

Status of Three-Neutrino Mixing and Beyond

Carlo Giunti

INFN, Sezione di Torino, and Dipartimento di Fisica Teorica, Università di Torino

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

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

Portoroz 2013

Probing the Standard Model and New Physics
at Low and High Energies

14-18 April 2013, Portoroz, Slovenia

Neutrino Oscillations

- ▶ 1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \Leftrightarrow \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)
- ▶ Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- ▶ Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- ▶ A Flavor Neutrino is a **superposition** of Massive Neutrinos

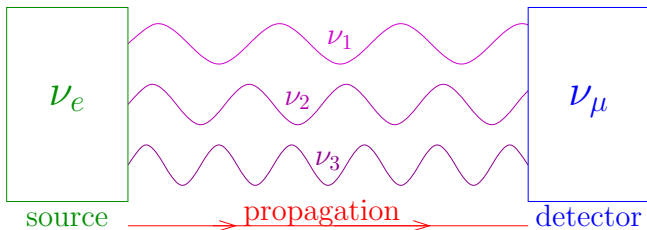
$$|\nu_e\rangle = U_{e1} |\nu_1\rangle + U_{e2} |\nu_2\rangle + U_{e3} |\nu_3\rangle$$

$$|\nu_\mu\rangle = U_{\mu1} |\nu_1\rangle + U_{\mu2} |\nu_2\rangle + U_{\mu3} |\nu_3\rangle$$

$$|\nu_\tau\rangle = U_{\tau1} |\nu_1\rangle + U_{\tau2} |\nu_2\rangle + U_{\tau3} |\nu_3\rangle$$

- ▶ U is the 3×3 Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1} |\nu_1\rangle + U_{e2} |\nu_2\rangle + U_{e3} |\nu_3\rangle$$



$$|\nu(t > 0)\rangle = U_{e1} e^{-iE_1 t} |\nu_1\rangle + U_{e2} e^{-iE_2 t} |\nu_2\rangle + U_{e3} e^{-iE_3 t} |\nu_3\rangle \neq |\nu_e\rangle$$

$$E_k^2 = p^2 + m_k^2$$

at the detector there is a **probability** > 0 to see the neutrino as a ν_μ

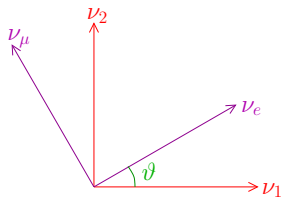
Neutrino Oscillations are Flavor Transitions

$$\begin{array}{cccc} \nu_e \rightarrow \nu_\mu & \nu_e \rightarrow \nu_\tau & \nu_\mu \rightarrow \nu_e & \nu_\mu \rightarrow \nu_\tau \\ \bar{\nu}_e \rightarrow \bar{\nu}_\mu & \bar{\nu}_e \rightarrow \bar{\nu}_\tau & \bar{\nu}_\mu \rightarrow \bar{\nu}_e & \bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \end{array}$$

transition probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

Two-Neutrino Mixing and Oscillations

$$|\nu_\alpha\rangle = \sum_{k=1}^2 U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu)$$



$$U = \begin{pmatrix} \cos \vartheta & \sin \vartheta \\ -\sin \vartheta & \cos \vartheta \end{pmatrix}$$

$$\begin{aligned} |\nu_e\rangle &= \cos \vartheta |\nu_1\rangle + \sin \vartheta |\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin \vartheta |\nu_1\rangle + \cos \vartheta |\nu_2\rangle \end{aligned}$$

$$\Delta m^2 \equiv \Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

Transition Probability: $P_{\nu_e \rightarrow \nu_\mu} = P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\vartheta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$

Survival Probabilities: $P_{\nu_e \rightarrow \nu_e} = P_{\nu_\mu \rightarrow \nu_\mu} = 1 - P_{\nu_e \rightarrow \nu_\mu}$

Experimental Evidences of Neutrino Oscillations

Solar
 $\nu_e \rightarrow \nu_\mu, \nu_\tau$

VLBL Reactor
 $\bar{\nu}_e$ disappearance

(SNO, BOREXino
Super-Kamiokande
GALLEX/GNO, SAGE
Homestake, Kamiokande
KamLAND)

$$\rightarrow \left\{ \begin{array}{l} \Delta m_S^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2 \\ \sin^2 \vartheta_S \simeq 0.30 \end{array} \right.$$

Atmospheric
 $\nu_\mu \rightarrow \nu_\tau$

LBL Accelerator
 ν_μ disappearance

LBL Accelerator
 $\nu_\mu \rightarrow \nu_\tau$

(Super-Kamiokande
Kamiokande, IMB
MACRO, Soudan-2
K2K, MINOS, T2K
Opera)

$$\rightarrow \left\{ \begin{array}{l} \Delta m_A^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2 \\ \sin^2 \vartheta_A \simeq 0.50 \end{array} \right.$$

