Phenomenology of Neutrino Oscillations and Mixing

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

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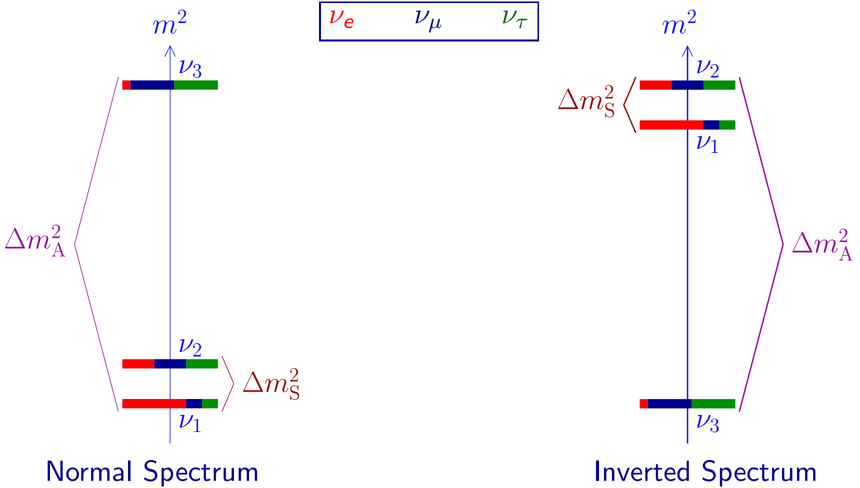
Experimental Evidences of Neutrino Oscillations

Experiment	Detectors	Result
Solar $\nu_e \to \nu_\mu, \nu_\tau$	SNO, BOREXino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake, Kamiokande	$\Delta m^2_{\text{S}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$, $\sin^2\vartheta_{\text{S}} \simeq 0.30$
VLBL Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	
Atmospheric $\nu_\mu \to \nu_\tau$	Super-Kamiokande; Kamiokande, IMB; MACRO, Soudan-2	$\Delta m^2_{\text{A}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$, $\sin^2\vartheta_{\text{A}} \simeq 0.50$
LBL Accelerator ν_μ disappearance	(K2K, MINOS, T2K)	
LBL Accelerator $\nu_\mu \to \nu_\tau$	(Opera)	
LBL Accelerator $\nu_\mu \to \nu_e$	(T2K, MINOS)	Δm^2_{A}, $\sin^2\vartheta_{13} \simeq 0.023$
LBL Reactor $\bar{\nu}_e$ disappearance	Daya Bay, RENO; Double Chooz	

Three-Neutrino Mixing Paradigm



$$\Delta m^2_{\rm S} = \Delta m^2_{21} = 7.50 \pm 0.20 \times 10^{-5}\,\text{eV}^2$$ uncertainty $\simeq 2.6\%$

$$\Delta m^2_{\rm A} = |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\text{eV}^2$$ uncertainty $\simeq 5\%$

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

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

$\vartheta_{23} = \vartheta_{\text{A}}$

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

Chooz, Palo Verde

T2K, MINOS

Daya Bay, RENO

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

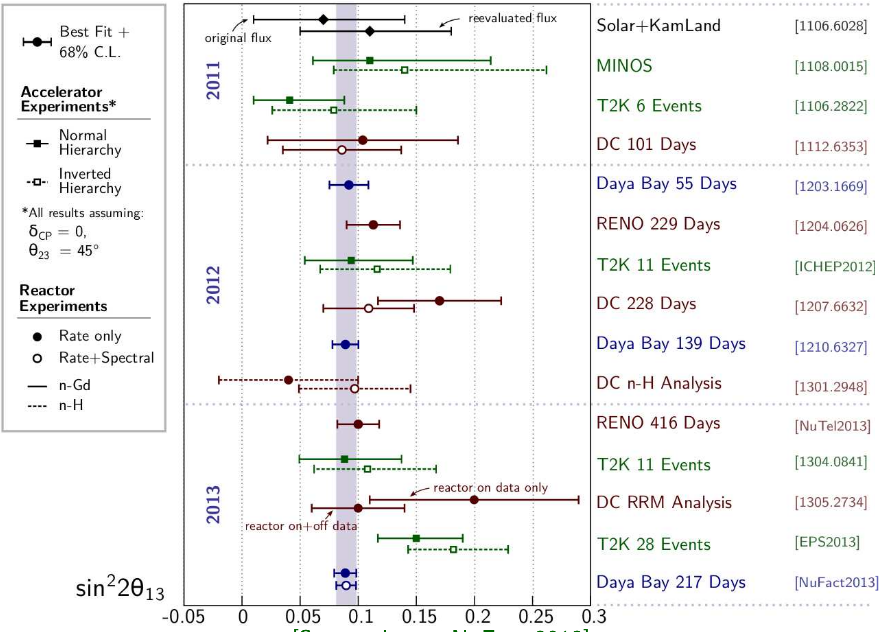
$\vartheta_{12} = \vartheta_{\text{S}}$

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

$\beta\beta_{0\nu}$

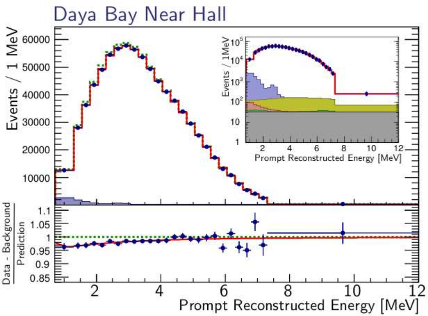
$$\frac{\delta \sin^2\vartheta_{23}}{\sin^2\vartheta_{23}} \simeq 40\% \qquad \frac{\delta \sin^2\vartheta_{13}}{\sin^2\vartheta_{13}} \simeq 10\% \qquad \frac{\delta \sin^2\vartheta_{12}}{\sin^2\vartheta_{12}} \simeq 5\%$$

