Towards 3+1 Neutrino Mixing

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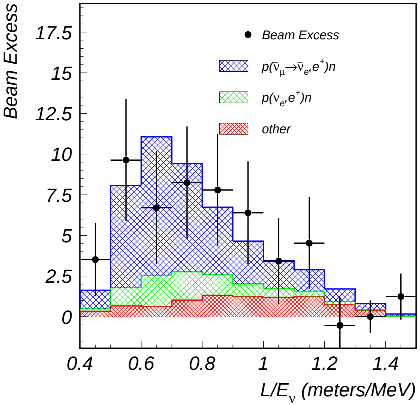
Frontiers in Neutrino Physics

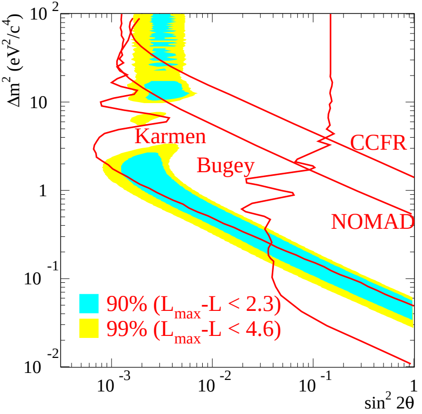
4-6 October 2011, APC, Paris, France

LSND

[LSND, PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\text{m}$ $\quad 20\,\text{MeV} \le E \le 200\,\text{MeV}$



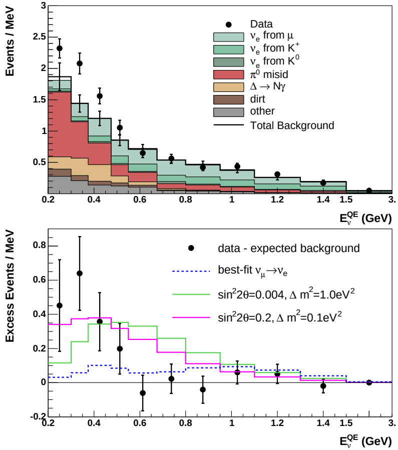


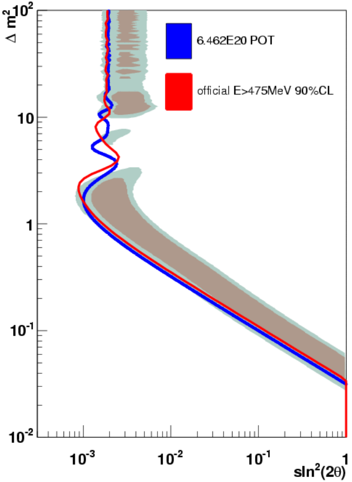
$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \quad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$

MiniBooNE Neutrinos

[PRL 98 (2007) 231801; PRL 102 (2009) 101802]

$\nu_\mu \to \nu_e$ $\qquad L \simeq 541\,\text{m}$ $\qquad 475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$





[MiniBooNE, PRL 102 (2009) 101802, arXiv:0812.2243]

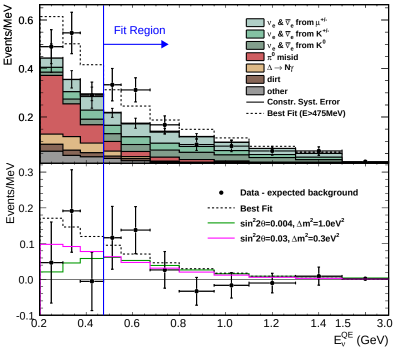
[Djurcic, arXiv:0901.1648]

Low-Energy Anomaly!

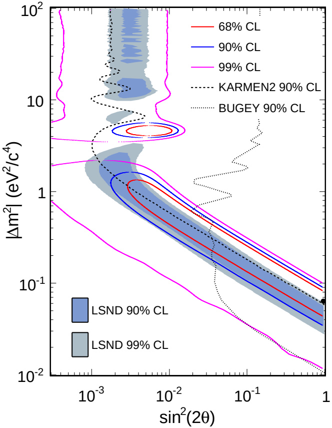
MiniBooNE Antineutrinos

[PRL 103 (2009) 111801; PRL 105 (2010) 181801]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 541\,\text{m}$ $\quad 475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$



[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

Similar L/E but different L and E $\Longrightarrow$ Oscillations!