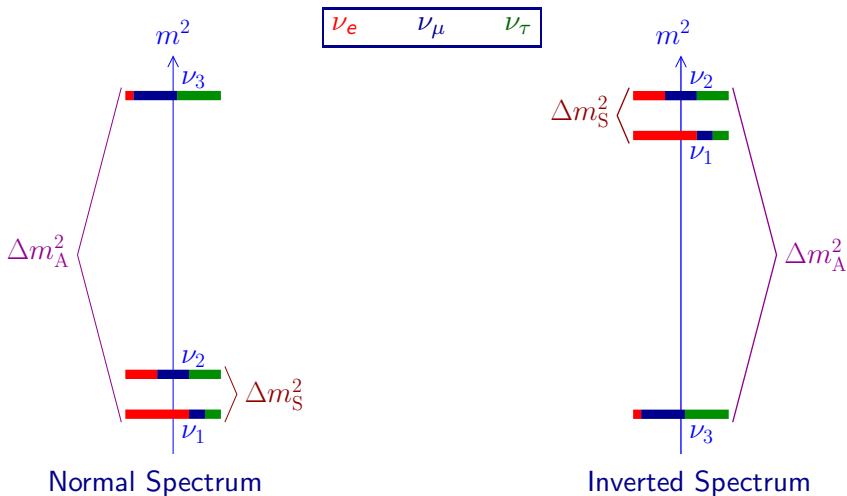
LBL Accelerator
 $\nu_\mu \rightarrow \nu_e$

LBL Reactor
 $\bar{\nu}_e$ disappearance

(T2K, MINOS
Daya Bay, RENO
Double Chooz)

$$\rightarrow \left\{ \begin{array}{l} \Delta m_A^2 \\ \sin^2 \vartheta_{13} \simeq 0.023 \end{array} \right.$$

Three-Neutrino Mixing Paradigm



$$\Delta m_{\text{S}}^2 = \Delta m_{21}^2$$

$$\Delta m_{\text{A}}^2 = |\Delta m_{31}^2| \simeq |\Delta m_{32}^2|$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$\vartheta_{23} = \vartheta_A$$

$$\sin^2 \vartheta_{23} \simeq 0.4 - 0.6$$

Chooz, Palo Verde

T2K, MINOS

Daya Bay, RENO

$$\sin^2 \vartheta_{13} = 0.023 \pm 0.002$$

$$\vartheta_{12} = \vartheta_S$$

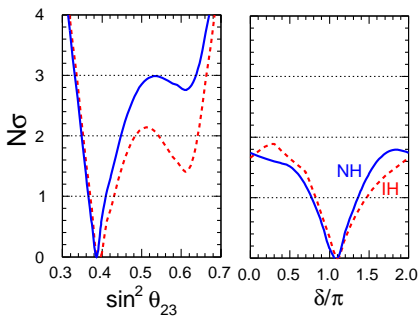
$$\sin^2 \vartheta_{12} = 0.30 \pm 0.01$$

$\beta\beta_{0\nu}$

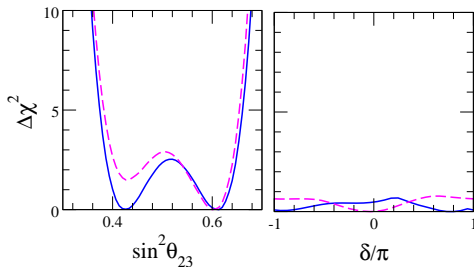
$$\frac{\delta \sin^2 \vartheta_{23}}{\sin^2 \vartheta_{23}} \simeq 40\%$$

$$\frac{\delta \sin^2 \vartheta_{13}}{\sin^2 \vartheta_{13}} \simeq 10\%$$

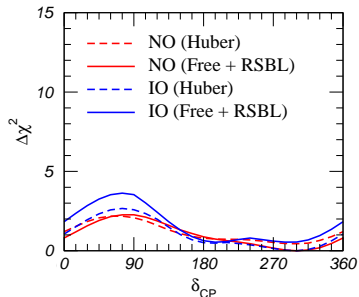
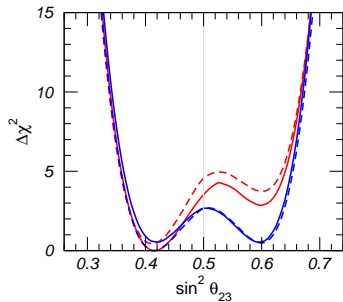
$$\frac{\delta \sin^2 \vartheta_{12}}{\sin^2 \vartheta_{12}} \simeq 5\%$$



[Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno, PRD 86 (2012) 013012]



[Forero, Tortola, Valle, PRD 86 (2012) 073012]

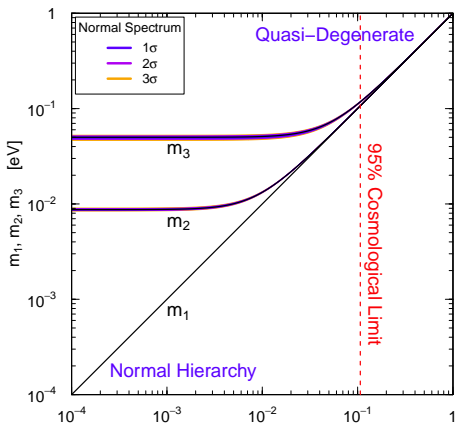


[Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 12 (2012) 123; <http://www.nu-fit.org>]

Open Problems

- ▶ $\vartheta_{23} < 45^\circ$?
 - ▶ Atmospheric ν , T2K, NO ν A,
- ▶ Mass Hierarchy ?
 - ▶ NO ν A, Atmospheric ν , Day Bay II, RENO-50, Supernova ν , ...
- ▶ CP violation ?
 - ▶ NO ν A, LBNE, LBNO, HyperK, ...
- ▶ Absolute Mass Scale ?
 - ▶ β Decay, Neutrinoless Double- β Decay, Cosmology, ...
- ▶ Dirac or Majorana ?
 - ▶ Neutrinoless Double- β Decay, ...
- ▶ Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