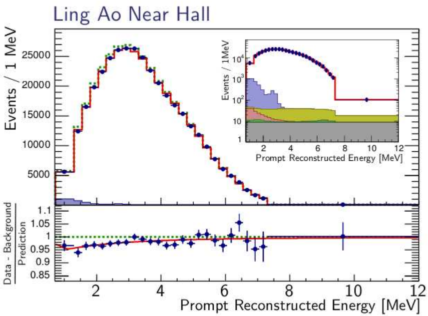
Global Comparison of ϑ_{13} Measurements

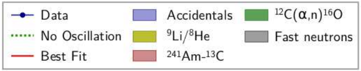


[Soeren Jetter, NuFact 2013]

Daya Bay - 22 August 2013

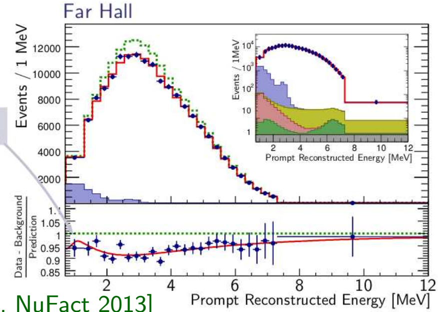




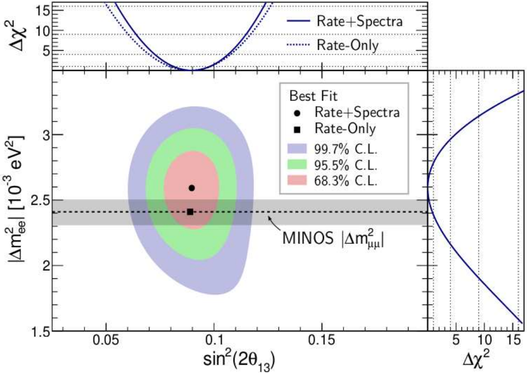


Spectral distortion consistent with oscillation

- Both background and predicted no-oscillation spectra from best fit
- Statistical errors only



[Soeren Jetter, NuFact 2013]

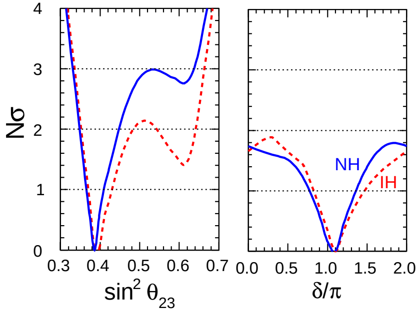


$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

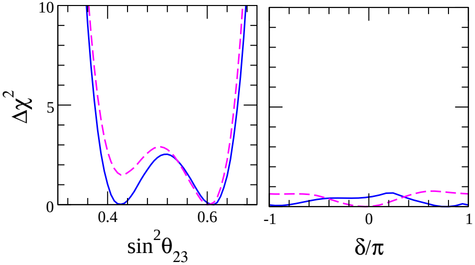
$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\mathrm{eV}^2$$

$$\chi^2/N_{\mathrm{DoF}} = 162.7/153$$

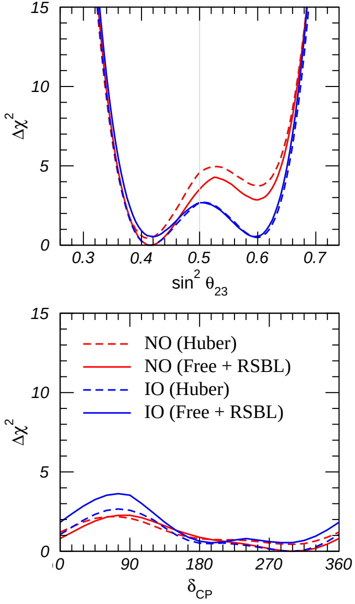
[Soeren Jetter, NuFact 2013]



[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]

