

Phenomenology of Sterile Neutrinos

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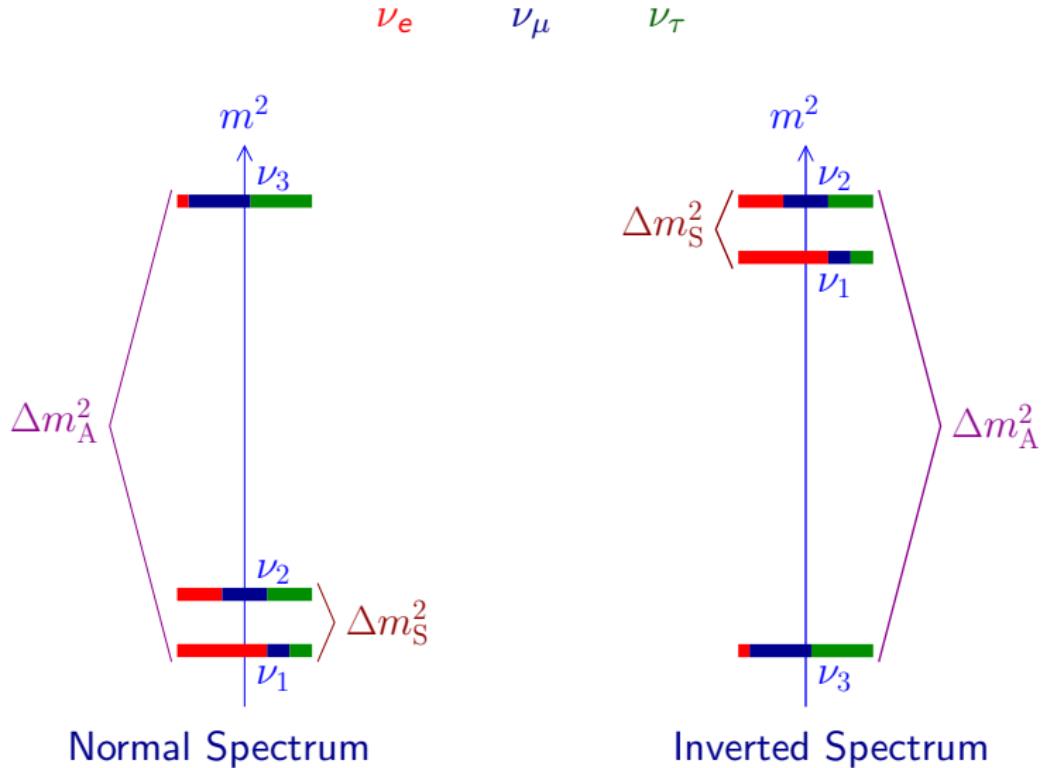
<mailto://giunti@to.infn.it>

Neutrino Unbound: <http://www.nu.to.infn.it>

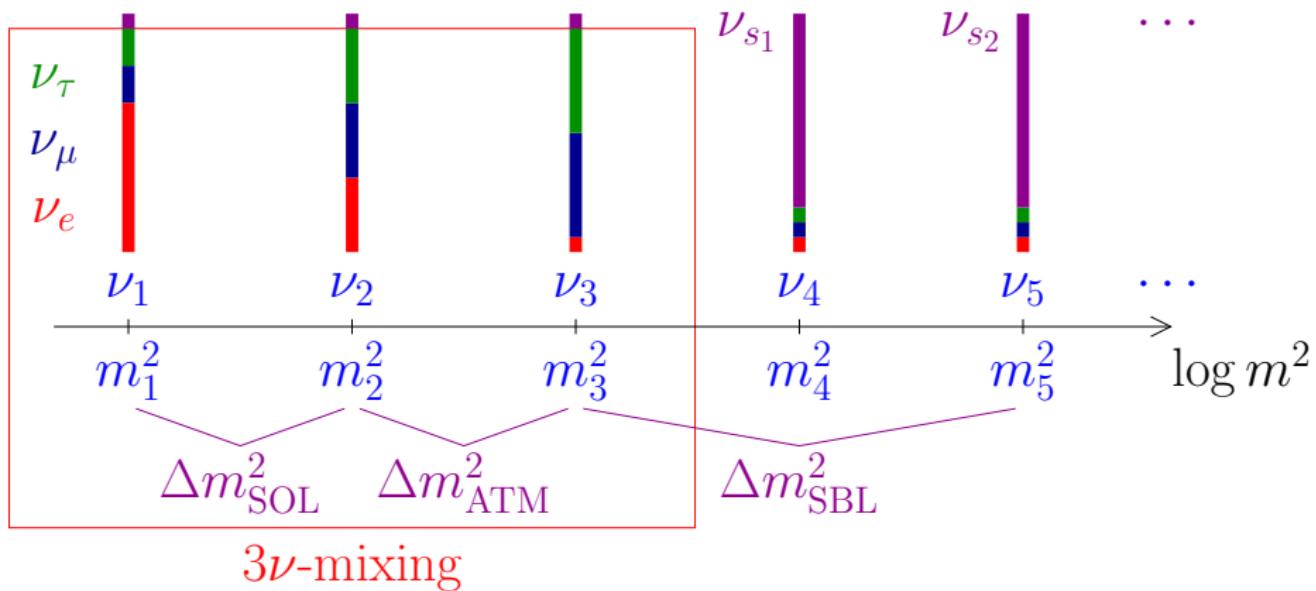
V International Pontecorvo Neutrino Physics School

6-16 September 2012, Alushta, Crimea, Ukraine

Three-Neutrino Mixing Paradigm



Beyond Three-Neutrino Mixing



Standard Model

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

Extension of the SM: Massive Neutrinos

- ▶ Simplest extension: introduce right-handed component ν_R
(singlet of $SU(2)_L \times U(1)_Y$)
- ▶ One generation: Dirac mass $m_D \overline{\nu}_R \nu_L$ + Majorana mass $m_M \overline{\nu}_R^c \nu_R$
⇒ 2 massive Majorana neutrinos
- ▶ Three left-handed fields + N_R right-handed fields:
 $\nu_{eL}, \nu_{\mu L}, \nu_{\tau L} + \nu_{1R}, \dots, \nu_{N_R R}$
⇒ 3 + N_R massive Majorana neutrinos

Sterile Neutrinos

- ▶ Light anti- ν_R are called sterile neutrinos

$$\nu_R^c \rightarrow \nu_{sL} \quad (\text{left-handed})$$

- ▶ Sterile means no standard model interactions
- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) can oscillate into sterile neutrinos (ν_s)
- ▶ Observables:
 - ▶ Disappearance of active neutrinos (neutral current deficit)
 - ▶ Indirect evidence through combined fit of data (current indication)
- ▶ Short-baseline anomalies + 3ν -mixing:

$$\Delta m_{21}^2 \ll |\Delta m_{31}^2| \ll |\Delta m_{41}^2| \leq \dots$$

ν_1	ν_2	ν_3	ν_4	\dots
ν_e	ν_μ	ν_τ	ν_{s_1}	\dots

- ▶ In this talk I consider sterile neutrinos with mass scale $\sim 1\text{ eV}$ in light of LSND, MiniBooNE, Reactor Anomaly, Gallium Anomaly.
- ▶ Other possibilities (not incompatible):
 - ▶ Very light sterile neutrinos with mass scale $\ll 1\text{ eV}$: important for solar neutrino phenomenology
[de Holanda, Smirnov, PRD 83 (2011) 113011]
 - ▶ Heavy sterile neutrinos with mass scale $\gg 1\text{ eV}$: could be Warm Dark Matter

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

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

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

No CP Violation!

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right) \quad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

Perturbation of 3ν Mixing

$$|U_{e4}|^2 \ll 1, \quad |U_{\mu 4}|^2 \ll 1, \quad |U_{\tau 4}|^2 \ll 1, \quad |U_{s4}|^2 \simeq 1$$

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

↑
SBL

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

↓

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

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

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

$$P_{\substack{(-) \\ \nu_\mu \rightarrow \nu_e}} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\ + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \eta)$$

$$P_{\substack{(-) \\ \nu_\alpha \rightarrow \nu_\alpha}} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \phi_{41} + |U_{\alpha 5}|^2 \sin^2 \phi_{51}) \\ - 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54}$$

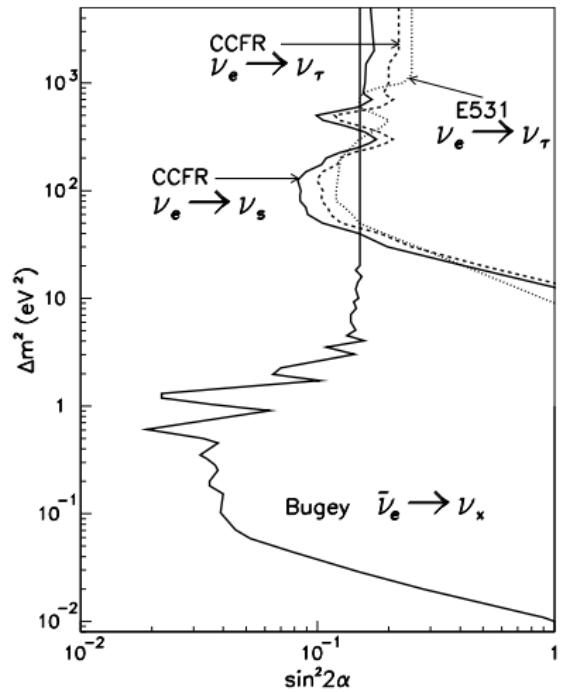
- More parameters: 7 (vs 3 in 3+1)
- CP violation

[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, arXiv:1205.5230]