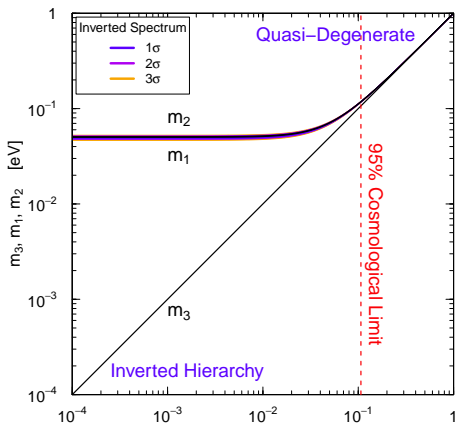
Absolute Scale of Neutrino Masses



Lightest mass: m_1 [eV]

$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$

$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$



Lightest mass: m_3 [eV]

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$

$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2} \text{ eV}$

95% Cosmological Limit: Planck + WMAP9 + highL + BAO [arXiv:1303.5076]

Tritium Beta-Decay

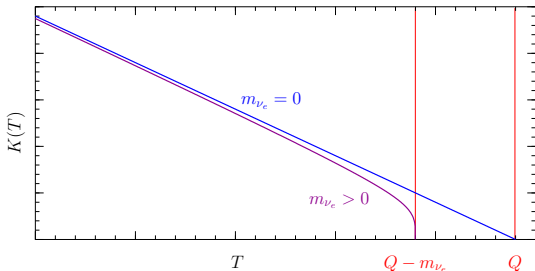


$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E (Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2}$$

$$Q = M_{{}^3\text{H}} - M_{{}^3\text{He}} - m_e = 18.58 \text{ keV}$$

Kurie plot

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E}} = \left[(Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2} \right]^{1/2}$$



$$m_{\nu_e} < 2.2 \text{ eV} \quad (95\% \text{ C.L.})$$

Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

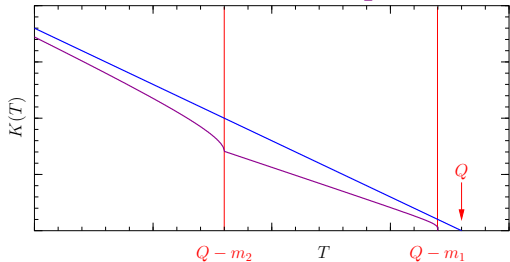
future: KATRIN

[www.katrin.kit.edu]

start data taking in 2015

sensitivity: $m_{\nu_e} \simeq 0.2 \text{ eV}$

$$\text{Neutrino Mixing} \implies K(T) = \left[(Q - T) \sum_k |U_{ek}|^2 \sqrt{(Q - T)^2 - m_k^2} \right]^{1/2}$$



analysis of data is different from the no-mixing case:

$2N - 1$ parameters

$$\left(\sum_k |U_{ek}|^2 = 1 \right)$$

if experiment is not sensitive to masses ($m_k \ll Q - T$)

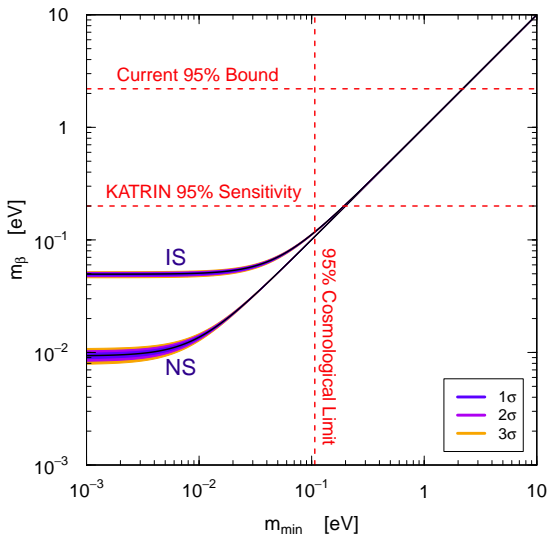
effective mass:

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

$$\begin{aligned} K^2 &= (Q - T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q - T)^2}} \simeq (Q - T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q - T)^2} \right] \\ &= (Q - T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q - T)^2} \right] \simeq (Q - T) \sqrt{(Q - T)^2 - m_\beta^2} \end{aligned}$$

Predictions of 3ν -Mixing Paradigm

$$m_\beta^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$



- ▶ Quasi-Degenerate:

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

- ▶ Inverted Hierarchy:

$$m_\beta^2 \simeq (1 - s_{13}^2) \Delta m_A^2 \simeq \Delta m_A^2$$

- ▶ Normal Hierarchy:

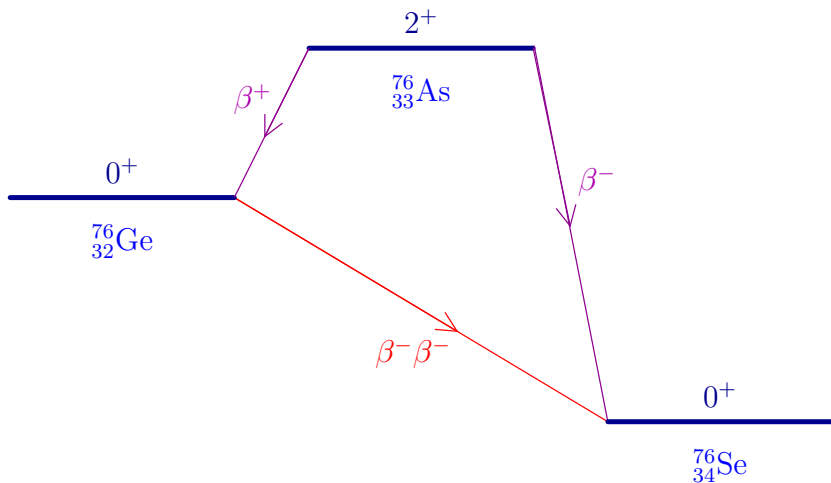
$$m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2 \\ \simeq 2 \times 10^{-5} + 6 \times 10^{-5} \text{ eV}^2$$