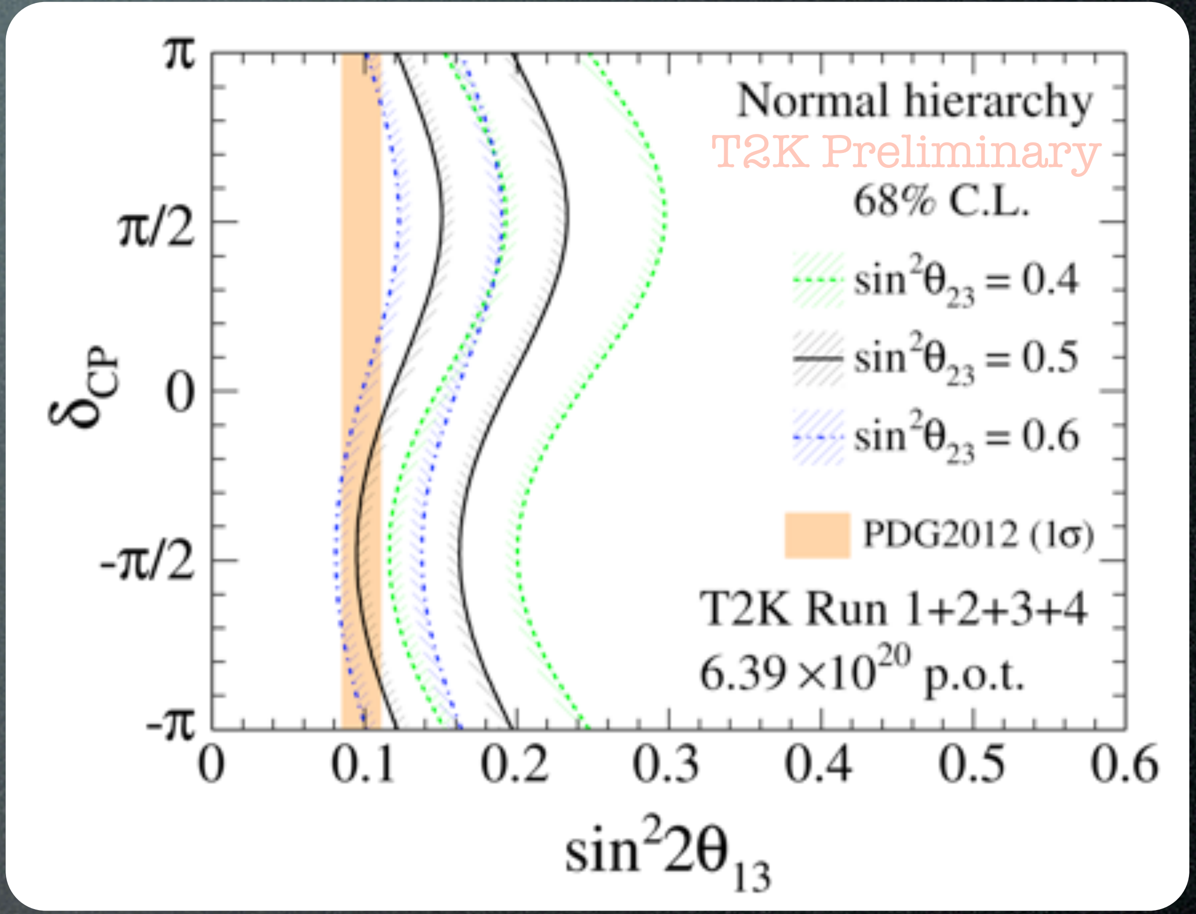
Open Problems

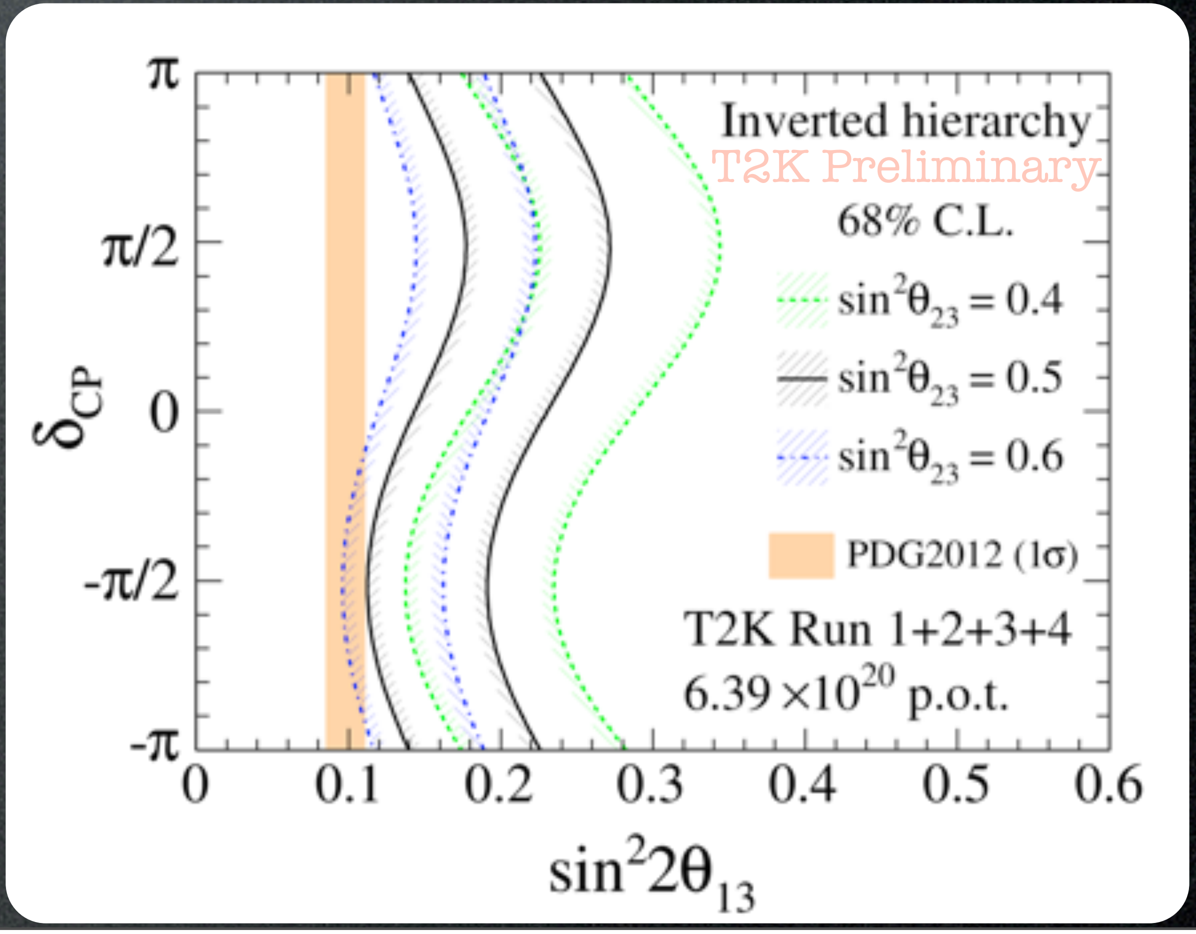
- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - Atmospheric ν, T2K, NOνA, ...
- Mass Hierarchy ?
  - NOνA, Atmospheric ν, JUNO (Daya Bay II), RENO-50, Supernova ν, ...
- CP violation ?
  - NOνA, LAGUNA-LBNO, LBNE (USA), HyperK, ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

