-independent information

$\Uparrow$

ratios of spectra at different distances

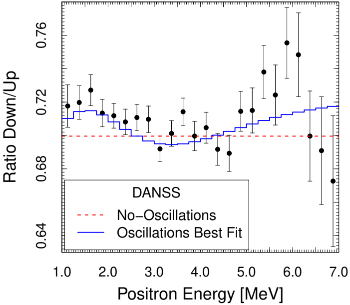
Reactor Spectral Ratios

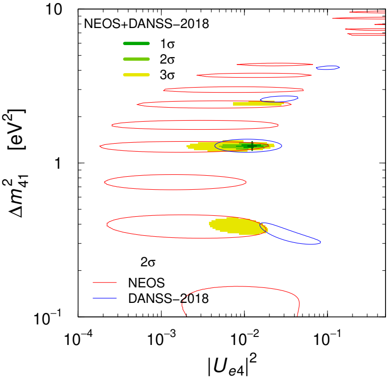
NEOS [PRL 118 (2017) 121802 (arXiv:1610.05134)]



DANSS-2018

[PLB 787 (2018) 56, arXiv:1804.04046]





2018 model independent indication in favor of SBL oscillations

NEOS: $\sim 1.7\sigma$

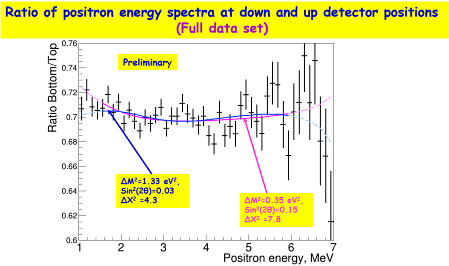
DANSS-2018: $\sim 2.7\sigma$

Combined: $\sim 3.5\sigma$

[Gariazzo, Giunti, Laveder, Li, arXiv:1801.06467]

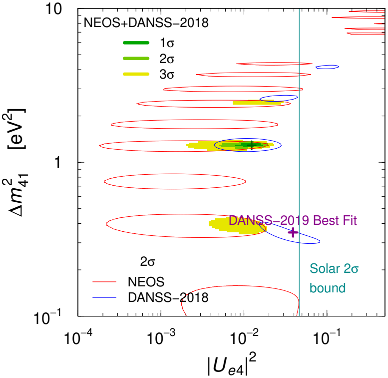
[Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

New DANSS results @ EPS-HEP 2019



- The best 4ν point (ΔM^2=0.35eV², $Sin^2(2\theta)$=0.15, ΔX^2 =7.8) has CL of 1.8σ.
- Best point in old data (ΔM^2=1.33 eV²) is also shown

[Danilov @ EPS-HEP 2019]



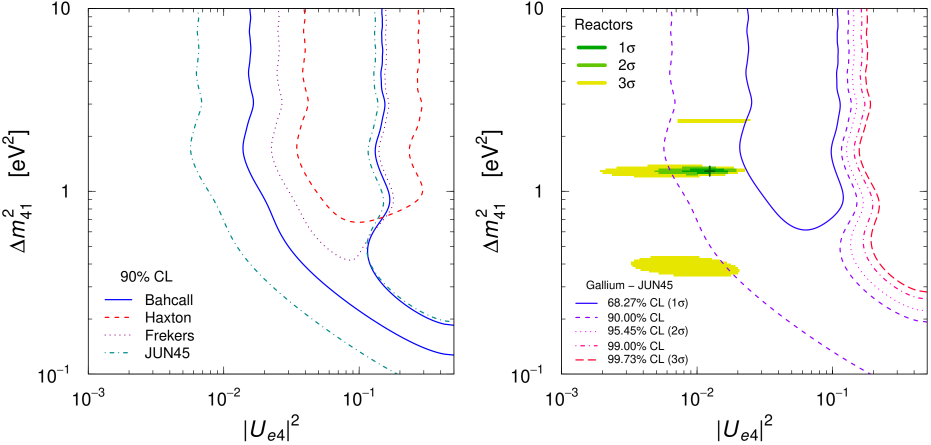
- The DANSS-2019 best fit has too large mixing.
- The agreement between NEOS and DANSS has diminished.
- Reactor indications in favor of SBL oscillations seem to be fadind away.
- We wait independent checks of PROSPECT, STEREO and SoLiD.