- ▶ $m_\beta \lesssim 4 \times 10^{-2} \text{ eV}$



Normal Spectrum

Neutrinoless Double-Beta Decay



Effective Majorana Neutrino Mass:

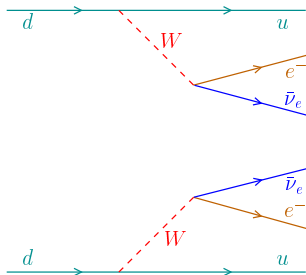
$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$

Two-Neutrino Double- β Decay: $\Delta L = 0$

$$\mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z + 2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu} |\mathcal{M}_{2\nu}|^2$$

second order weak interaction process
in the Standard Model



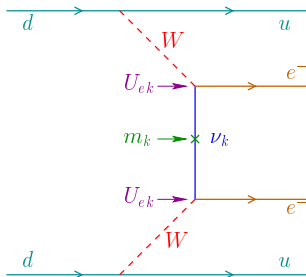
Neutrinoless Double- β Decay: $\Delta L = 2$

$$\mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z + 2) + e^- + e^-$$

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$$

effective
Majorana
mass

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

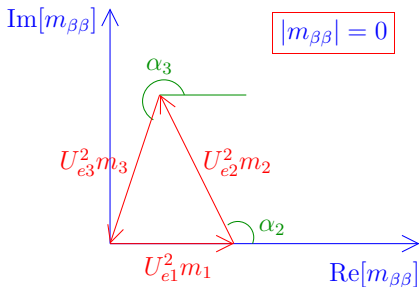
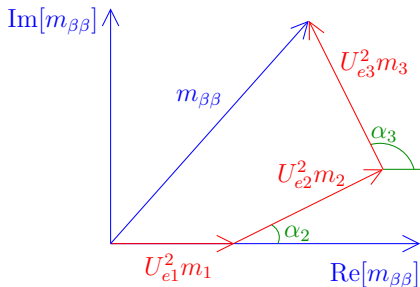


Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k \quad \text{complex } U_{ek} \Rightarrow \text{possible cancellations}$$

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$

$$\alpha_2 = 2\lambda_2 \quad \alpha_3 = 2(\lambda_3 - \delta_{13})$$



Experimental Bounds

KamLAND-Zen (^{136}Xe) [arXiv:1211.3863]

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.12 - 0.25 \text{ eV (KLZ+EXO)}$$

EXO (^{136}Xe) [PRL 109 (2012) 032505]

$$T_{1/2}^{0\nu} > 1.6 \times 10^{25} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.14 - 0.38 \text{ eV}$$

CUORICINO (^{130}Te) [AP 34 (2011) 822]

$$T_{1/2}^{0\nu} > 2.8 \times 10^{24} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.3 - 0.7 \text{ eV}$$

Heidelberg-Moscow (^{76}Ge) [EPJA 12 (2001) 147]

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.32 - 1.0 \text{ eV}$$

IGEX (^{76}Ge) [PRD 65 (2002) 092007]

$$T_{1/2}^{0\nu} > 1.57 \times 10^{25} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.33 - 1.35 \text{ eV}$$

NEMO 3 (^{100}Mo) [PRL 95 (2005) 182302]

$$T_{1/2}^{0\nu} > 4.6 \times 10^{23} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.7 - 2.8 \text{ eV}$$

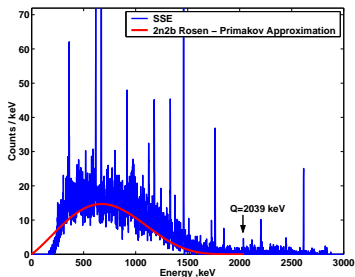
Experimental Positive Indication

[Klapdor et al., MPLA 16 (2001) 2409]

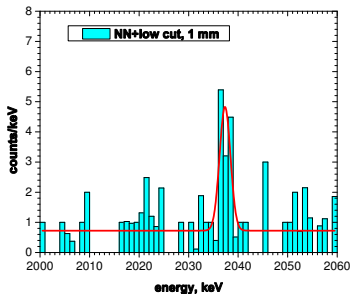
$$T_{1/2}^{0\nu} = (2.23_{-0.31}^{+0.44}) \times 10^{25} \text{ y}$$

6.5 σ evidence

[MPLA 21 (2006) 1547]



[PLB 586 (2004) 198]