Direct Searches of Active-Sterile Transitions

CCFR

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



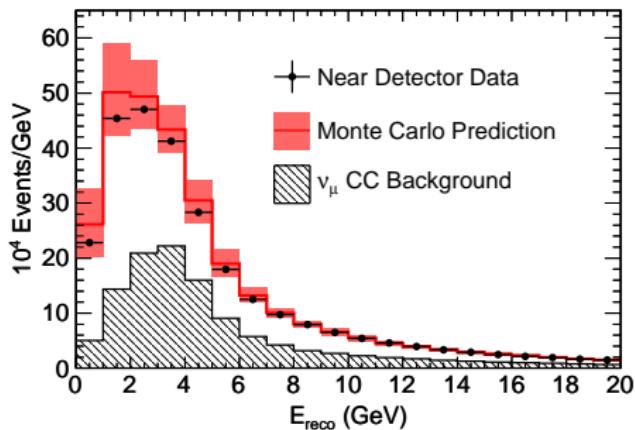
NC interactions

$E \sim 100 \text{ GeV}$

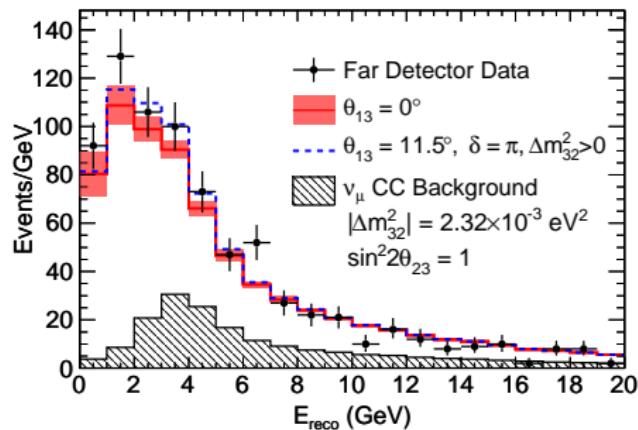
$L \simeq 1.4 \text{ km}$

NC sample: 89% efficiency and 61% purity

97% of ν_e -induced CC events misidentified as NC



$$L_{\text{ND}} = 1.04 \text{ km}$$



$$L_{\text{FD}} = 735 \text{ km}$$

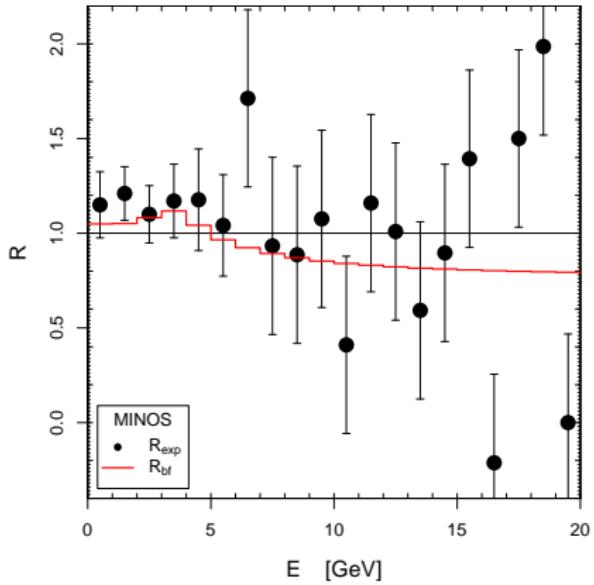
ϑ_{13}	χ^2/NDF	ϑ_{23}	ϑ_{24}	ϑ_{34}
0	130.4/122	45.0^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+17}_{-0.0}$
11.5	128.5/122	45.6^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+25}_{-0.0}$

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

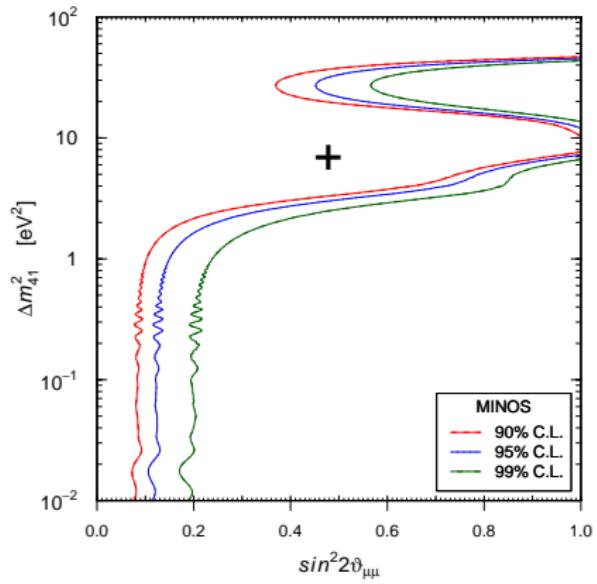
$$|U_{\mu 4}|^2 \lesssim 0.035 \text{ at } 99\% \text{ C.L.}$$

Hernandez, Smirnov, PLB 706 (2012) 360, arXiv:1105.5946

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



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



[Giunti, Laveder, PRD 84 (2011) 093006, arXiv:1109.4033]

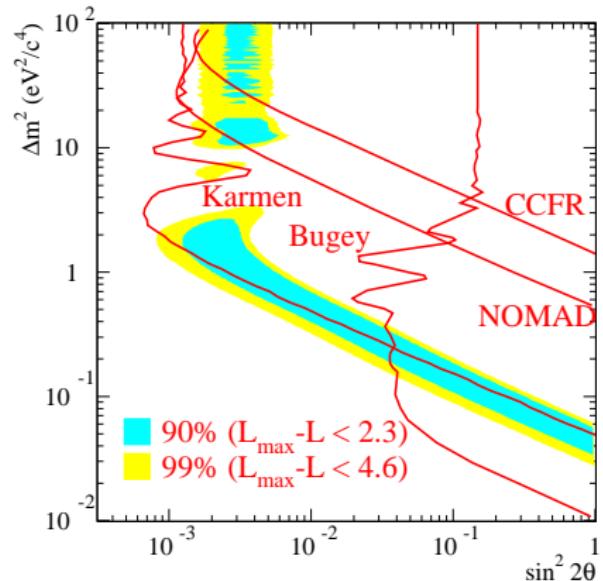
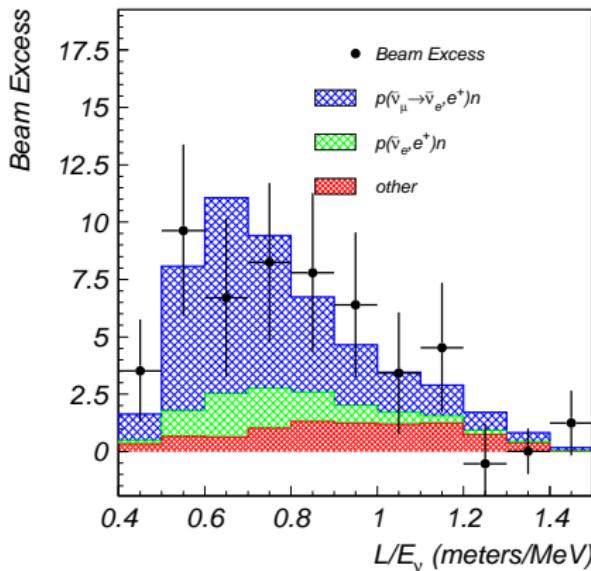
LSND

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

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$L \simeq 30 \text{ m}$$

$$20 \text{ MeV} \leq E \leq 200 \text{ MeV}$$



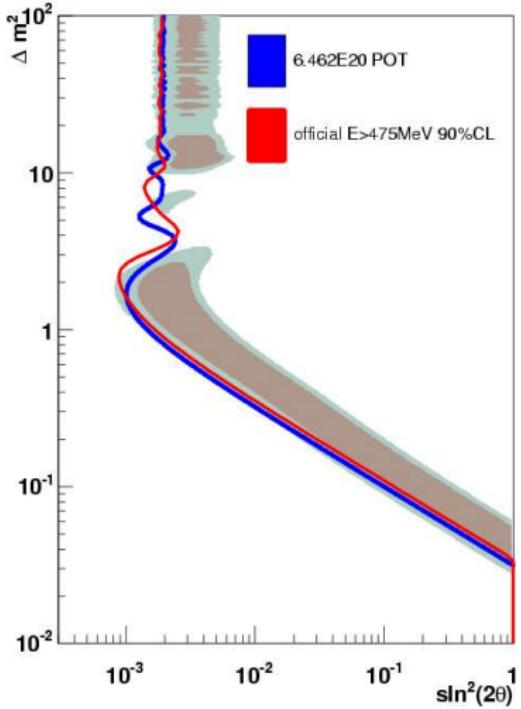
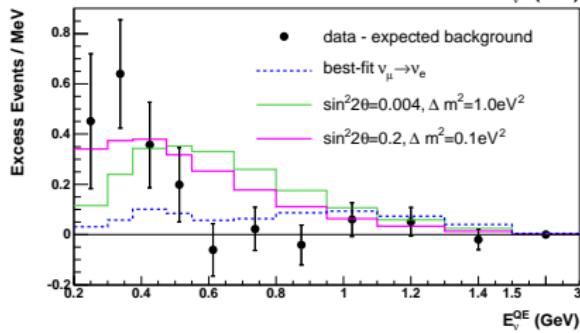
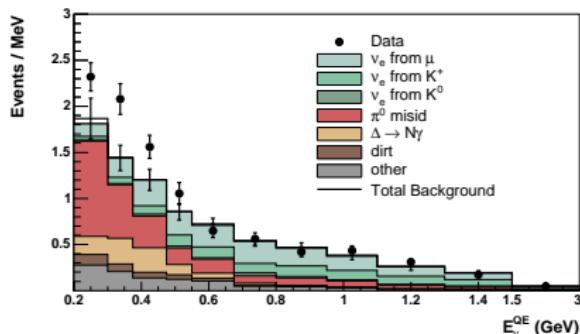
$$\Delta m_{\text{LSND}}^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_A^2 \gg \Delta m_S^2)$$

MiniBooNE Neutrinos

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

$\nu_\mu \rightarrow \nu_e$ $L \simeq 541 \text{ m}$

$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$



[MiniBooNE, PRL 102 (2009) 101802]

[Djurcic, arXiv:0901.1648]

- no $\nu_\mu \rightarrow \nu_e$ signal corresponding to LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal ($E > 475 \text{ MeV}$)
- low-energy anomaly