The Gallium Anomaly Revisited

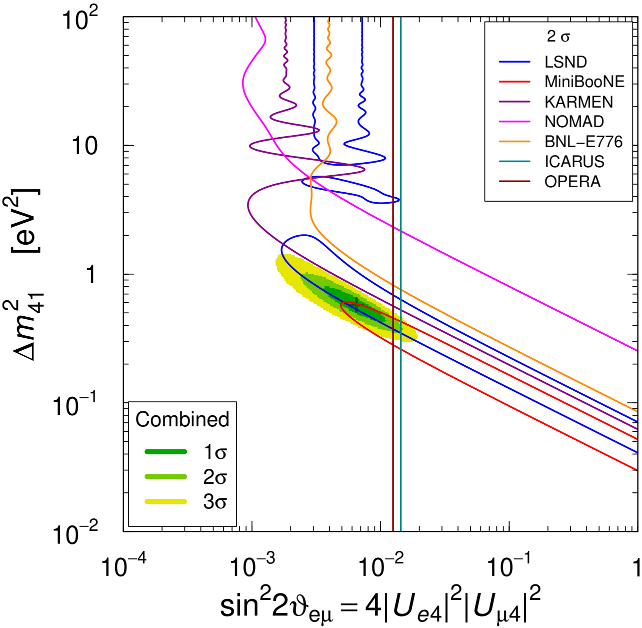
[Kostensalo, Suhonen, Giunti, Srivastava, arXiv:1906.10980]

- New JUN45 shell-model calculation of the cross section of

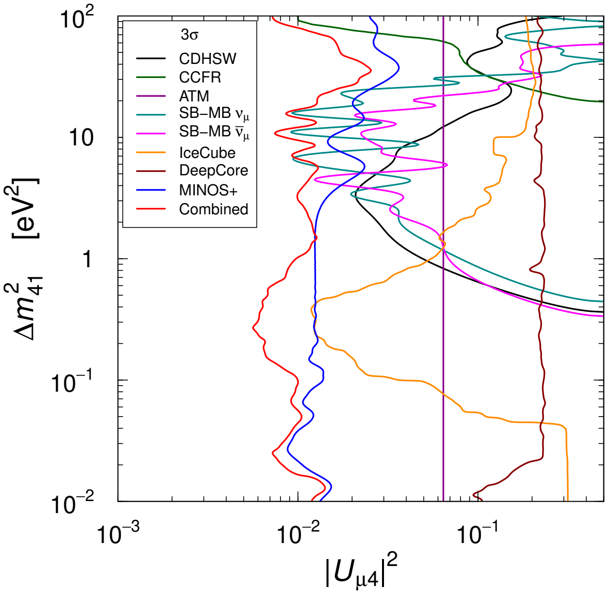
$$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$$



$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



ν_μ and $\bar{\nu}_\mu$ Disappearance



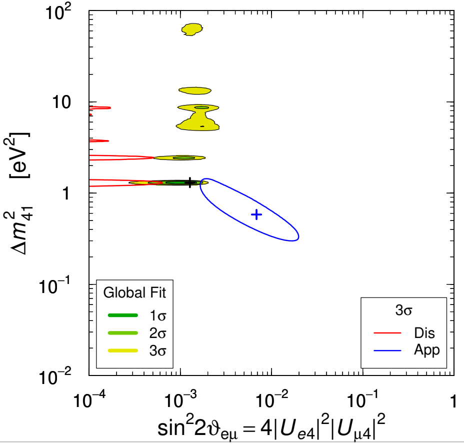
[Gariazzo, Giunti, Ternes, in preparation]

Global Appearance-Disappearance Tension

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Global Fit:

  $\chi^2/\text{NDF} = 831.7/797$

  $\text{GoF} = 19\%$

  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 42.8/2$

  $\text{GoF}_{\text{PG}} = 5 \times 10^{-10}$ $\leftarrow$ ☹
- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

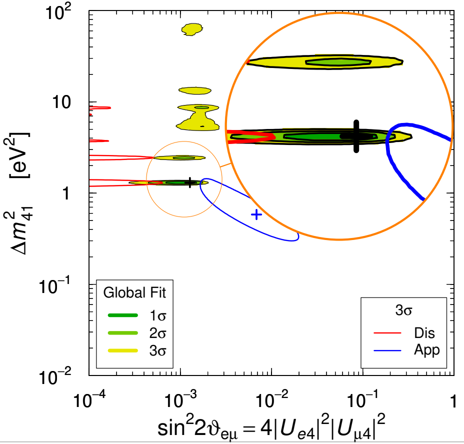
[Giunti, Zavanin, MPLA 31 (2015) 1650003]