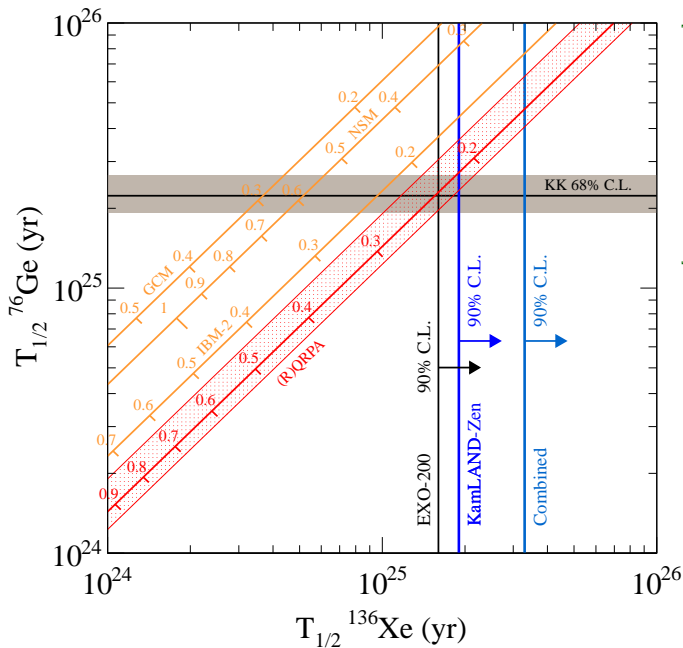
[MPLA 21 (2006) 1547]

$$|m_{\beta\beta}| = 0.32 \pm 0.03 \text{ eV}$$

[MPLA 21 (2006) 1547]

very exciting: Majorana ν and large mass scale

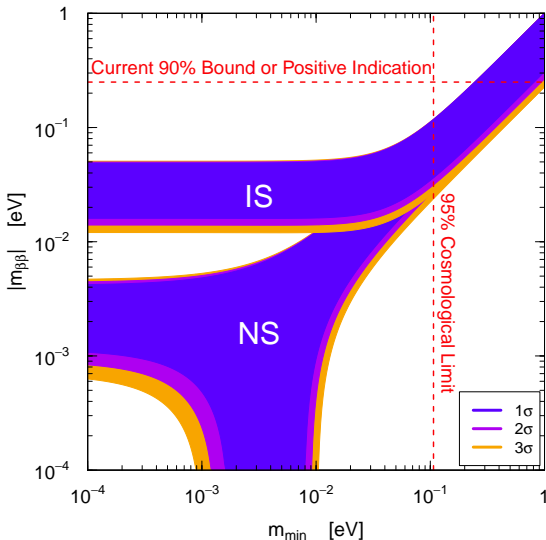
partially excluded by KamLAND-Zen, EXO and CUORICINO



[KamLAND-Zen, arXiv:1211.3863]

Predictions of 3ν -Mixing Paradigm

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$



▶ Positive indication:
tension with cosmology

▶ Quasi-Degenerate:

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s_{2\vartheta_{12}}^2 s_{\alpha_2}^2}$$

▶ Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m_A^2 (1 - s_{2\vartheta_{12}}^2 s_{\alpha_2}^2)}$$

▶ Normal Hierarchy:

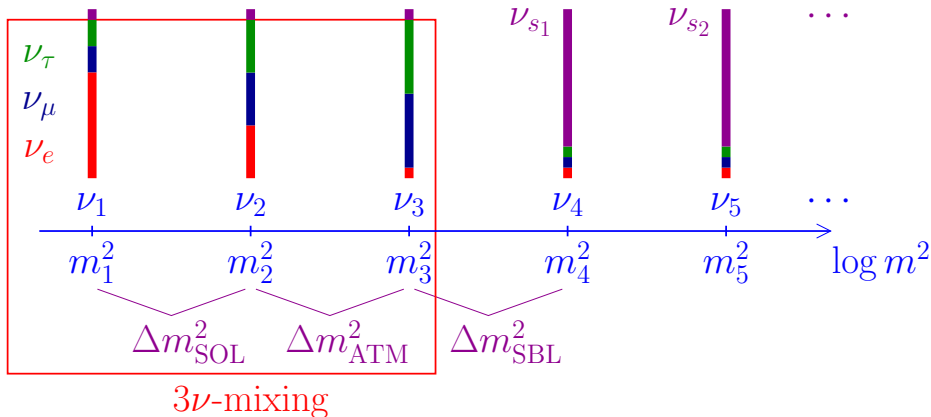
$$|m_{\beta\beta}| \simeq |s_{12}^2 \sqrt{\Delta m_S^2} + e^{i\alpha} s_{13}^2 \sqrt{\Delta m_A^2}|$$

$$\simeq |2.7 + 1.2e^{i\alpha}| \times 10^{-3} \text{ eV}$$

$m_1 \gtrsim 10^{-3} \text{ eV} \Rightarrow$ cancellation?

$|m_{\beta\beta}| \lesssim 10^{-2} \text{ eV} \Rightarrow$ Normal Spectrum

Beyond Three-Neutrino Mixing



Sterile Neutrinos from Physics Beyond the SM

- ▶ Neutrinos are special in the Standard Model: the only **neutral fermions**
- ▶ In extensions of SM neutrinos can mix with non-SM fermions

▶ SM: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \quad \tilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$

- ▶ SM singlet $\overline{L}_L \tilde{\Phi}$ can couple to new singlet chiral fermion field f_R related to physics beyond the SM $[Y(\overline{L}_L) = +1, Y(\tilde{\Phi}) = -1]$

- ▶ Known examples: light ν_R from see-saw, SUSY (ν_R , axino, ...), extra dimensions (Kaluza-Klein modes), mirror world, ...