Effect of θ_{23} Uncertainty

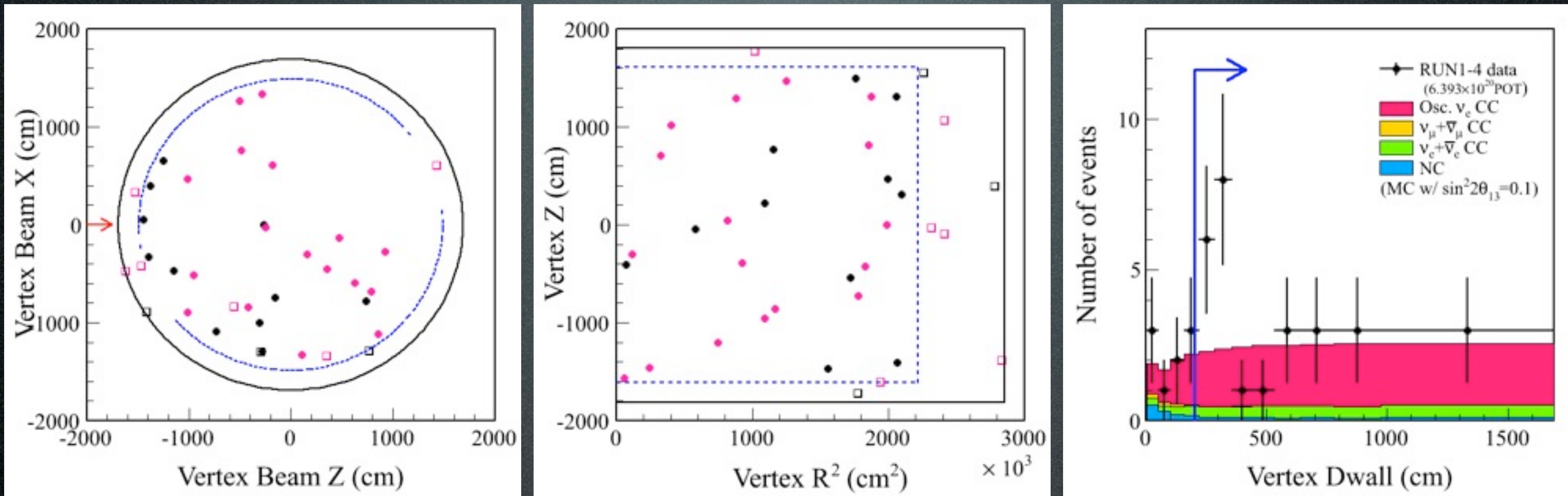
- ν_e appearance probability also depends on the value of θ_{23}
- If θ_{23} is fixed at values near the edge of the current allowed region, the fit contours shift
- Future improved measurements of θ_{23} will be important to extract information about other oscillation parameters (including δ_{CP}) in long-baseline experiments
  - A T2K combined ν_e+ν_μ analysis is underway

Note: these are 1D contours for various values of δ_{CP}, not 2D contours





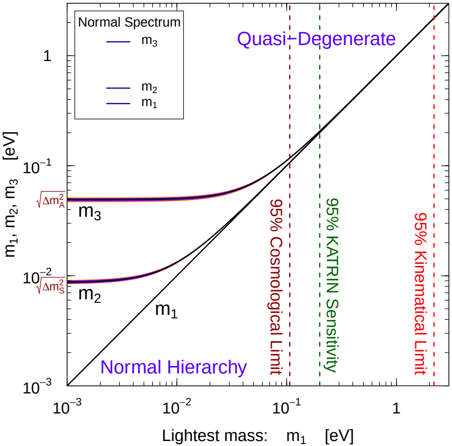
Far Detector ν_e Vertex Distribution

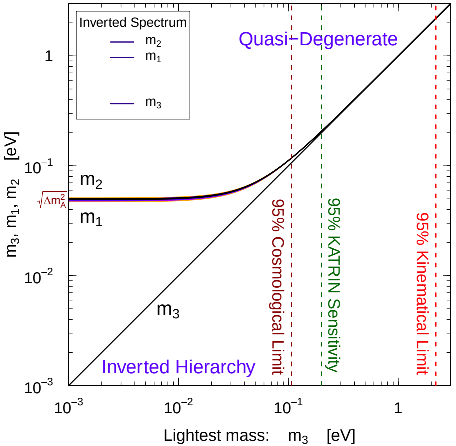


	RUN1+2+3	RUN4	RUN1+2+3+4
Dwall	34.4%	54.7%	20.9%
Fromwall $\text{beam}_{\parallel}$	6.04%	85.6%	8.93%
$R^2 + Z$	32.4%	98.1%	64.5%

- With increased statistics, the p-values for the test distributions have increased

Absolute Scale of Neutrino Masses





$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

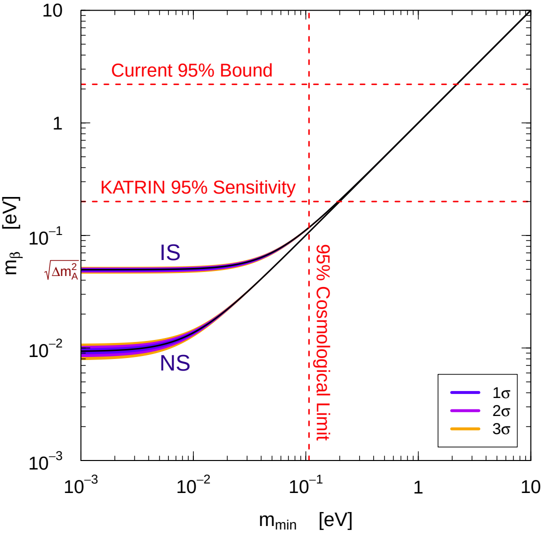
$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