Global Appearance-Disappearance Tension

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$



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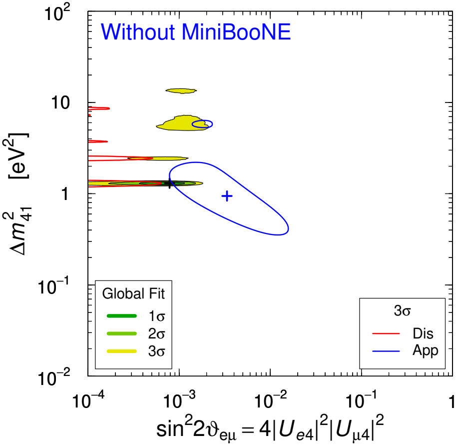
  $\text{GoF}_{\text{PG}} = 5 \times 10^{-10}$ ← ☹

- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[Giunti, Zavanin, MPLA 31 (2015) 1650003]

Global Fit Without MiniBooNE



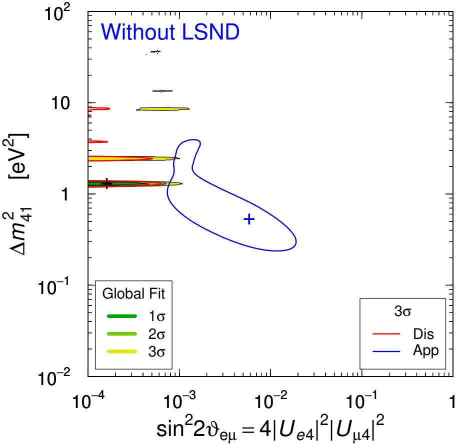
$\chi^2/\text{NDF} = 768.9/763$

$\text{GoF} = 43\%$

$\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 28.7/2$

$\text{GoF}_{\text{PG}} = 6 \times 10^{-7}$ ← ☹

Global Fit Without LSND



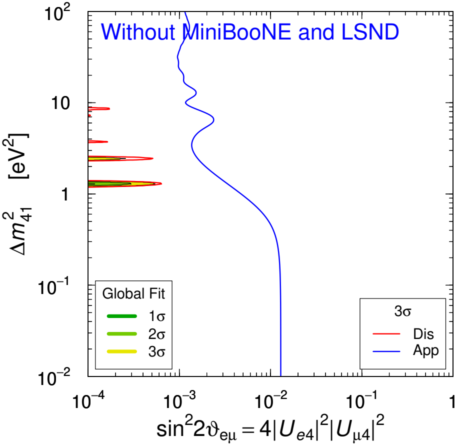
$\chi^2/\text{NDF} = 802.9/793$

$\text{GoF} = 40\%$

$\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 22.1/2$

$\text{GoF}_{\text{PG}} = 2 \times 10^{-5}$ ← ☹

Global Fit Without LSND and MiniBooNE



$\chi^2/\mathrm{NDF} = 727.4/759$

$\mathrm{GoF} = 79\%$

$\chi^2_{\mathrm{PG}}/\mathrm{NDF}_{\mathrm{PG}} = 0/2$

$\mathrm{GoF}_{\mathrm{PG}} = 1 \quad \leftarrow$ ☺

Conclusions

- Neutrinos can be powerful messengers of new physics beyond the SM as the existence of light sterile neutrinos indicated by the reactor, Gallium and LSND anomalies.
- Exciting 2018 model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments in approximate agreement with the reactor and Gallium anomalies.
- 2019 DANSS data do not confirm the 2018 indication and the reactor indications in favor of SBL oscillations seem to be fadind away.
- Important checks in the near future by the reactor experiments PROSPECT, STEREO, SoLid. (Neutrino-4?)
- Independent tests through the effect of m_4 in β-decay (KATRIN), electron-capture (ECHo, HOLMES) and $\beta\beta_{0\nu}$-decay experiments.
- The MINOS+ bound (if correct) disfavors the LSND and MiniBooNE short-baseline $\nu_\mu \to \nu_e$ signals.
- Status of Light Sterile Neutrinos? They do not seem to feel well.