▶ Dirac mass term $\sim \overline{L}_L \tilde{\Phi} f_R$ + Majorana mass term $\sim \overline{f_R^c} f_R$

- ▶ f_R is often called **Right-Handed Neutrino**: $f_R \rightarrow \nu_R$

Light 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 light 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:

$$\begin{array}{ccccc} \Delta m_{21}^2 & \ll & |\Delta m_{31}^2| & \ll & |\Delta m_{41}^2| \leq \dots \\ \nu_1 & & \nu_2 & & \nu_3 & & \nu_4 & & \dots \\ \nu_e & & \nu_\mu & & \nu_\tau & & \nu_{s1} & & \dots \end{array}$$

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

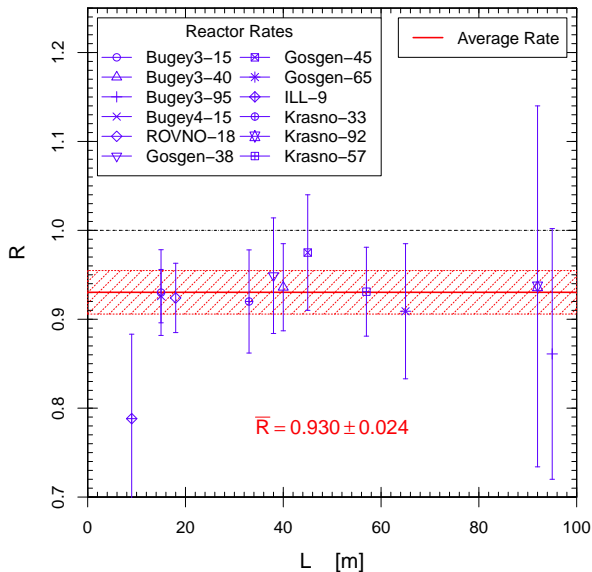
[update in White Paper, arXiv:1204.5379]

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

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

[Huber, PRC 84 (2011) 024617]

2.8 σ anomaly



Gallium Anomaly

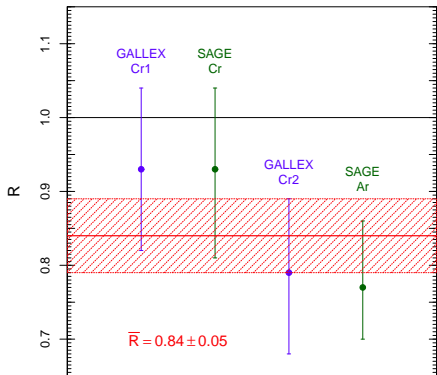
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

Anomaly supported by new ${}^{71}\text{Ga}({}^3\text{He}, {}^3\text{H}){}^{71}\text{Ge}$ cross section measurement

[Frekers et al., PLB 706 (2011) 134]



$E \sim 0.7 \text{ MeV}$

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

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

2.9σ anomaly

3+1 SBL ν_e and $\bar{\nu}_e$ Survival Probability

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

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

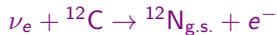
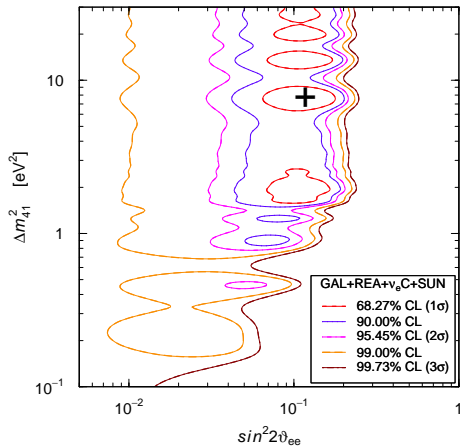
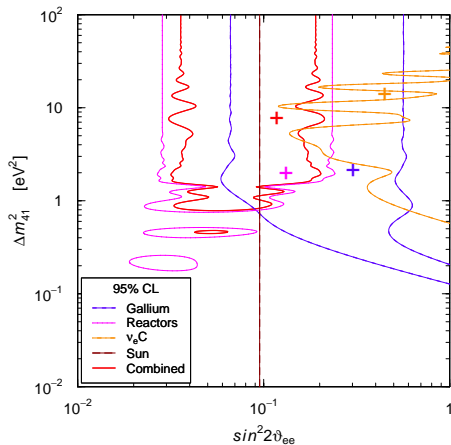
standard parameterization

$$U_{e1} = c_{12}c_{13}c_{14} \quad U_{e2} = s_{12}c_{13}c_{14} \quad U_{e3} = s_{13}c_{14}e^{-i\delta_{13}} \quad U_{e4} = s_{14}e^{-i\delta_{14}}$$

$$\sin^2 2\vartheta_{ee} = \sin^2 2\vartheta_{14}$$

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

[Giunti, Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, PRD 86 (2012) 113014]



KARMEN + LSND

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

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

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}

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

[Palazzo, PRD 83 (2011) 113013]