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]

Effective Neutrino Mass in Beta-Decay

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



- 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:

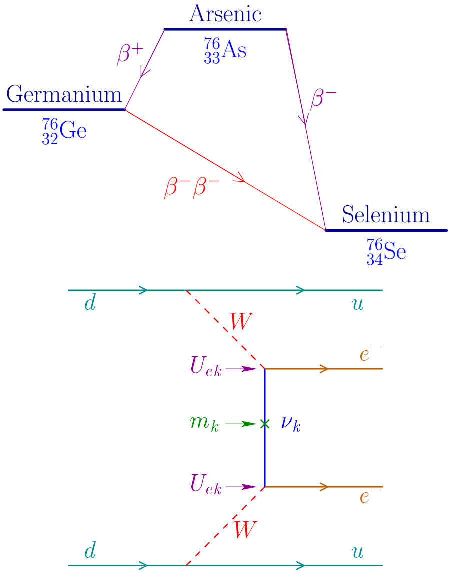
$$m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2$$
$$\simeq 2 \times 10^{-5} + 6 \times 10^{-5}\,\text{eV}^2$$

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

$\Downarrow$

Normal Spectrum

Majorana ν: Neutrinoless Double-Beta Decay



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

Effective Majorana Mass

$$m_{\beta\beta} = \left| \sum_{k=1}^{3} U^2_{ek}\, m_k \right|$$

EXO + KamLAND-Zen

$$^{136}_{54}\text{Xe} \to {}^{136}_{56}\text{Ba} + e^- + e^-$$

[PRL 109 (2012) 032505; PRL 110 (2013) 062502]

$$|m_{\beta\beta}| \lesssim 0.12 - 0.25\,\text{eV} \quad (90\%\text{C.L.})$$

GERDA

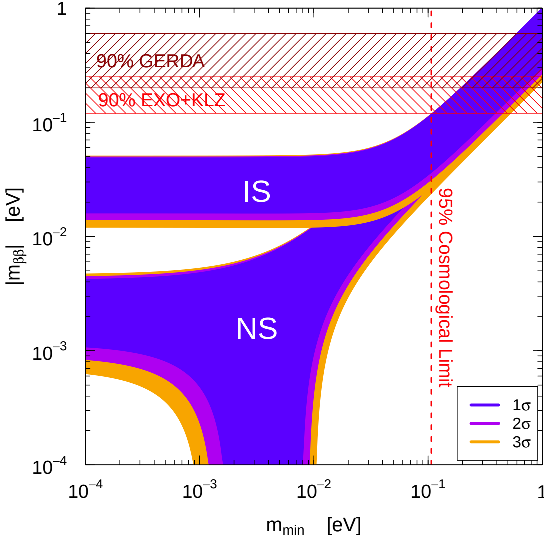
$$^{76}_{32}\text{Ge} \to {}^{76}_{34}\text{Se} + e^- + e^-$$

[arXiv:1307.4720]

$$|m_{\beta\beta}| \lesssim 0.2 - 0.6\,\text{eV} \quad (90\%\text{C.L.})$$

Effective Majorana Neutrino Mass

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



- Quasi-Degenerate:

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

- Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m^2_{\text{A}} (1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2})}$$

- Normal Hierarchy:

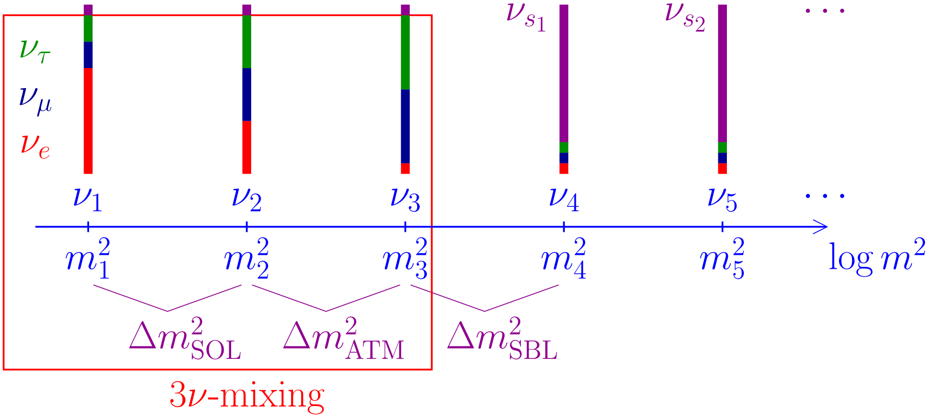
$$|m_{\beta\beta}| \simeq |s^2_{12} \sqrt{\Delta m^2_{\text{S}}} + e^{i\alpha} s^2_{13} \sqrt{\Delta m^2_{\text{A}}}|$$

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

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

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

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Light Sterile Neutrinos

- Sterile means no standard model interactions

  [Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ 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)

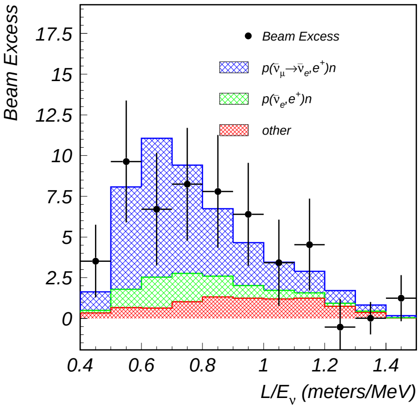
- Short-baseline anomalies + 3ν-mixing:

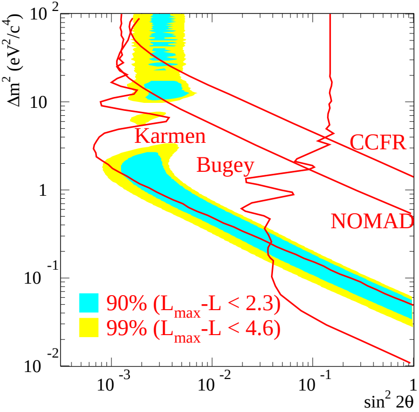
$$
\begin{array}{ccccc}
 & \Delta m^2_{21} \ll & |\Delta m^2_{31}| \ll & |\Delta m^2_{41}| \leq & \ldots \\
\nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\
\nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots
\end{array}
$$

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\qquad L \simeq 30\,\mathrm{m}$ $\qquad 20\,\mathrm{MeV} \leq E \leq 200\,\mathrm{MeV}$





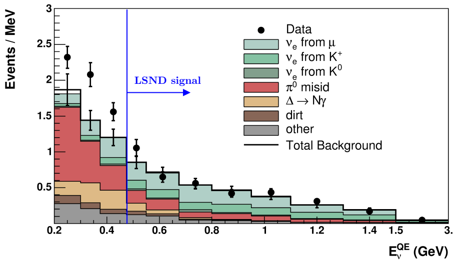
3.8σ excess $\qquad \Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

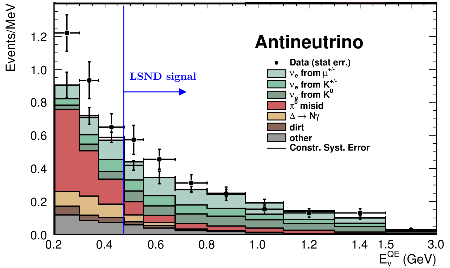
MiniBooNE

$L \simeq 541\,\text{m} \qquad 200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]

$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]





- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Reactor Electron Antineutrino Anomaly

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

[update in White Paper, arXiv:1204.5379]

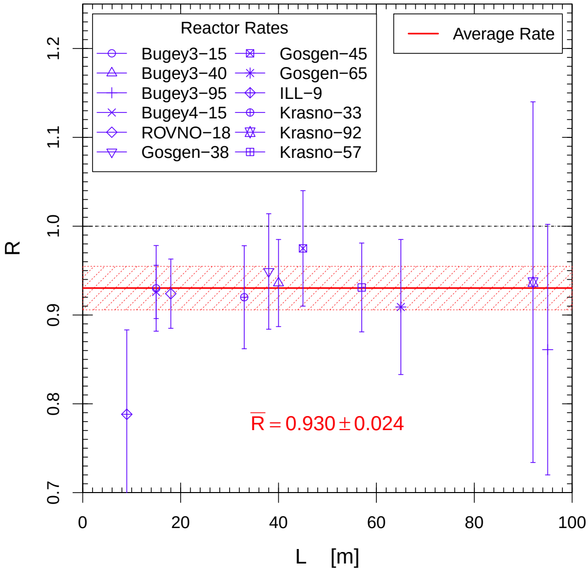
new reactor $\bar{\nu}_e$ fluxes

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

[Huber, PRC 84 (2011) 024617]

$\sim 2.8\sigma$ anomaly

[see also: Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Ivanov et al, arXiv:1306.1995]



Gallium Anomaly

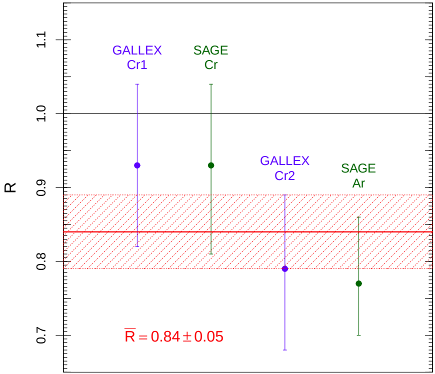
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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]



$E \sim 0.7\,\text{MeV}$

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

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

$\sim 2.9\sigma$ anomaly

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Perturbation of 3ν Mixing

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

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

↑ SBL (last column)

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

$$\Downarrow$$

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

3+1: Appearance vs Disappearance

- ν_e disappearance experiments:

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

- ν_μ disappearance experiments:

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

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

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

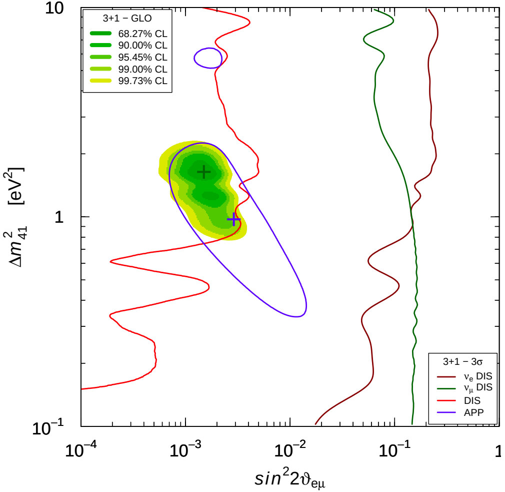
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

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

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

3+1 Global Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, arXiv:1308.5288]



- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND (Y), MiniBooNE (?), OPERA (N), ICARUS (N), KARMEN (N), NOMAD (N), BNL-E776 (N)
- DIS ν_e & $\bar{\nu}_e$: Reactors (Y), Gallium (Y), ν_eC (N), Solar (N)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N), MINOS (N), Atmospheric (N), MiniBooNE/SciBooNE (N)