Updated MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Result

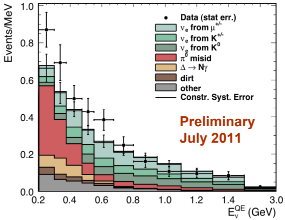
See E. Zimmerman talk yesterday for details

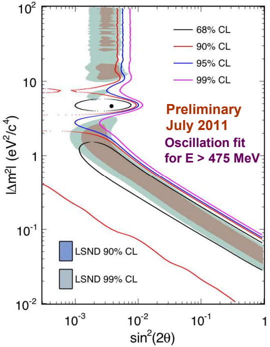
- Updated result from previous publication
  - 5.66E20 ⇒ 8.58E20 protons-on-target (x1.5)
  - Reduced systematic uncertainties especially backgrounds from beam K$^+$ decays

- For E > 475 MeV (>200 MeV), oscillations favored over background only (null) hypothesis at the 91.1% CL (97.6% CL)
  - Consistent with LSND but less strong than previous result (99.4%)
  - Best fit: χ^2 prob. = 35.5% (51%)
    Null: χ^2prob. = 14.9% (10%)

- Low energy excess now more prominent for antineutrino running than previous result
  - For E< 475 MeV, excess = 38.6 ± 18.5
    (For all energies, excess = 57.7 ± 28.5)
  - Neutrino and antineutrino results are now more similar.

- MiniBooNE will continue running through spring 2012 (at least) towards the request of 15E20 pot (~x2 from this update)
  - Full data set will probe LSND signal at the 2-3 sigma level



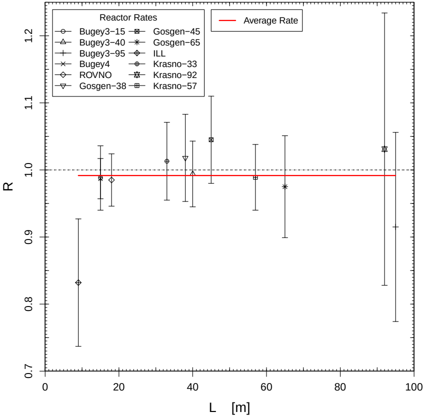


from M. Shaevitz, PANIC11, 26 July 2011

Reactor Antineutrino Anomaly

[Mention et al, arXiv:1101.2755]

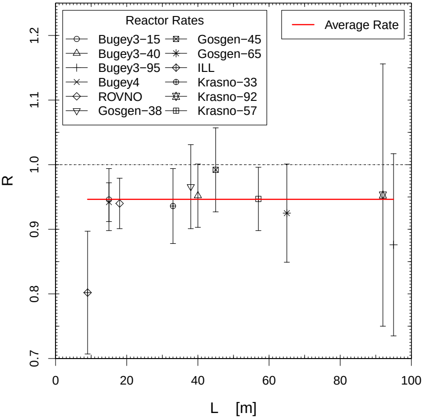
Old Reactor $\bar{\nu}_e$ Fluxes



$$\overline{R} = 0.992 \pm 0.024$$

New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al, arXiv:1101.2663]



$$\overline{R} = 0.946 \pm 0.024$$

Gallium Anomaly

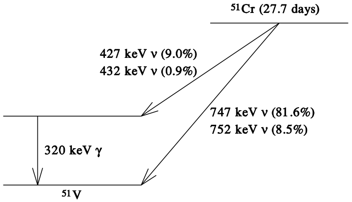
Gallium Radioactive Source Experiments

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

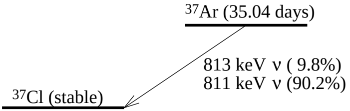
Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

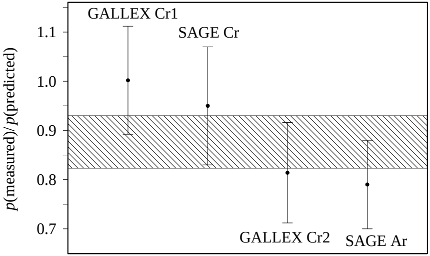
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]



$$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$$

$$\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$$

[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$R_B^{\text{Gallex-Cr1}} = 0.953 \pm 0.11$$
$$R_B^{\text{Gallex-Cr2}} = 0.812^{+0.10}_{-0.11}$$
$$R_B^{\text{SAGE-Cr}} = 0.95 \pm 0.12$$
$$R_B^{\text{SAGE-Ar}} = 0.791^{+0.084}_{-0.078}$$