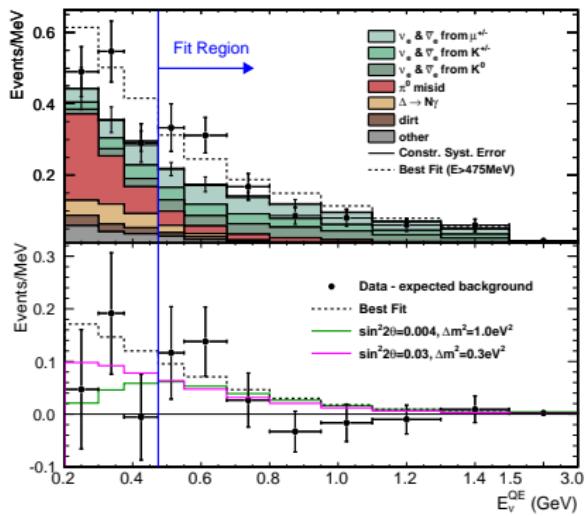
MiniBooNE Antineutrinos - 2009-2010

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

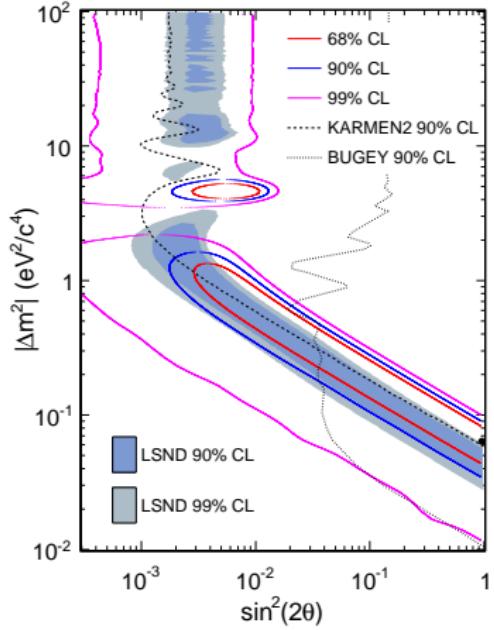
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$L \simeq 541 \text{ m}$$

$$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$$



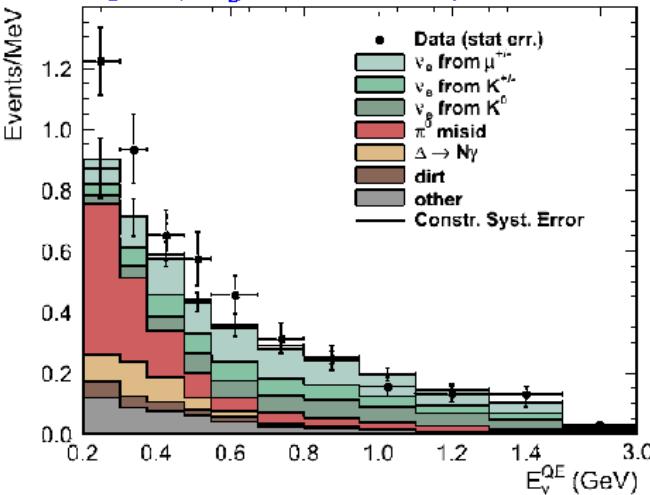
[MiniBooNE, PRL 105 (2010) 181801]



- ▶ 5.7e20 POT: agreement with LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal ($E > 475 \text{ MeV}$)
- ▶ similar L/E but different L and $E \Rightarrow$ oscillations

MiniBooNE $\bar{\nu}$ - Neutrino 2012 - 6 June

anti- ν_e CCQE signal candidates w/ 11.3e20 POT



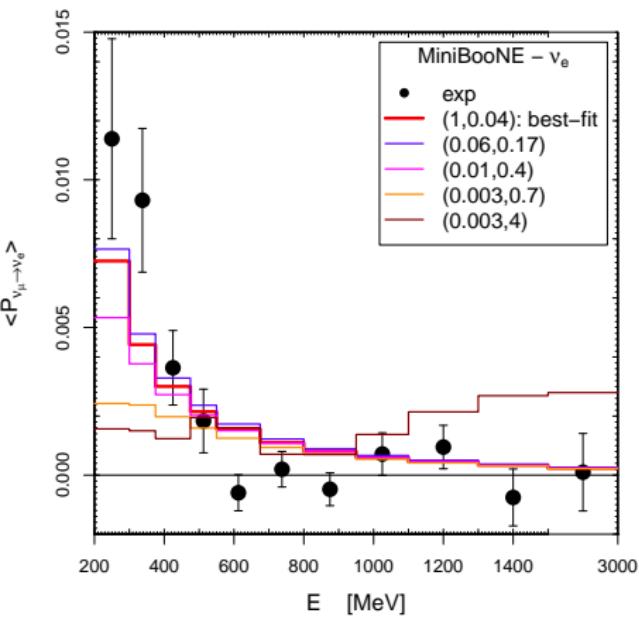
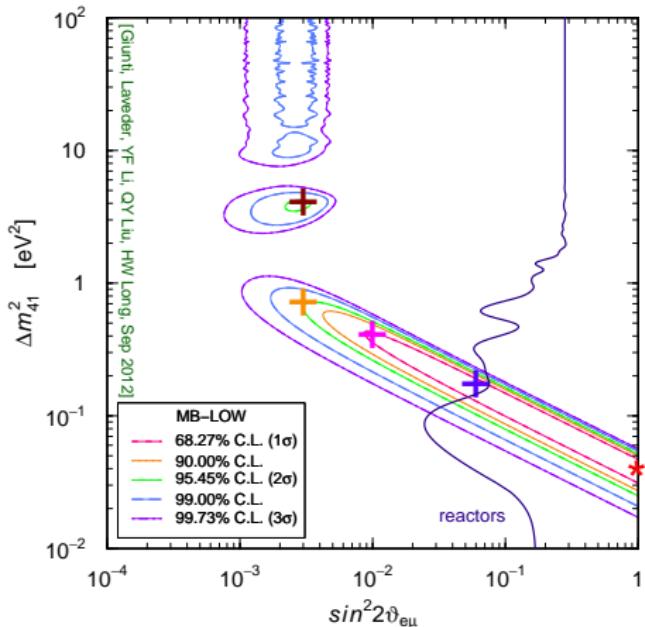
Higher stat anti-neutrino data is now much more consistent with what was observed in the data taken with a neutrino beam

* Systematic error after all other data constraints applied, e.g.
 ν_μ CCQE, NC π^0 , dirt events,
SciBooNE K^+

	1st half			2nd half		
	data	mc	excess	data	mc	excess
200-475	119	100.5 ± 14.3	18.5 (1.3s)	138	100.0 ± 14.1	38 (2.7s)
475-1250	120	99.1 ± 14.0	20.9 (1.5s)	101	103.1 ± 14.4	-2.2 (-0.2s)

agreement with LSND signal is sadly vanishing

New MiniBooNE data: arXiv:1207.4809

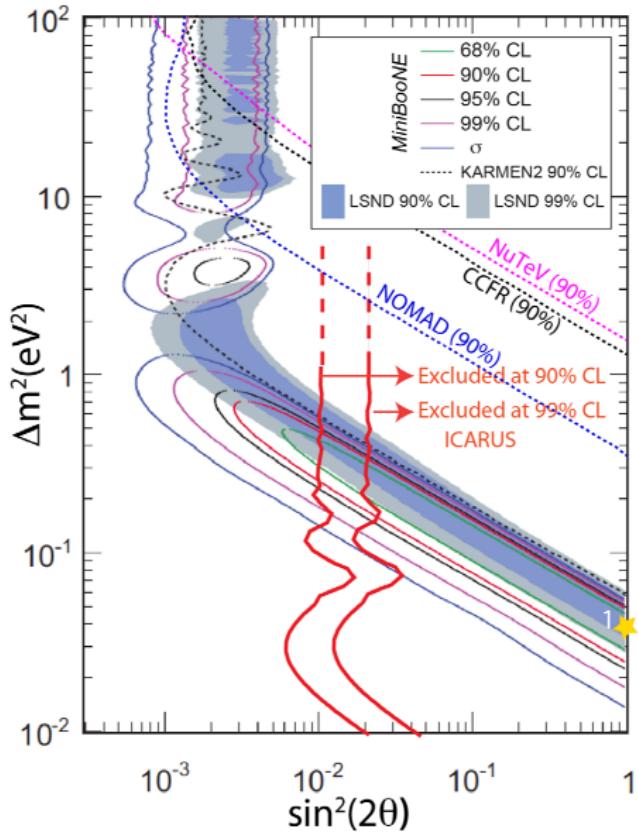


- ▶ Fit of low-energy excess is marginal
- ▶ It requires $\Delta m^2_{41} \lesssim 0.4 \text{ eV}^2$
- ▶ Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, arXiv:1202.4745]

ICARUS

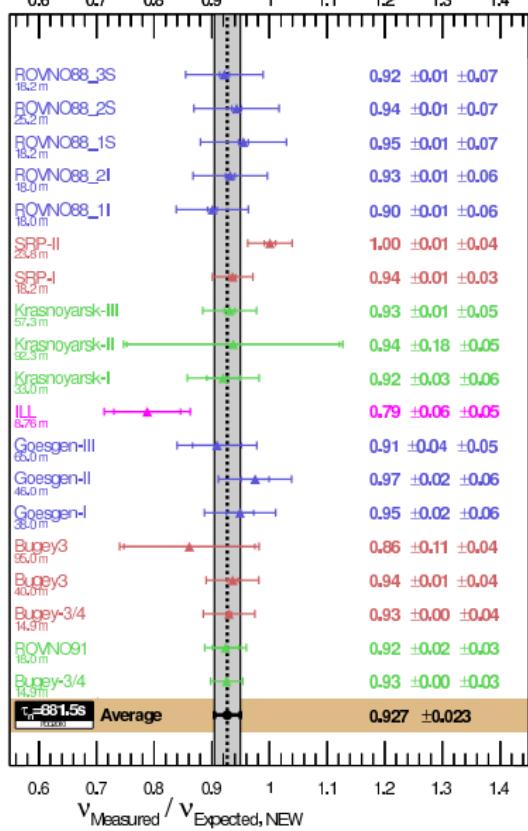
[arXiv:1209.0122]

- ▶ $\nu_\mu \rightarrow \nu_e$
- ▶ $L = 730 \text{ km}$ (CNGS)
- ▶ $10 < E < 30 \text{ GeV}$
- ▶ $3 \times 10^{-3} < \frac{E}{L} < 9 \times 10^{-3} \text{ eV}^2$
- ▶ 2 observed ν_e events
- ▶ 3.7 background ν_e events



Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006; update in White Paper, arXiv:1204.5379]



new reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615]