MiniBooNE $E > 475\,\text{MeV}$

GoF = 29% PGoF = 9%

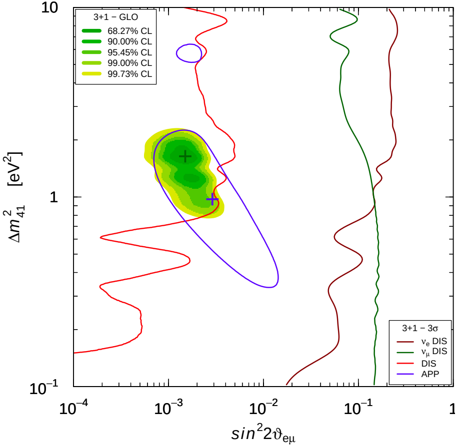
No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

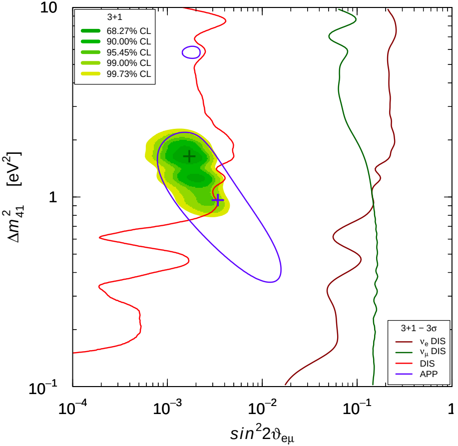
[different approach and conclusions: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

MiniBooNE Impact on SBL Oscillations?

with MiniBooNE



without MiniBooNE



With MiniBooNE: GoF = 29% PGoF = 9%

No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

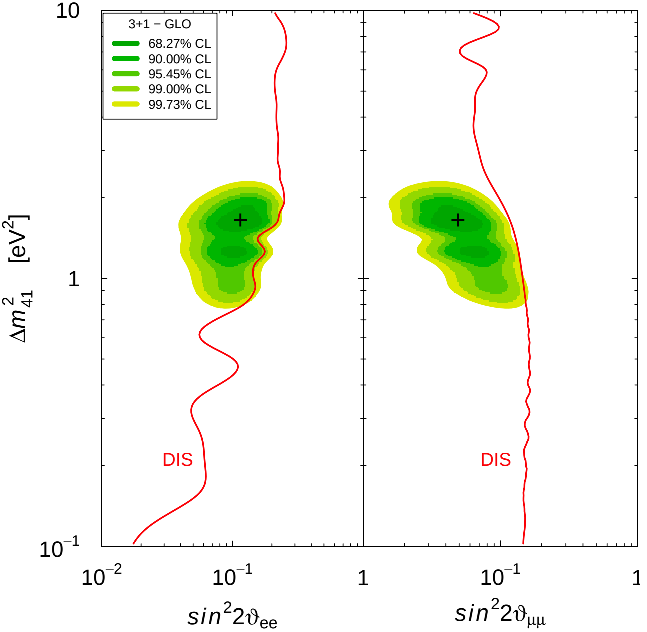
Without MiniBooNE: GoF = 19% PGoF = 8%

No Osc. excluded at 6.3σ

$\Delta\chi^2/\text{NDF} = 47.1/3$

Without LSND: No Osc. excluded only at 2.1σ $(\Delta\chi^2/\text{NDF} = 8.3/3)$

ν_e and ν_μ Disappearance



Many Exciting New Experiments and Projects

- Reactor $\bar{\nu}_e$ Disappearance:
  - Nucifer (OSIRIS, Saclay), Stereo (ILL, Grenoble) [arXiv:1204.5379]
  - DANSS (Kalinin Nuclear Power Plant, Russia) [arXiv:1304.3696], POSEIDON (PIK, Gatchina, Russia) [arXiv:1204.2449]
  - SCRAAM (San Onofre, California) [arXiv:1204.5379]
  - CARR (China Advanced Research Reactor) [arXiv:1303.0607]
  - Neutrino-4 (SM-3, Dimitrovgrad, Russia), SOLID (BR2, Belgium), Hanaro (Korea) [D. Lhuillier, EPSHEP 2013]
- Radioactive Source ν_e and $\bar{\nu}_e$ Disappearance:
  - SOX (Borexino, Gran Sasso, Italy) [arXiv:1304.7721]
  - CeLAND (^{144}Ce@KamLAND, Japan) [arXiv:1107.2335]
  - SAGE (Baksan, Russia) [arXiv:1006.2103]
  - IsoDAR (DAEδALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
  - SNO+, JUNO, RENO [T. Lasserre, Neutrino 2012]
- Accelerator $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Appearance:
  - ICARUS/NESSIE (CERN) [arXiv:1304.2047, arXiv:1306.3455]
  - nuSTORM [arXiv:1308.0494]
  - OscSNS (Oak Ridge, USA) [arXiv:1305.4189, arXiv:1307.7097]

Conclusions

- Robust Three-Neutrino Mixing Paradigm. Open problems: $\vartheta_{23} \lesseqgtr 45°$?, 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 $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - MiniBooNE experiment has been inconclusive
  - If $|U_{e4}| > 0$ why not $|U_{\mu 4}| > 0$? $\Longrightarrow$ Maybe LSND luckily observed a fluctuation of a small $\bar{\nu}_\mu \to \bar{\nu}_e$ transition probability with amplitude $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$, which has not been seen by other appearance experiments
  - Better experiments are needed to check LSND signal
- Cosmology:
  - Important effects of sterile neutrinos
  - Implications depend on theoretical framework and considered data set
  - Cosmological indications must be checked by laboratory experiments