$$\boxed{R_B^{\text{Ga}} = 0.86 \pm 0.05}$$

Bahcall cross section without uncertainty

[Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

$$R^{\text{Gallex-Cr1}} = 0.84^{+0.13}_{-0.12}$$
$$R^{\text{Gallex-Cr2}} = 0.71^{+0.12}_{-0.11}$$
$$R^{\text{SAGE-Cr}} = 0.84^{+0.14}_{-0.13}$$
$$R^{\text{SAGE-Ar}} = 0.70^{+0.10}_{-0.09}$$

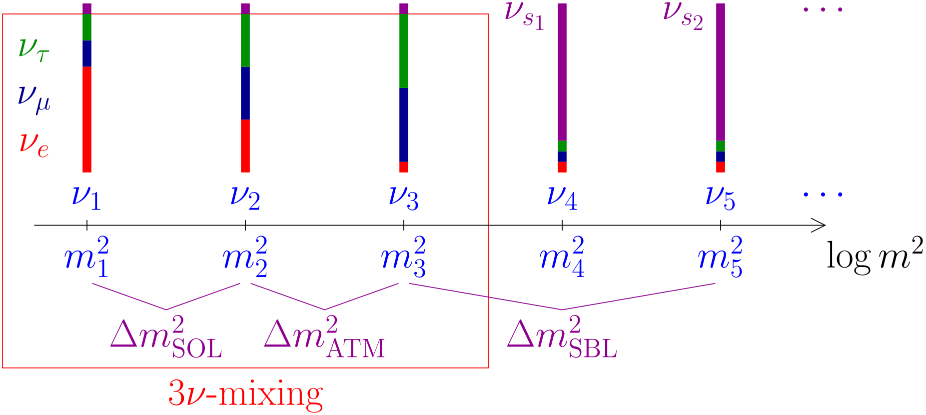
$$\boxed{R^{\text{Ga}} = 0.76^{+0.09}_{-0.08}}$$

[Giunti, Laveder, PRC 83 (2011) 065504, arXiv:1006.3244]

Haxton cross section and uncertainty

[Haxton, PLB 431 (1998) 110, arXiv:nucl-th/9804011]

Beyond Three-Neutrino Mixing



Standard Model

- Neutrinos are the only massless fermions
- Neutrinos are the only fermions with only left-handed component ν_L

Extension of the SM: Massive Neutrinos

- Simplest extension: introduce right-handed component ν_R
- Dirac mass $m_{\text{D}}\overline{\nu_R}\nu_L$ + Majorana mass $m_{\text{M}}\overline{\nu_R^c}\nu_R$
- $\nu_{eL}\,,\ \nu_{\mu L}\,,\ \nu_{\tau L}\ +\ \nu_{eR}\,,\ \nu_{\mu R}\,,\ \nu_{\tau R} \quad \Longrightarrow$ 6 massive Majorana neutrinos

Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Powerful window on new physics beyond the Standard Model

- In this talk I consider sterile neutrinos with mass scale $\sim 1\,\mathrm{eV}$ in light of LSND, MiniBooNE, Reactor Anomaly, Gallium Anomaly.
- Other possibilities (not exclusive):
  - Very light sterile neutrinos with mass scale $\ll 1\,\mathrm{eV}$: important for solar neutrino phenomenology

    [de Holanda, Smirnov, PRD 83 (2011) 113011, arXiv:1012.5627]
  - Heavy sterile neutrinos with mass scale $\gg 1\,\mathrm{eV}$: could be Warm Dark Matter

    [Kusenko, Phys. Rept. 481 (2009) 1, arXiv:0906.2968]

    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191, arXiv:0901.0011]

Cosmology

- N_s = number of thermalized sterile neutrinos (not necessarily integer)

- CMB and LSS in ΛCDM: $N_s = 1.3 \pm 0.9$ $m_s < 0.66\,\text{eV}$ (95% C.L.)

[Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301, arXiv:1006.5276]

$$N_s = 1.61 \pm 0.92 \qquad m_s < 0.70\,\text{eV} \quad (95\%\ \text{C.L.})$$

[Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, PRD 83 (2011) 115023, arXiv:1102.4774]

$N_s = 1.12^{+0.86}_{-0.74}$ (95% C.L.) [Archidiacono, Calabrese, Melchiorri, arXiv:1109.2767]

- BBN:

$$\begin{cases} N_s = 0.22 \pm 0.59 \\ N_s = 0.64^{+0.40}_{-0.35} \\ N_s \leq 1 \text{ at } 95\%\ \text{C.L.} \end{cases}$$

[Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033]
[Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]
[Mangano, Serpico, PLB 701 (2011) 296, arXiv:1103.1261]

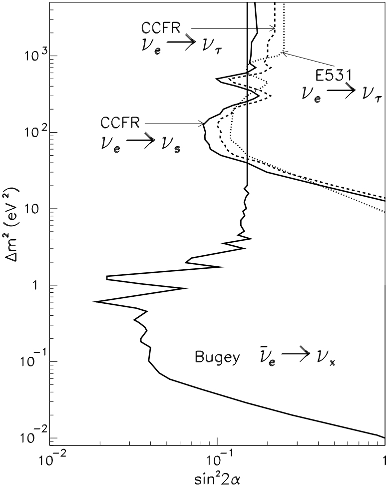
- CMB+LSS+BBN: $N_s = 0.85^{+0.39}_{-0.56}$ (95% C.L.)

[Hamann, Hannestad, Raffelt, Wong, arXiv:1108.4136]

Direct Searches of Active-Sterile Transitions

CCFR

[PRD 59 (1999) 031101, arXiv:hep-ex/9809023]



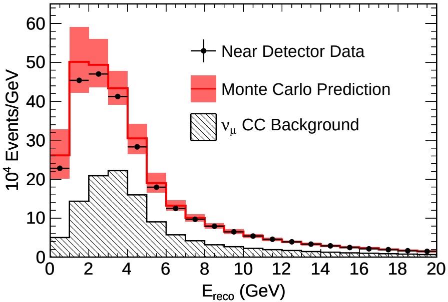
NC interactions $\quad E \sim 100\,\text{GeV} \quad L \simeq 1.4\,\text{km}$

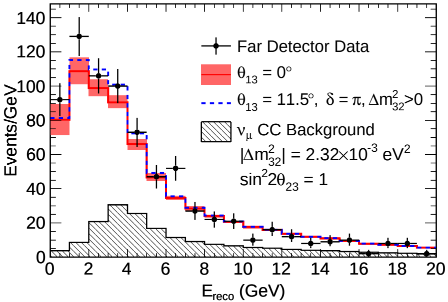
MINOS

[MINOS, PRL 107 (2011) 011802, arXiv:1104.3922]

NC sample: 89% efficiency and 61% purity

97% of ν_e-induced CC events misidentified as NC





$L_{ND} = 1.04$ km $\qquad L_{FD} = 735$ km

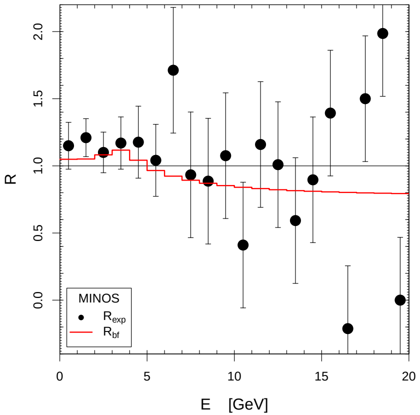
ϑ_{13}	χ^2/NDF	ϑ_{23}	ϑ_{24}	ϑ_{34}
0	130.4/122	45.0^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+17}_{-0.0}$
11.5	128.5/122	45.6^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+25}_{-0.0}$

$$\vartheta_{24} \lesssim 8^\circ \text{ at } 90\% \text{ C.L.} \quad \Longrightarrow \quad |U_{\mu 4}|^2 \simeq \sin^2\vartheta_{24} \lesssim 0.019$$

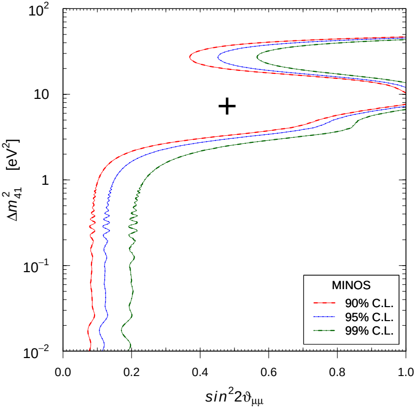
$$\boxed{|U_{\mu 4}|^2 \lesssim 0.035 \text{ at } 99\% \text{ C.L.}}$$