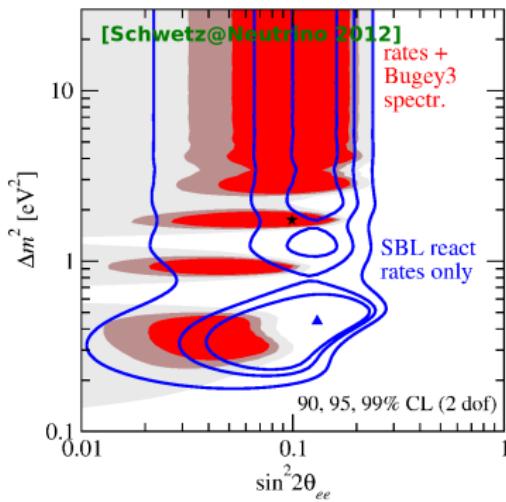
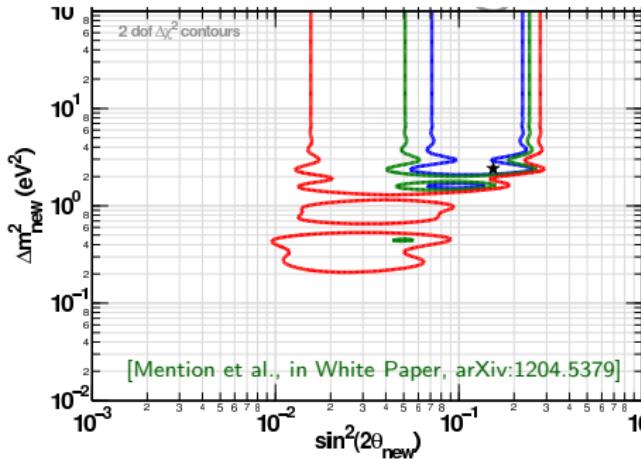
[Huber, PRC 84 (2011) 024617]

Detection: $\sigma(\bar{\nu}_e + p \rightarrow n + e^+) \propto \tau_n^{-1}$

PDG	neutron lifetime τ_n
1995	887.0 ± 2.0 sec
1998	886.7 ± 1.9 sec
2002	885.7 ± 0.8 sec
2011	881.5 ± 1.5 sec
2012	880.1 ± 1.1 sec

change of predicted event rates

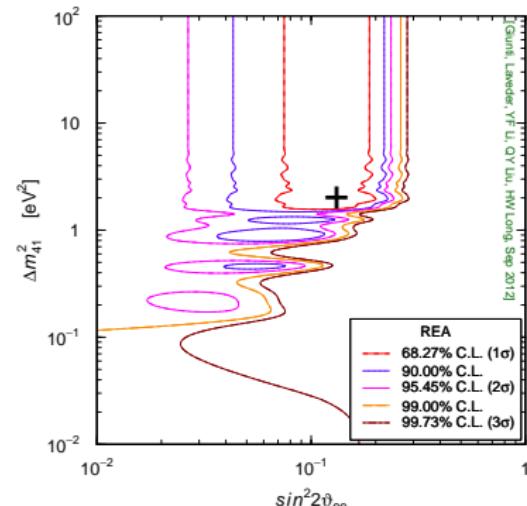
^{235}U	^{238}U	^{239}Pu	^{241}Pu
+3.7%	+9.8%	+4.2%	+4.7%



Reactor $\bar{\nu}_e$ Disappearance

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\vartheta_{ee} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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



Gallium Anomaly

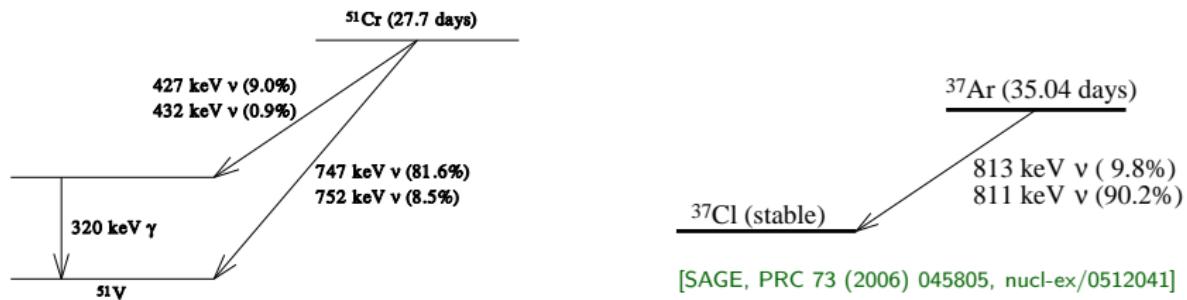
Gallium Radioactive Source Experiments

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

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

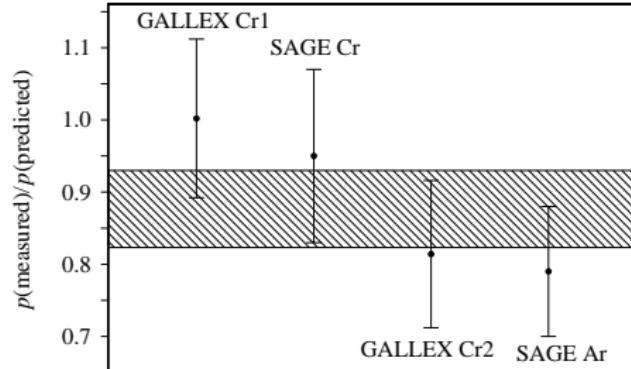
ν_e Sources: $e^- + {}^{51}\text{Cr} \rightarrow {}^{51}\text{V} + \nu_e$ $e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + \nu_e$

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



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

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



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

$$R_B^{\text{GALLEX-Cr1}} = 0.953 \pm 0.11$$

$$R_B^{\text{GALLEX-Cr2}} = 0.812^{+0.10}_{-0.11}$$

$$R_B^{\text{SAGE-Cr}} = 0.95 \pm 0.12$$

$$R_B^{\text{SAGE-Ar}} = 0.791^{+0.084}_{-0.078}$$

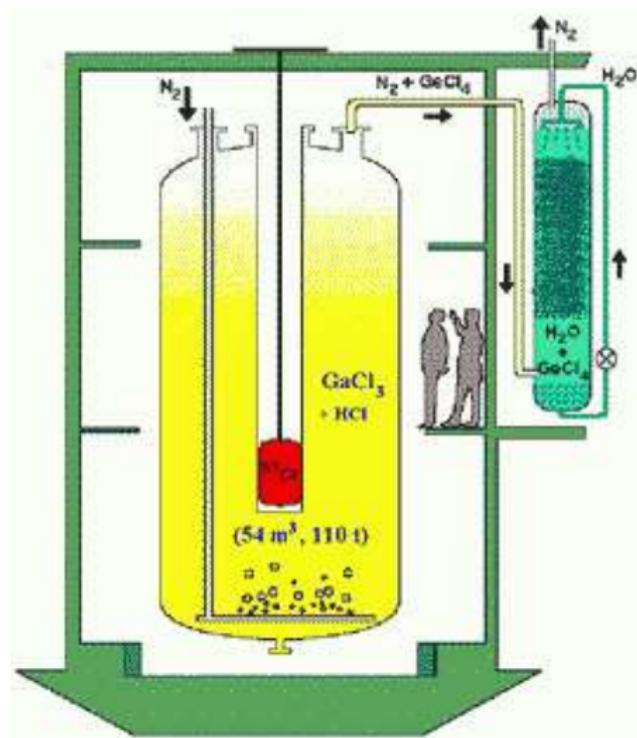
$$R_B^{\text{Ga}} = 0.86 \pm 0.05$$

Bahcall cross section without uncertainty

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

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

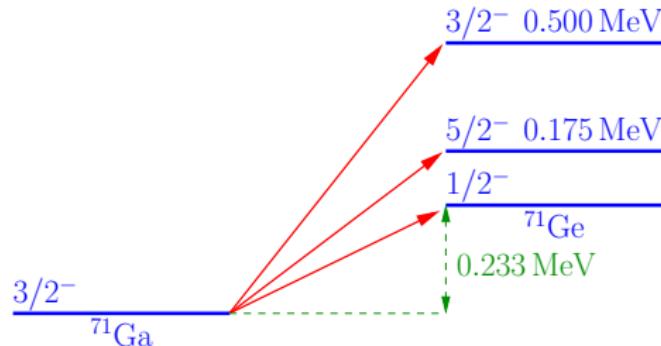
$$\langle L \rangle_{\text{SAGE}} = 0.6 \text{ m}$$



[GALLEX]

- Deficit could be due to overestimate of
 $\sigma(\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-)$

- Calculation: Bahcall, PRC 56 (1997) 3391



- $\sigma_{\text{G.S.}}$ from $T_{1/2}({}^{71}\text{Ge}) = 11.43 \pm 0.03$ days [Hampel, Remsberg, PRC 31 (1985) 666]

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = 55.3 \times 10^{-46} \text{ cm}^2 (1 \pm 0.004)_{3\sigma}$$

$$\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669 \frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}} + 0.220 \frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}} \right)$$

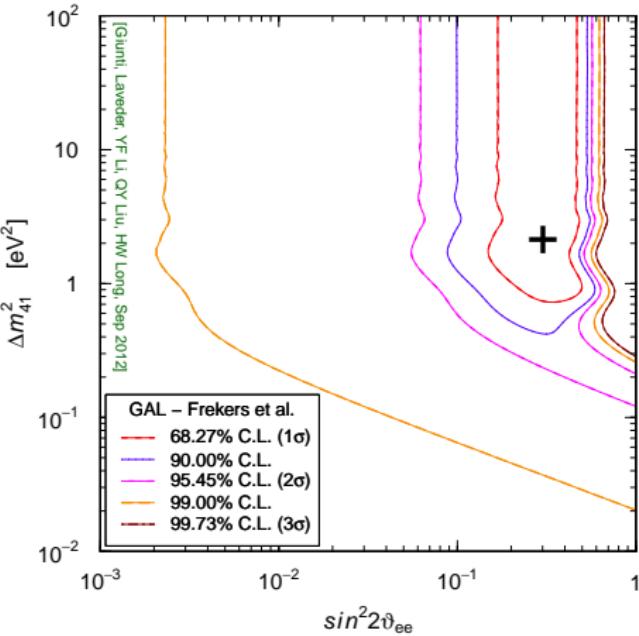
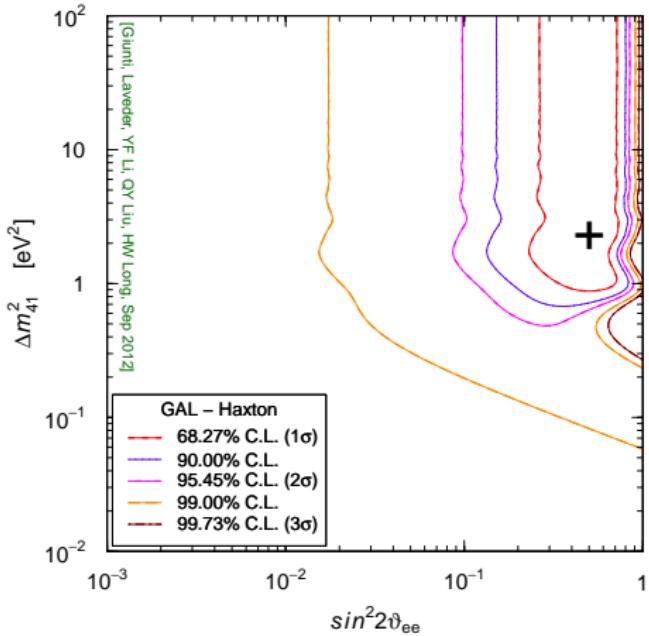
- Contribution of Excited States only 5%!