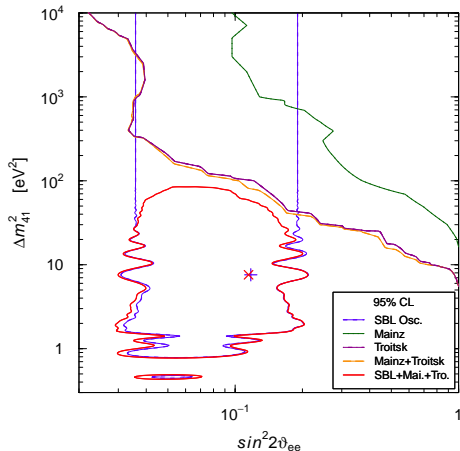
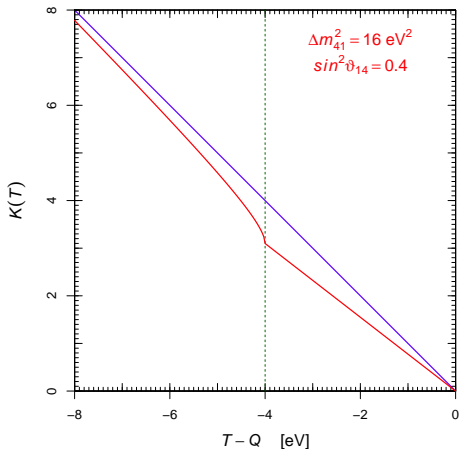
[Palazzo, PRD 85 (2012) 077301]

Mainz and Troitsk Limit on m_4^2

[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]

[Belesev, Berlev, Geraskin, Golubev, Likhovid, Nozik, Pantuev, Parfenov, Skasyrskaya, arXiv:1211.7193]

$$m_4 \gg m_1, m_2, m_3 \implies \Delta m_{41}^2 \equiv m_4^2 - m_1^2 \simeq m_4^2$$



[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 87 (2013) 013004]