Hernandez, Smirnov, arXiv:1105.5946

- Limit valid for $\Delta m^2_{41} \lesssim 0.5\,\text{eV}^2$.
- For $\Delta m^2_{41} \gtrsim 0.5\,\text{eV}^2$ SBL oscillations at Near Detector.
- MINOS insensitive to oscillations for $\Delta m^2_{41} \gtrsim 15\,\text{eV}^2$ because oscillations already averaged at Near Detector.



$$R = \frac{\langle 1 - P_{\nu_\mu \to \nu_s} \rangle_{\text{FD}}}{\langle 1 - P_{\nu_\mu \to \nu_s} \rangle_{\text{ND}}}$$



[Giunti, Laveder, arXiv:1109.4033]

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha\to\nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

No CP Violation!

$$P_{\nu_\alpha\to\nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2\left(1 - |U_{\alpha4}|^2\right)$$

Perturbation of 3ν Mixing

$$|U_{e4}|^2 \ll 1\,, \quad |U_{\mu4}|^2 \ll 1\,, \quad |U_{\tau4}|^2 \ll 1\,, \quad |U_{s4}|^2 \simeq 1$$

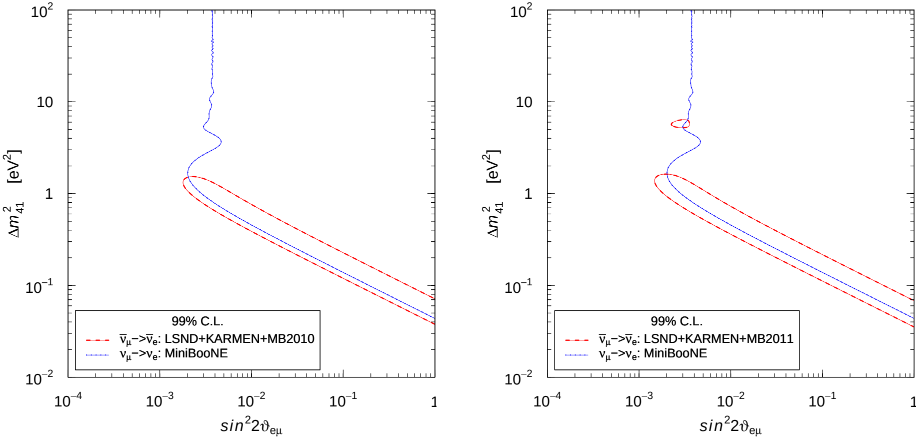
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$

$$\Downarrow$$

$$|U_{\alpha4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$



- Tension between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ data is reduced with MiniBooNE 2011 antineutrino data.
- 3+2 $\Longrightarrow$ CP Violation [Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004, hep-ph/0305255], [Maltoni, Schwetz, PRD 76, 093005 (2007), arXiv:0705.0107], [Karagiorgi et al, PRD 80 (2009) 073001, arXiv:0906.1997], [Kopp, Maltoni, Schwetz, arXiv:1103.4570], [Giunti, Laveder, arXiv:1107.1452]

Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\phi_{kj} = \Delta m^2_{kj} L/4E$$

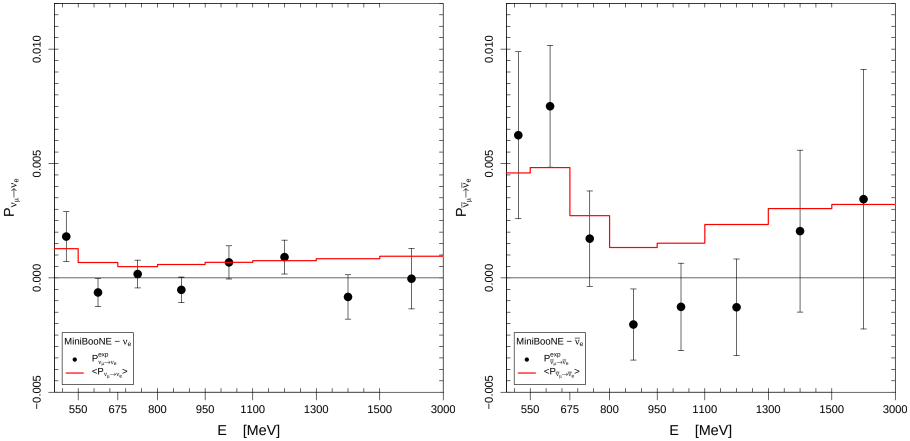
$$\eta = \arg[U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}]$$