		$\frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}}$	$\frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}}$
Krofcheck et al. PRL 55 (1985) 1051	$^{71}\text{Ga}(p, n)^{71}\text{Ge}$	< 0.056	0.126 ± 0.023
Haxton PLB 431 (1998) 110	Shell Model	0.19 ± 0.18	
Frekers et al. PLB 706 (2011) 134	$^{71}\text{Ga}({}^3\text{He}, {}^3\text{H})^{71}\text{Ge}$	0.039 ± 0.030	0.202 ± 0.016

- ▶ Haxton: [Haxton, PLB 431 (1998) 110]

“a sophisticated shell model calculation is performed ... for the transition to the first excited state in ^{71}Ge . The calculation predicts destructive interference between the (p, n) spin and spin-tensor matrix elements”
- ▶ 2.7σ discrepancy of $\text{BGT}_{500}/\text{BGT}_{\text{G.S.}}$ measurements
- ▶ Anyhow, new $^{71}\text{Ga}({}^3\text{He}, {}^3\text{H})^{71}\text{Ge}$ data support Gallium Anomaly!

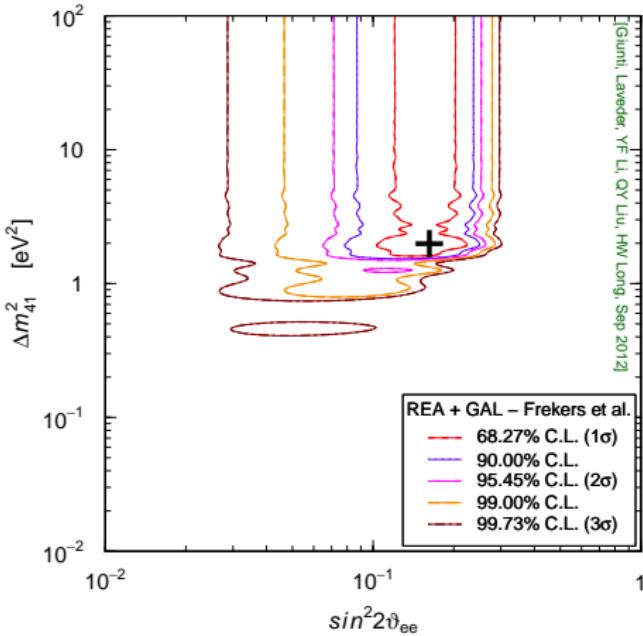
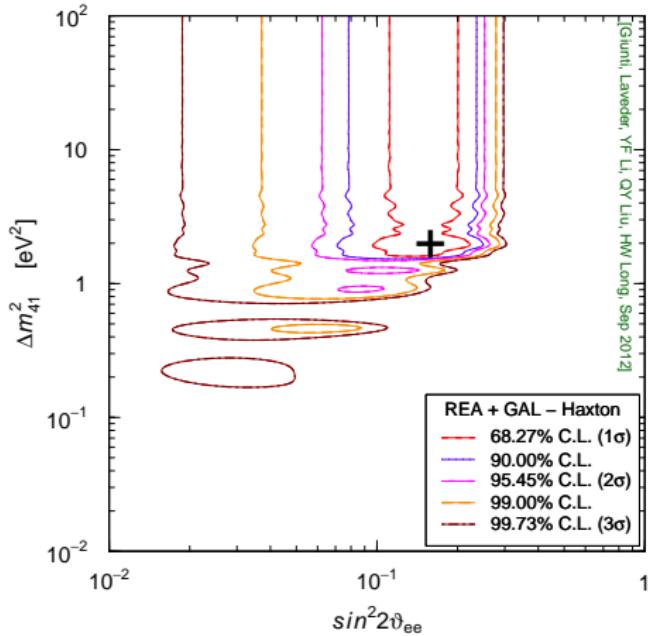
Gallium ν_e Disappearance



No Osc.	χ^2_{\min}	14.8
	NDF	4
	GoF	0.5 %
3+1	χ^2_{\min}	4.8
	NDF	2
	GoF	9.1 %
	Δm_{41}^2 [eV ²]	2.24
	$\sin^2 2\vartheta_{ee}$	0.50

No Osc.	χ^2_{\min}	17.2
	NDF	4
	GoF	0.2 %
3+1	χ^2_{\min}	7.9
	NDF	2
	GoF	1.9 %
	Δm_{41}^2 [eV ²]	2.09
	$\sin^2 2\vartheta_{ee}$	0.30

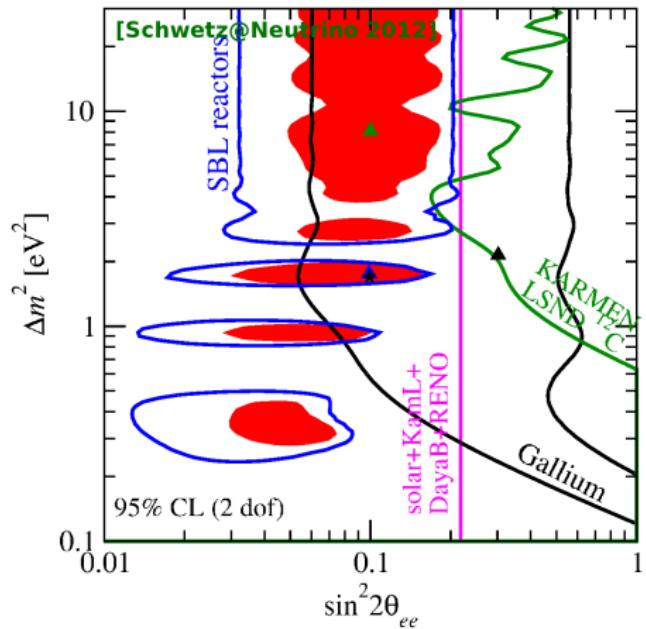
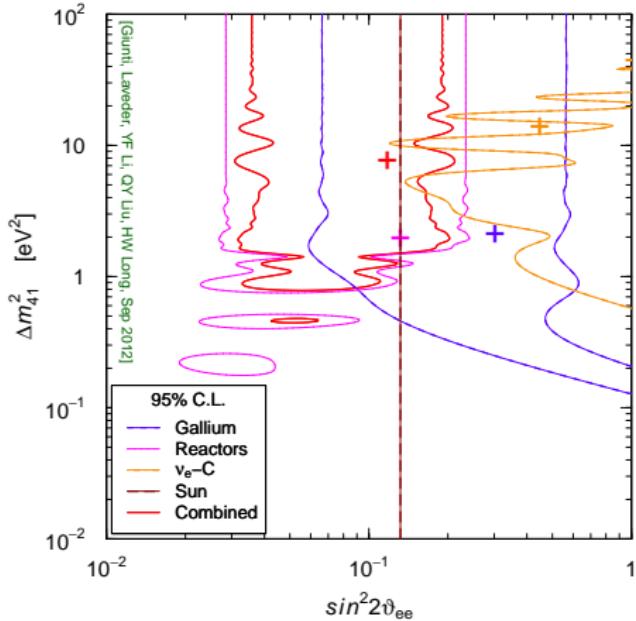
Reactor $\bar{\nu}_e$ and Gallium ν_e Disappearance



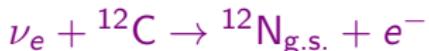
No Osc.	χ^2_{\min}	45.6
	NDF	42
	GoF	32.3 %
3+1	χ^2_{\min}	30.8
	NDF	40
	GoF	85 %
	Δm_{41}^2 [eV 2]	1.95
	$\sin^2 2\vartheta_{ee}$	0.16

No Osc.	χ^2_{\min}	48.9
	NDF	42
	GoF	21.5 %
3+1	χ^2_{\min}	32.2
	NDF	40
	GoF	80 %
	Δm_{41}^2 [eV 2]	1.95
	$\sin^2 2\vartheta_{ee}$	0.16

Global ν_e and $\bar{\nu}_e$ Disappearance



KARMEN + LSND



[Conrad, Shaevitz, PRD 85 (2012) 013017]

[Giunti, Laveder, PLB 706 (2011) 200]

SUN&KamLAND + ϑ_{13}

[Giunti, Li, PRD 80 (2009) 113007]

[Palazzo, PRD 83 (2011) 113013]

[Palazzo, PRD 85 (2012) 077301]

SUN&KamLAND + ϑ_{13} bound on $|U_{e4}|^2$

[Giunti, Li, PRD 80 (2009) 113007; Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301]