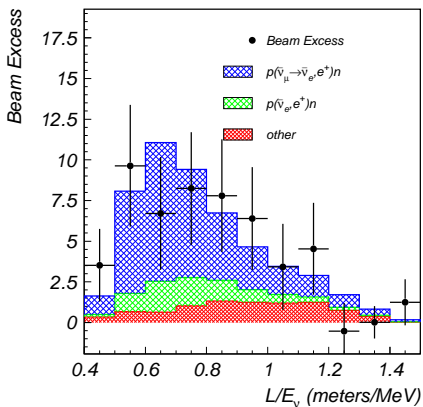
LSND

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

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

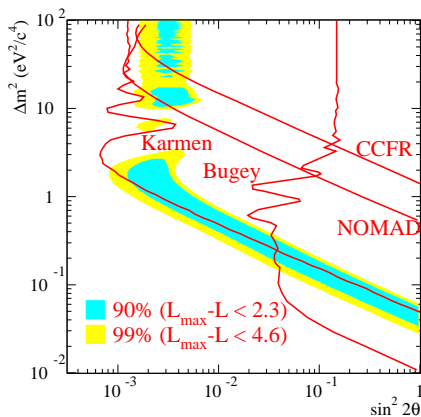
$$L \simeq 30 \text{ m}$$

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



3.8 σ excess

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



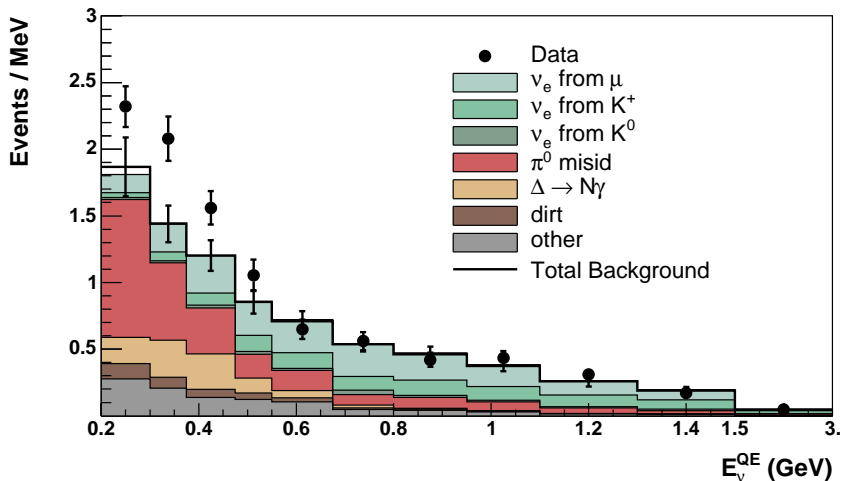
MiniBooNE Neutrinos

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

$\nu_\mu \rightarrow \nu_e$

$L \simeq 541$ m

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



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

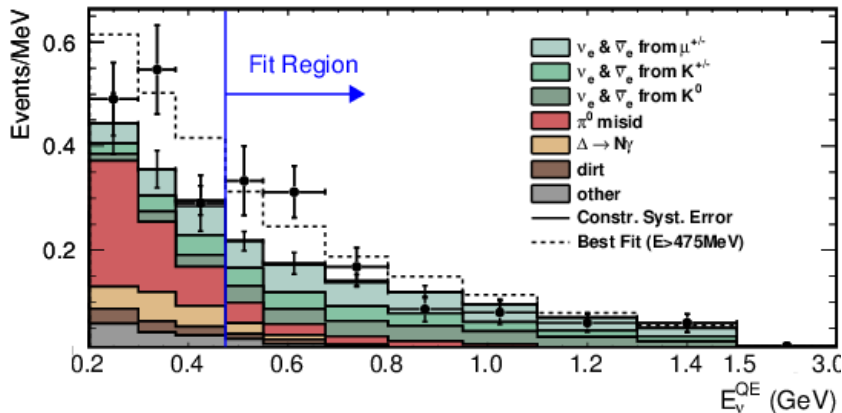
MiniBooNE Antineutrinos - 2009-2010

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

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

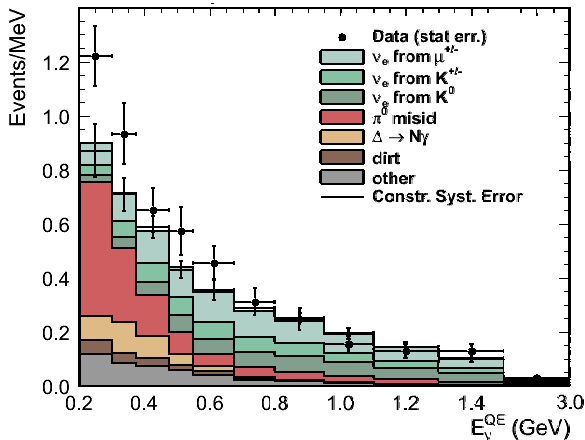
$$L \simeq 541 \text{ m}$$

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



- ▶ agreement with LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal ($E > 475 \text{ MeV}$)
- ▶ similar L/E but different L and $E \implies$ oscillations
- ▶ CP violation?

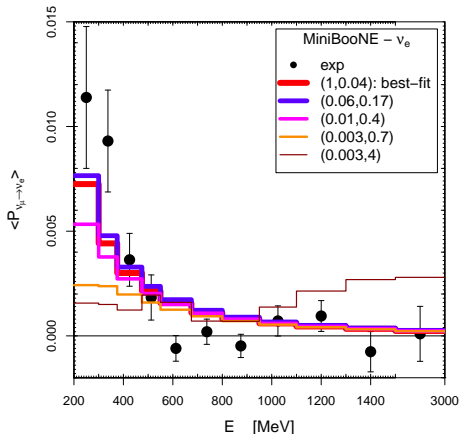
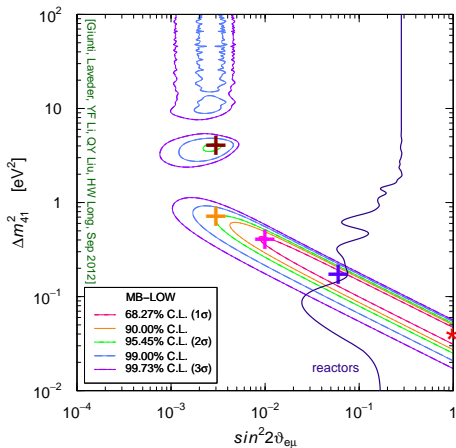
MiniBooNE $\bar{\nu}$ - Neutrino 2012 - 6 June



	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 ? CP violation ?

MiniBooNE ν and $\bar{\nu}$ - arXiv:1207.4809



- ▶ Fit of low-energy excess is marginal
- ▶ It requires $\Delta m_{41}^2 \lesssim 0.4 \text{eV}^2$
- ▶ Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, arXiv:1202.4745]

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

No CP Violation!

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

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

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



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

3+1: Appearance vs Disappearance

- ▶ 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:

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

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

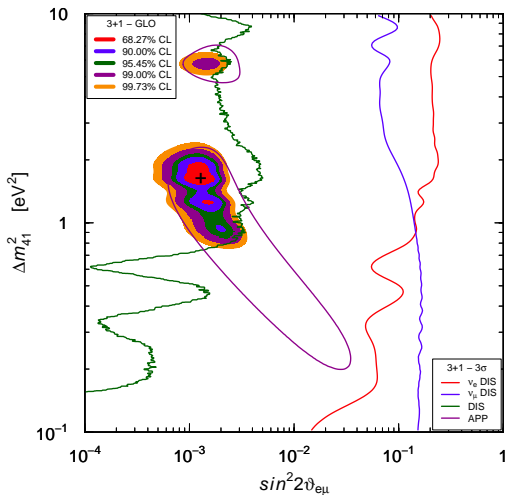
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

- ▶ Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \implies$ 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]

3+1 Global Fit



No Osc. GoF = 1.3%
3+1 GoF = 32%
PGoF = 4%

- ▶ APP $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:
LSND (Y), MiniBooNE (?),
ICARUS (N), KARMEN (N),
NOMAD (N)
- ▶ DIS ν_e & $\bar{\nu}_e$: Reactors (Y),
Gallium (Y), $\nu_e C$ (N),
Solar (N)
- ▶ DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N),
MINOS (N),
Atmospheric (N),
MiniBooNE/SciBooNE (N)

[see also Kopp, Machado,

Maltoni, Schwetz, arXiv:1303.3011]

Conclusions

- ▶ Robust Three-Neutrino Mixing Paradigm. Open problems: $\vartheta_{23} < 45^\circ?$, CP Violation, Mass Hierarchy, Absolute Mass Scale, Dirac or Majorana?
- ▶ Short-Baseline ν_e and $\bar{\nu}_e$ 3+1 Disappearance:
 - ▶ Reactor $\bar{\nu}_e$ anomaly is alive and exciting
 - ▶ Gallium ν_e anomaly 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
- ▶ Short-Baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ LSND Signal:
 - ▶ MiniBooNE experiment has been inconclusive
 - ▶ Better experiments are needed to check LSND signal
 - ▶ If LSND signal is confirmed $m_4 \sim 1$ eV, marginally compatible with Λ CDM
- ▶ Light Sterile Neutrinos:
 - ▶ First new particle beyond the Standard Model?
 - ▶ Strongest hint from Reactor and Gallium Anomalies will be checked in several near-future source and reactor experiments
 - ▶ Maybe LSND observed a fluctuation of small $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transition probability that can be observed in ICARUS@CERN
 - ▶ I have great hopes in near-future experiments!