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51}$$
$$+ 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2\phi_{41} + |U_{\alpha 5}|^2 \sin^2\phi_{51})$$
$$- 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2\phi_{54}$$

- Good: CP violation can solve the $\nu_\mu \to \nu_e$ vs $\bar{\nu}_\mu \to \bar{\nu}_e$ tension.
- Bad: 2 sterile neutrinos are disfavored by BBN. A large sum of masses is disfavored by CMB+LSS.

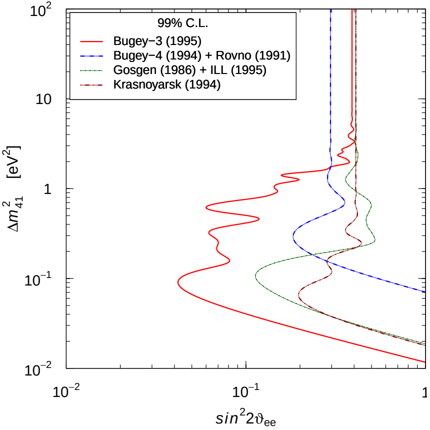
3+2: MiniBooNE $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$



$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2\phi_{51}$$
$$+ 4|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \cos\eta \left[\sin^2\phi_{41} + \sin^2\phi_{51} - \sin^2\phi_{54}\right]$$
$$\overset{(+)}{-} 2|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \sin\eta \left[\sin(2\phi_{41}) - \sin(2\phi_{51}) + \sin(2\phi_{54})\right]$$

Disappearance Constraints

$\bar{\nu}_e$ Disappearance

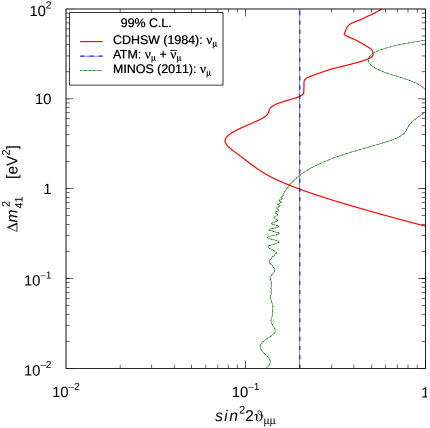


New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al., arXiv:1101.2663]

[Mention et al., arXiv:1101.2755]

ν_μ and $\bar{\nu}_\mu$ Disappearance



ATM constraint on $|U_{\mu 4}|^2$

[Maltoni, Schwetz, PRD 76 (2007) 093005, arXiv:0705.0107]

3+1

- ν_e disappearance experiments:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- ν_μ disappearance experiments:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

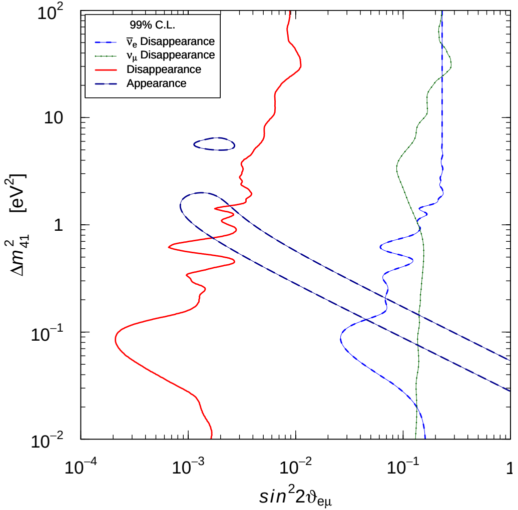
- $\nu_\mu \to \nu_e$ experiments:

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

- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694, arXiv:hep-ph/9606411]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]