3+1 with simplifying assumptions: $U_{\mu 4} = U_{\tau 4} = 0$, no CP violation

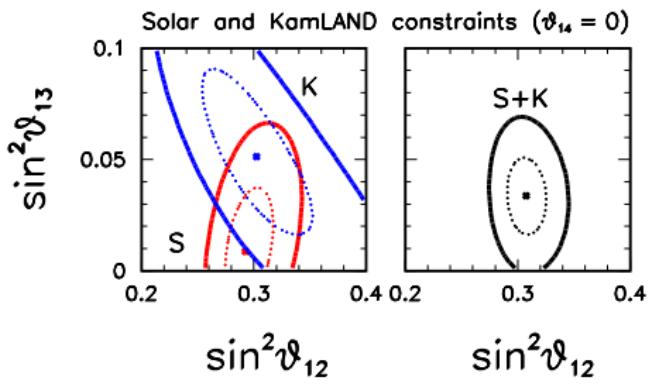
$$U_{e1} = c_{12}c_{13}c_{14} \quad U_{e2} = s_{12}c_{13}c_{14} \quad U_{e3} = s_{13}c_{14} \quad U_{e4} = s_{14}$$

$$U_{s1} = -c_{12}c_{13}s_{14} \quad U_{s2} = -s_{12}c_{13}s_{14} \quad U_{s3} = -s_{13}s_{14} \quad U_{s4} = c_{14}$$

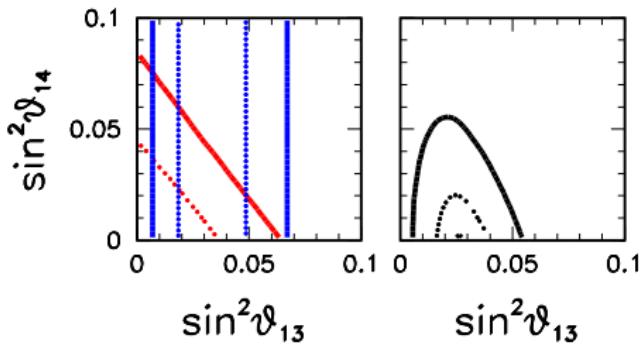
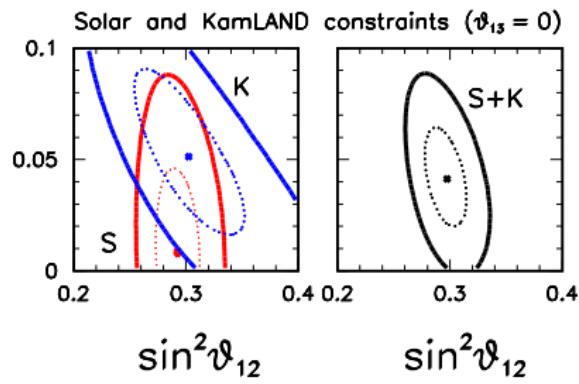
$$P_{\nu_e \rightarrow \nu_e} = c_{13}^4 c_{14}^4 P_{\nu_e \rightarrow \nu_e}^{2\nu} + s_{13}^4 c_{14}^4 + s_{14}^4$$

$$P_{\nu_e \rightarrow \nu_s} = c_{14}^2 s_{14}^2 (c_{13}^4 P_{\nu_e \rightarrow \nu_s}^{2\nu} + s_{13}^4 + 1)$$

$$\begin{aligned} V &= c_{13}^2 c_{14}^2 V_{CC} - c_{13}^2 s_{14}^2 V_{NC} \\ &= (|U_{e1}|^2 + |U_{e2}|^2) V_{CC} - (|U_{s1}|^2 + |U_{s2}|^2) V_{NC} \end{aligned}$$



[Palazzo, PRD 83 (2011) 113013]



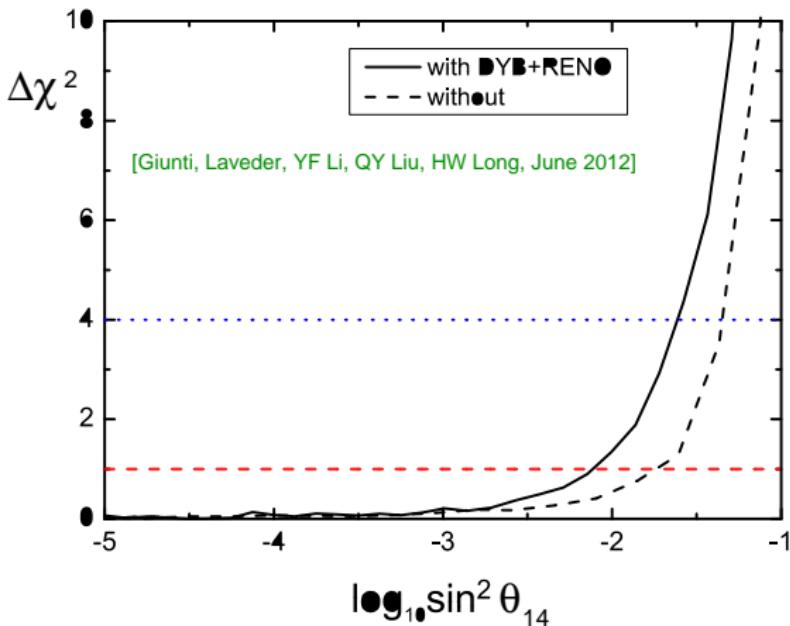
[Palazzo, PRD 85 (2012) 077301]

Daya Bay and RENO

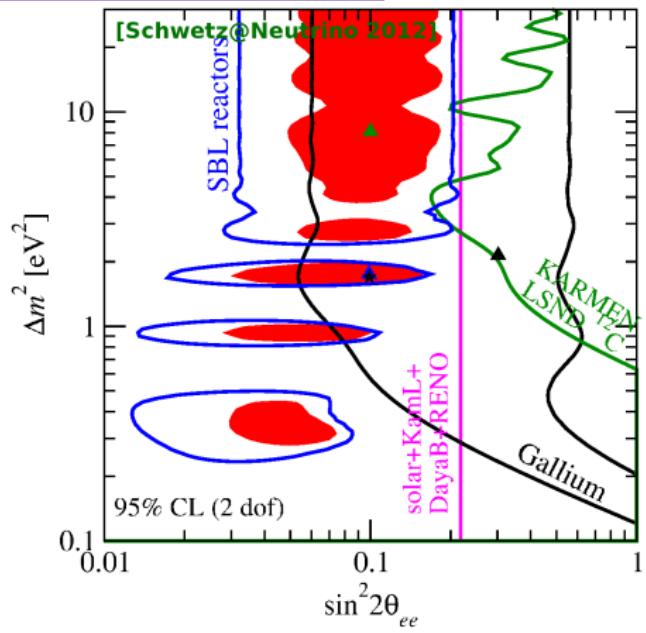
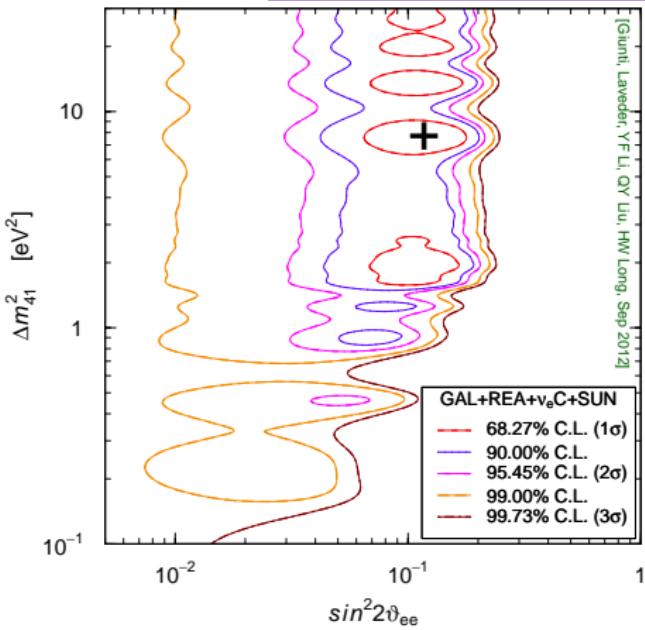
$$\sin^2 \vartheta_{13} = 0.025 \pm 0.004$$

$$|U_{e4}|^2 = \sin^2 \vartheta_{14} \lesssim 0.02 (1\sigma)$$

Fit of solar and KamLAND data with
Daya Bay and RENO constraint $\sin^2 \vartheta_{13} = 0.025 \pm 0.004$
and free $|U_{\mu 4}|$ and $|U_{\tau 4}|$ (no CP violation)



Global ν_e and $\bar{\nu}_e$ Disappearance

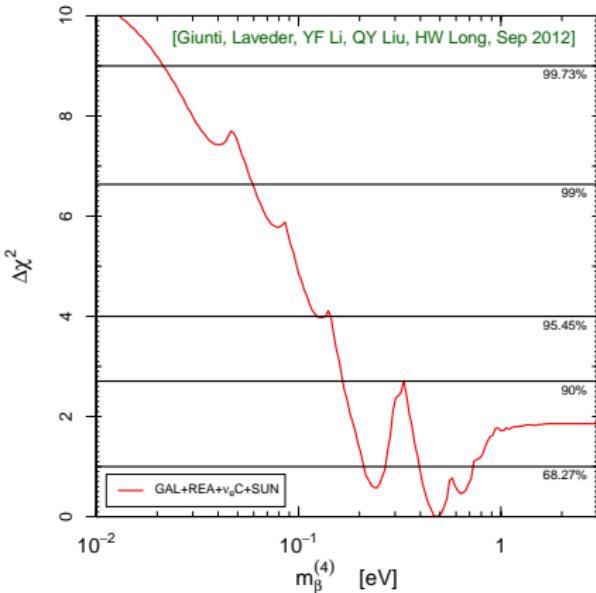


No Osc.	χ^2_{min}	56.1
	NDF	53
	GoF	35.8 %
3+1	χ^2_{min}	45.5
	NDF	51
	GoF	69 %
	Δm^2_{41} [eV ²]	7.59
	$\sin^2 2\theta_{ee}$	0.12

No Osc.	χ^2_{min}	318.4
	NDF	331
	GoF	68%
3+1	χ^2_{min}	306.0
	NDF	329
	GoF	80%
	Δm^2_{41} [eV ²]	1.71
	$\sin^2 2\theta_{ee}$	0.099

Testable Implications

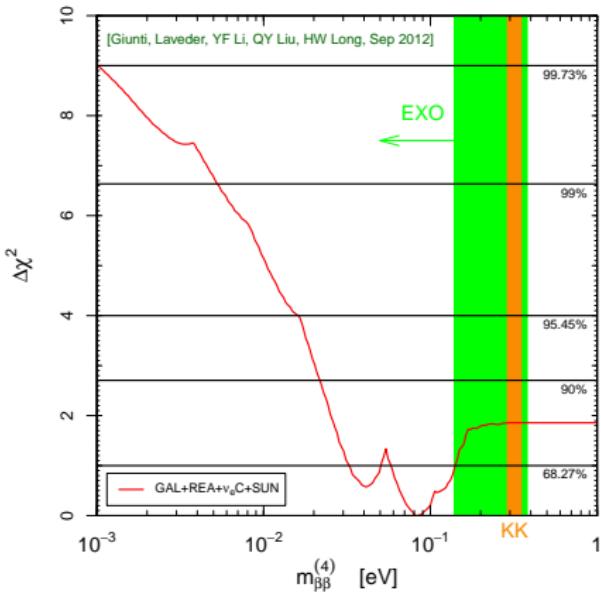
β Decay



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

$$m_\beta^{(4)} = |U_{e4}| \sqrt{\Delta m_{41}^2}$$

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



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

$$m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

Global 3+1 Fit: Disappearance Constraints

- ν_e disappearance experiments:

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

- ν_μ disappearance experiments:

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

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

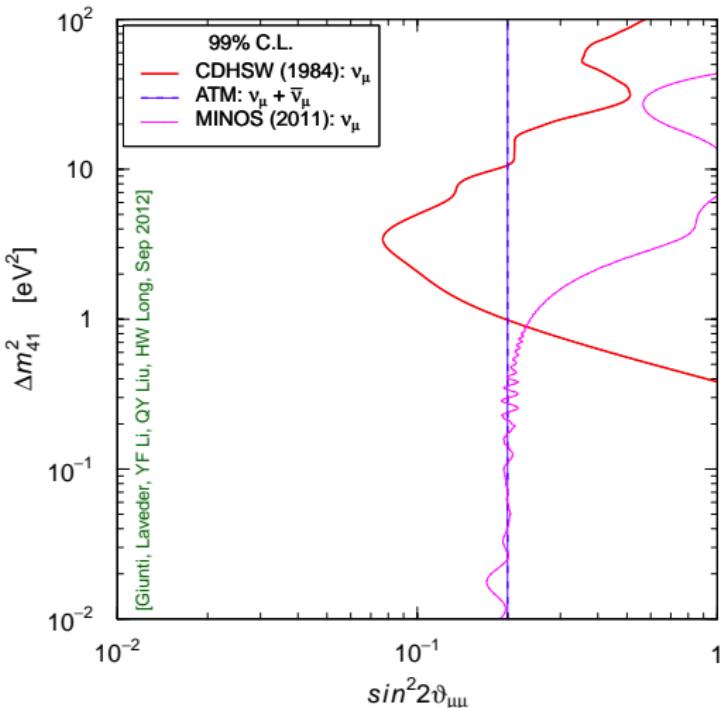
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

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

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694]

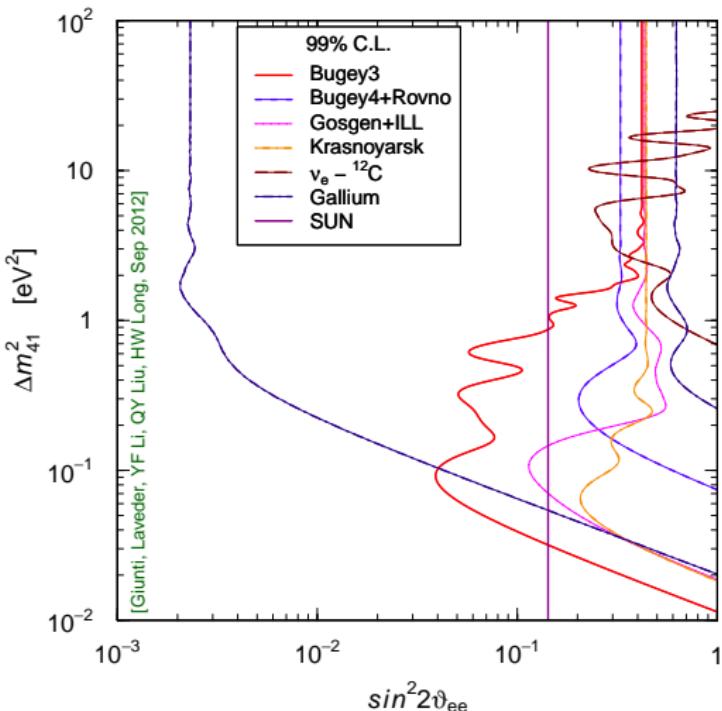
[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247]

ν_μ and $\bar{\nu}_\mu$ Disappearance

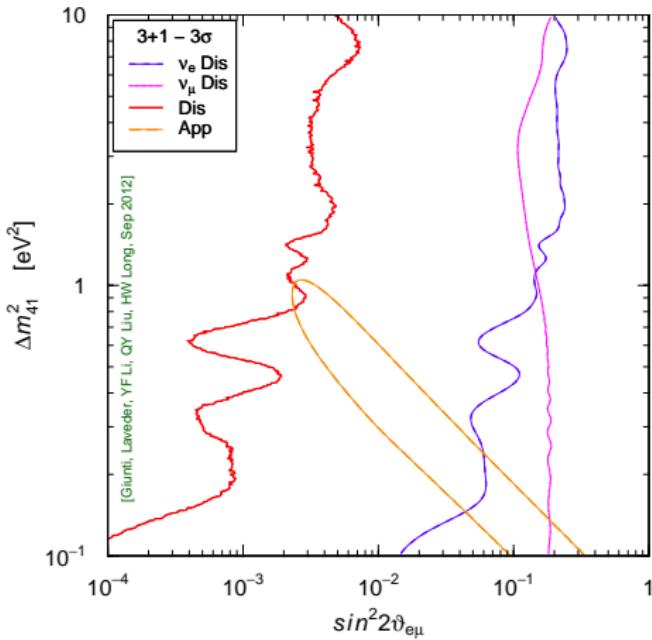


- ▶ ATM constraint on $|U_{\mu 4}|^2$
[Maltoni, Schwetz, PRD 76 (2007) 093005]
- ▶ MINOS constraint on $|U_{\mu 4}|^2$
[Giunti, Laveder, PRD 84 (2011) 093006]
- ▶ To be included soon:
MiniBooNE/SciBooNE limit
on SBL $\bar{\nu}_\mu$ disappearance
[arXiv:1208.0322]

ν_e and $\bar{\nu}_e$ Disappearance



- ▶ New Reactor $\bar{\nu}_e$ Fluxes
 - [Mueller et al., PRC 83 (2011) 054615]
 - [Mention et al., PRD 83 (2011) 073006]
 - [Huber, PRC 84 (2011) 024617]
- ▶ KARMEN + LSND
 - $\nu_e + {}^{12}\text{C} \rightarrow {}^{12}\text{N}_{\text{g.s.}} + e^-$
 - [Conrad, Shaevitz, PRD 85 (2012) 013017]
 - [Giunti, Laveder, PLB 706 (2011) 200]
- ▶ SUN&KamLAND + ϑ_{13}
 - [Giunti, Li, PRD 80 (2009) 113007]
 - [Palazzo, PRD 83 (2011) 113013]
 - [Palazzo, PRD 85 (2012) 077301]
 - [Giunti, Laveder, Li, Liu, Long, in preparation]



- ▶ 2012 MiniBooNE data
- ▶ GoF = 9.3%
- ▶ PGOF = 0.002%
- ▶ missing new ICARUS constraint (added later)

- ▶ 3+1 & 3+2: Appearance-Disappearance tension
- ▶ Tension reduced in 3+1+NSI [Akhmedov, Schwetz, JHEP 10 (2010) 115]
- ▶ No tension in 3+1+CPTV
 - [Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
 - [Giunti, Laveder, PRD 82 (2010) 093016, PRD 83 (2011) 053006]

Goodness of Fit

- ▶ Assumption or approximation: Gaussian uncertainties and linear model
- ▶ χ^2_{\min} has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF} = N_D - N_P$$

N_D = Number of Data N_P = Number of Fitted Parameters

- ▶ $\langle \chi^2_{\min} \rangle = \text{NDF}$ $\text{Var}(\chi^2_{\min}) = 2\text{NDF}$

- ▶ $\text{GoF} = \int_{\chi^2_{\min}}^{\infty} p_{\chi^2}(z, \text{NDF}) dz$ $p_{\chi^2}(z, n) = \frac{z^{n/2-1} e^{-z/2}}{2^{n/2} \Gamma(n/2)}$

Parameter Goodness of Fit

Maltoni, Schwetz, PRD 68 (2003) 033020, arXiv:hep-ph/0304176

- ▶ Measure compatibility of two (or more) sets of data points A and B under fitting model

- ▶ $\chi^2_{\text{PGoF}} = (\chi^2_{\min})_{A+B} - [(\chi^2_{\min})_A + (\chi^2_{\min})_B]$

- ▶ χ^2_{PGoF} has χ^2 distribution with Number of Degrees of Freedom

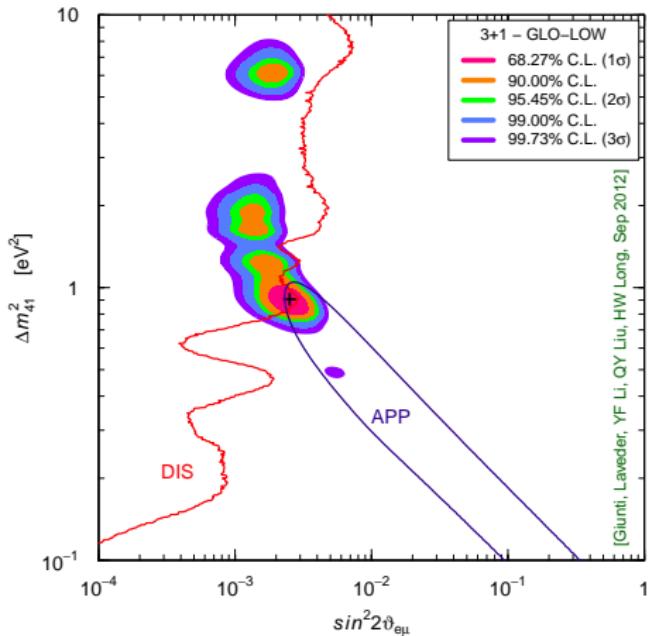
$$\text{NDF}_{\text{PGoF}} = N_P^A + N_P^B - N_P^{A+B}$$