3+1

GoF = 57%

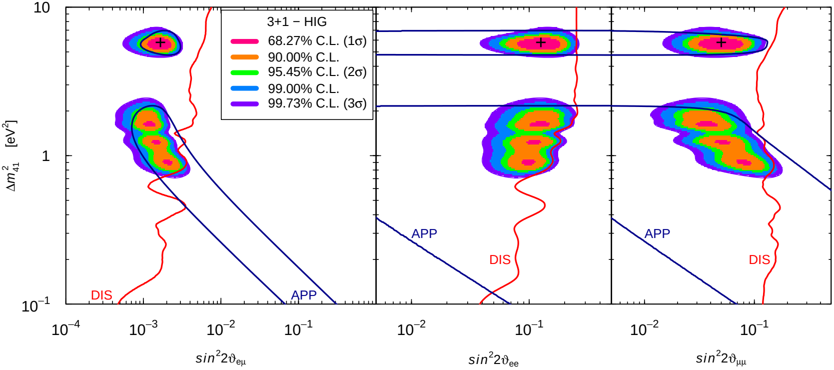
PGoF = 1%

- 3+1: Appearance-Disappearance tension
- 3+2: same tension [Kopp, Maltoni, Schwetz, arXiv:1103.4570], [Giunti, Laveder, arXiv:1107.1452]
- No tension in 3+1+CPTV [Barger, Marfatia, Whisnant, PLB 576 (2003) 303] [Giunti, Laveder, PRD 82 (2010) 093016, PRD 83 (2011) 053006]

Towards 3+1 Neutrino Mixing

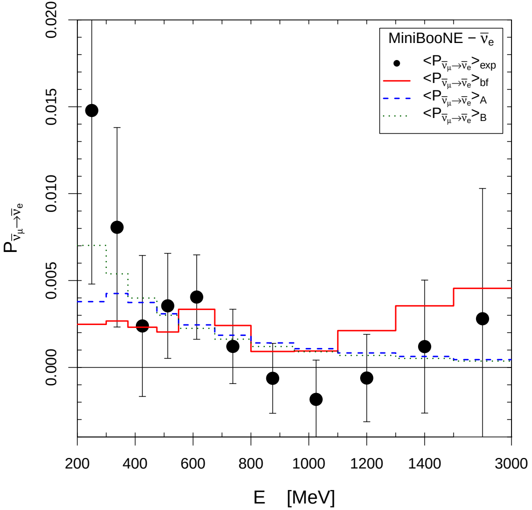
[Giunti, Laveder, arXiv:1109.4033]

- Simplest scheme beyond standard three-neutrino mixing which can partially explain the data.
- It corresponds to the natural addition of one new entity (a sterile neutrino) to explain a new effect (short-baseline oscillations).
- Global χ^2 is good: $\chi^2_{\text{min}}/\text{NDF} = 120.7/124$.
- Marginal APP-DIS compatibility: $\Delta\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 9.3/2$.
- Marginal compatibility with cosmology for $\Delta m^2_{41} \lesssim 1\,\text{eV}^2$.



- Best fit at $\Delta m^2_{41} \approx 5.6\,\text{eV}^2 \Longrightarrow m_4 \approx 2.4\,\text{eV} \Longrightarrow$ tension with standard cosmology.
- Large Δm^2_{41} preferred by MiniBooNE 2011 antineutrino data.
- Small Δm^2_{41} disfavored by MINOS constraint.
- Allowed regions at $\Delta m^2_{41} \approx 1 - 2\,\text{eV}^2$ marginally compatible with cosmology.