- ▶ $\text{PGoF} = \int_{\chi^2_{\text{PGoF}}}^{\infty} p_{\chi^2}(z, \text{NDF}_{\text{PGoF}}) dz$

3+2

- ▶ 3+2 is preferred to 3+1 only if there is CP-violating difference of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions
- ▶ 2010 MiniBooNE antineutrino data indicated neutrino-antineutrino difference
- ▶ in 2010 it was reasonable and useful to consider 3+2
- ▶ neutrino-antineutrino difference almost disappeared with 2012 MiniBooNE antineutrino data
- ▶ in 2012 3+2 is reduced to 3+1 by Okkam razor shaving

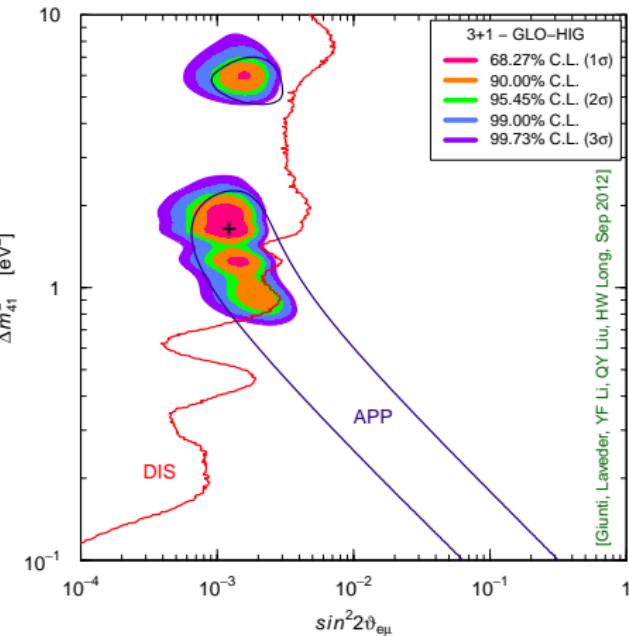
3+1 Global Fit without ICARUS



No Osc. GoF = 0.017%

3+1 GoF = 9.3%

PGoF = 0.002%

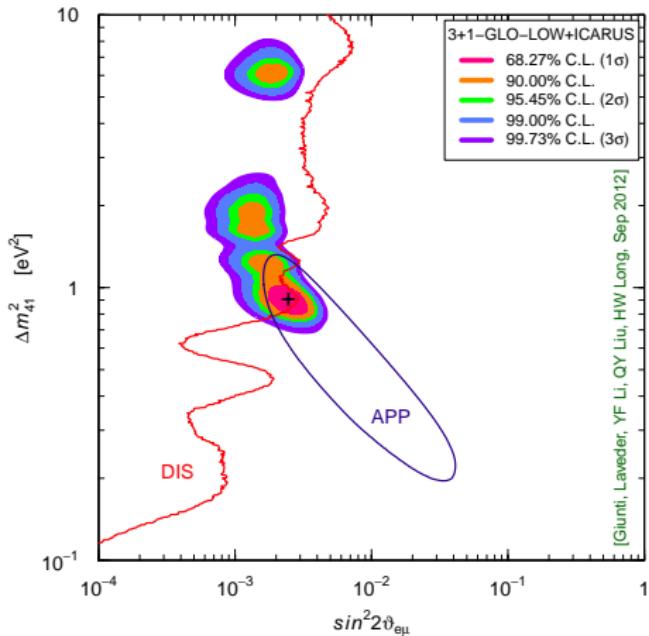


No Osc. GoF = 0.75%

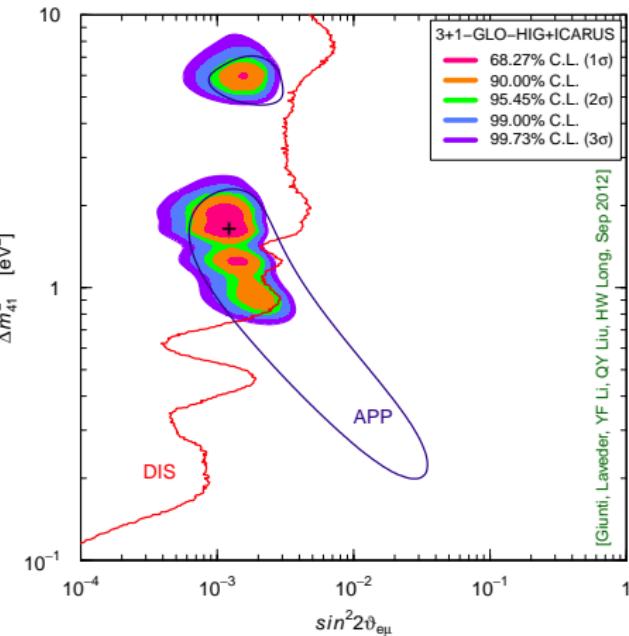
3+1 GoF = 30%

PGoF = 0.6%

3+1 Global Fit with ICARUS



No Osc. GoF = 0.021%
3+1 GoF = 9.9%
PGoF = 0.01%



No Osc. GoF = 0.87%
3+1 GoF = 32%
PGoF = 0.7%

Cosmology

- N_s = number of thermalized sterile neutrinos (not necessarily integer)
- CMB and LSS in Λ CDM: $N_s = 1.3 \pm 0.9$ $m_s < 0.66$ eV (95% C.L.)

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

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

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

$$N_s = 1.12_{-0.74}^{+0.86} \quad (95\% \text{ C.L.}) \quad [\text{Archidiacono, Calabrese, Melchiorri, PRD 84 (2011) 123008}]$$

- BBN: $\begin{cases} N_s = 0.22 \pm 0.59 \\ N_s = 0.64_{-0.35}^{+0.40} \\ N_s \leq 1 \text{ at 95\% C.L.} \end{cases}$
[Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313]
[Izotov, Thuan, ApJL 710 (2010) L67]
[Mangano, Serpico, PLB 701 (2011) 296]

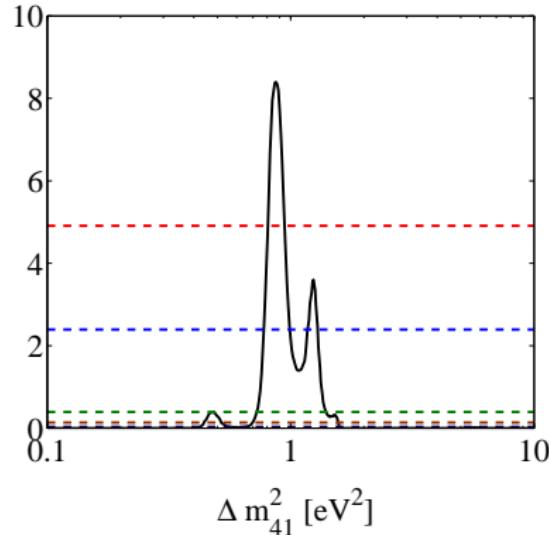
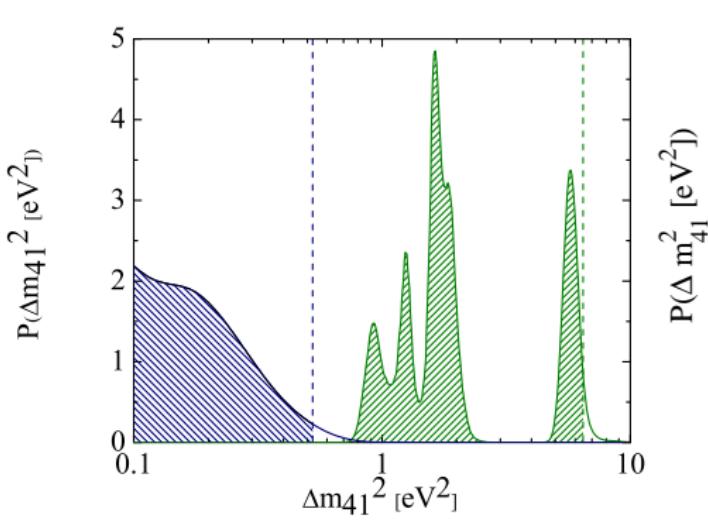
- CMB+LSS+BBN: $N_s = 0.85_{-0.56}^{+0.39} \quad (95\% \text{ C.L.})$

[Hamann, Hannestad, Raffelt, Wong, JCAP 1109 (2011) 034]

- Standard Λ CDM: 3+1 allowed, 3+2 disfavored

Combined Oscillation and Cosmology Fit

[Archidiacono, Fornengo, Giunti, Melchiorri, arXiv:1207.6515]



- Mass Hierarchy: $m_4 \gg m_3, m_2, m_1$ $\implies m_4 \simeq \sqrt{\Delta m_{41}^2}$
- Cosmology: $m_4 < 0.73 \text{ eV}^2$ (95% Bayesian CL)
- Oscillation + Cosmology: $0.85 < m_4 < 1.18 \text{ eV}^2$ (95% Bayesian CL)

Conclusions

- ▶ Short-baseline neutrino oscillation anomalies \Rightarrow sterile neutrinos
- ▶ Short-Baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Signal is not feeling well:
 - ▶ MiniBooNE 2011 antineutrino data were more similar to neutrino data than those of 2010 (LSND signal diminished and low-energy anomaly appeared)
 - ▶ MiniBooNE 2012 antineutrino data are even more similar to neutrino data
 - ▶ Probably there is no CP violation \Rightarrow no need of 3+2
 - ▶ The decrease of MiniBooNE-LSND agreement is discouraging
 - ▶ Better experiments are needed to clarify situation
- ▶ Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance is in good health:
 - ▶ Reactor $\bar{\nu}_e$ anomaly is alive and exciting
 - ▶ Gallium ν_e anomaly has been strengthened by new cross-section measurements
 - ▶ Many promising projects to test short-baseline ν_e and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources
 - ▶ Independent tests through effect of m_4 in β -decay and $(\beta\beta)_{0\nu}$ -decay