MiniBooNE Low-Energy Anomaly

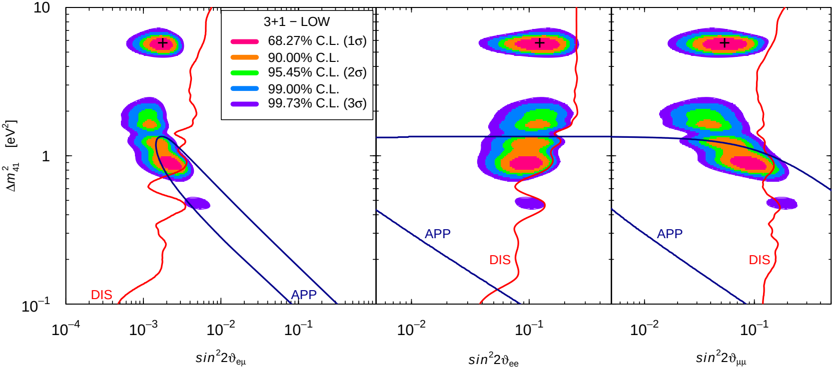


bf: $\sin^2 2\vartheta_{e\mu} = 0.005$, $\Delta m^2_{41} = 4.68\,\text{eV}^2$

A: $\sin^2 2\vartheta_{e\mu} = 0.005$, $\Delta m^2_{41} = 0.8\,\text{eV}^2$

B: $\sin^2 2\vartheta_{e\mu} = 0.01$, $\Delta m^2_{41} = 0.5\,\text{eV}^2$

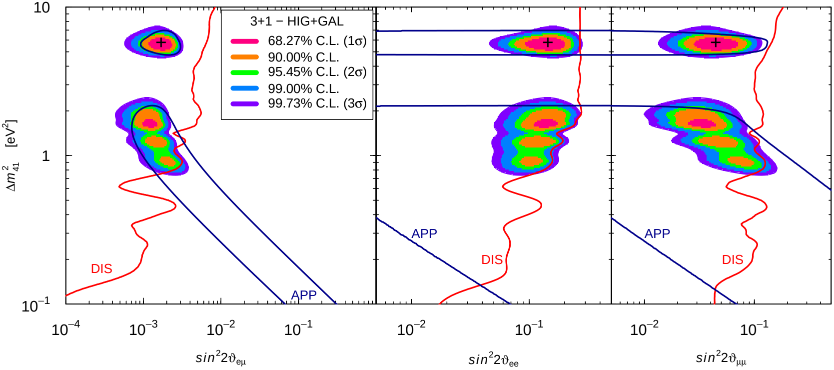
[Giunti, Laveder, arXiv:1109.4033]



GoF = 37% PGoF = 0.04%

- Best fit point lies out of the region of overlap of the 3σ APP and DIS allowed regions.
- Tension indicates that MiniBooNE low-energy anomaly may have an explanation different from $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ oscillations.

Gallium Anomaly

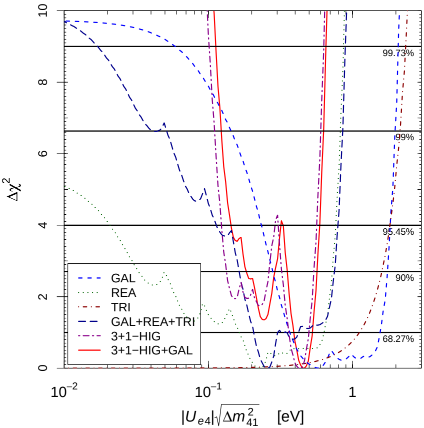


$\text{GoF} = 48\%$ $\text{PGoF} = 1\%$

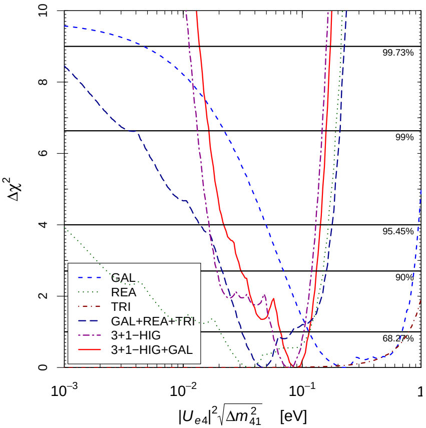
- Small impact because only four data points.
- Gallium data favor $\Delta m^2_{41} \gtrsim 1\,\text{eV}^2$.

Testable Implications

β Decay



$(\beta\beta)_{0\nu}$ Decay



$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

$$m_{\beta\beta} = \left| \sum_k U_{ek}^2 \, m_k \right|$$

[Giunti, Laveder, In Preparation]

Conclusions

- Suggestive LSND, MiniBooNE, Reactor and Gallium indications in favor of short-baseline neutrino oscillations $\Longrightarrow$ sterile neutrinos
- 3+1 Neutrino Mixing:
  - No CP violation $\Longrightarrow$ Neutrinos vs Antineutrinos tension
  - Appearance vs Disappearance tension
  - Marginal compatibility with cosmology.
- 3+2 Neutrino Mixing:
  - CP violation $\Longrightarrow$ no Neutrinos vs Antineutrinos tension
  - Appearance vs Disappearance tension
  - Tension with cosmology.
- Neutrinos vs Antineutrinos tension has diminished with 2011 MiniBooNE data.
- Simpler 3+1 Neutrino Mixing may be enough (Occam's Razor).
- New short-baseline neutrino oscillation experiments are needed!