Backup Slides

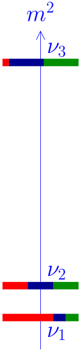
Mass Hierarchy

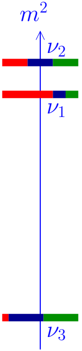
1. Matter Effect: Atmospheric, Long-Baseline, Supernova Experiments
   - $\nu_e \leftrightarrows \nu_\mu$ MSW resonance: $V = \frac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \quad \Leftrightarrow \quad \Delta m^2_{13} > 0$ NH
   - $\bar{\nu}_e \leftrightarrows \bar{\nu}_\mu$ MSW resonance: $V = -\frac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \quad \Leftrightarrow \quad \Delta m^2_{13} < 0$ IH
2. Phase Difference: Reactor $\bar{\nu}_e \to \bar{\nu}_e$: JUNO - Daya Bay II (China), RENO-50 (Korea)

Normal Hierarchy

$$|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$

$$|\Delta m^2_{31}| > |\Delta m^2_{32}|$$

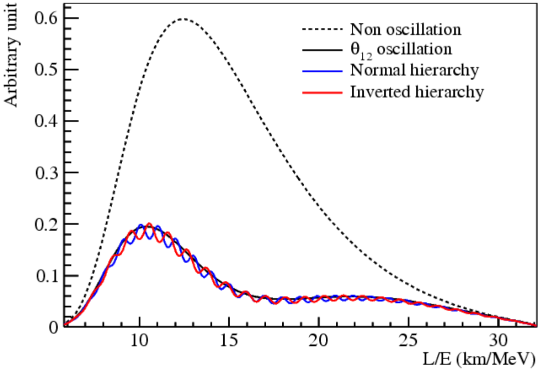




Inverted Hierarchy

$$|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

$$|\Delta m^2_{31}| < |\Delta m^2_{32}|$$



S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

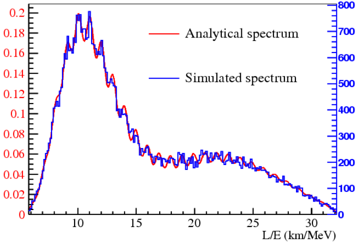
Precision energy spectrum measurement: Looking for interference between P_{31} and P_{32}

➔ relative measurement

$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

$$\Delta_{21} << \Delta_{31} \approx \Delta_{32}$$



[Miao He, NuFact 2013]

CP Violation

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} = -16 J_{\alpha\beta} \sin\left(\frac{\Delta m^2_{21} L}{4E}\right) \sin\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$J_{\alpha\beta} = \mathrm{Im}(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2}) = \pm J$$

$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} \sin\delta_{13}$$

Necessary conditions for observation of CP violation:

- Sensitivity to all mixing angles: ϑ_{12}, ϑ_{23} and smaller ϑ_{13}
- Sensitivity to oscillations due to small Δm^2_{21} and large Δm^2_{31}

$(\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21})$

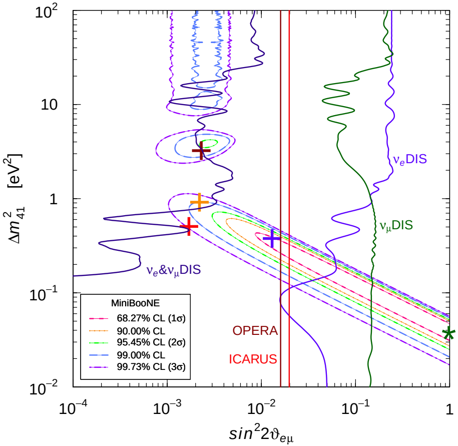
Sterile Neutrinos from Physics Beyond the SM

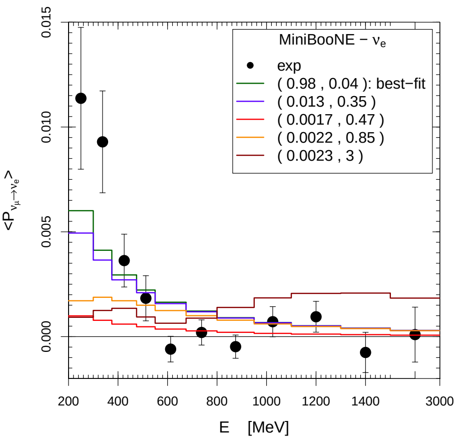
- Neutrinos are special in the Standard Model: the only neutral fermions
- In extensions of SM neutrinos can mix with non-SM fermions
- SM: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$ $\qquad \widetilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$
- SM singlet $\overline{L_L}\widetilde{\Phi}$ can couple to new singlet chiral fermion field ν_R (right-handed neutrino) related to physics beyond the SM
- Known examples: SUSY, new symmetries, extra dimensions, mirror world, ... [see http://www.nu.to.infn.it/Sterile_Neutrinos/]
- Dirac mass term $\sim \overline{L_L}\widetilde{\Phi}\nu_R$ $\quad + \quad$ Majorana mass term $\sim \overline{\nu_R^c}\nu_R$
- Diagonalization of mass matrix $\implies$ massive Majorana neutrinos

		LOW	HIG	noMB	noLSND
No	χ^2	339.2	308.0	283.2	286.7
Osc.	NDF	259	253	221	255
	GoF	0.06 %	1 %	0.3 %	8 %
3+1	χ^2_{min}	291.7	261.8	236.1	278.4
Osc.	NDF	256	250	218	252
	GoF	6 %	29 %	19 %	12 %
	$\Delta m^2_{41}[\text{eV}^2]$	1.6	1.6	1.6	1.7
	$\lvert U_{e4}\rvert^2$	0.033	0.03	0.03	0.024
	$\lvert U_{\mu 4}\rvert^2$	0.012	0.013	0.014	0.0073
	$\sin^2 2\vartheta_{e\mu}$	0.0016	0.0015	0.0017	0.0007
	$\sin^2 2\vartheta_{ee}$	0.13	0.11	0.12	0.093
	$\sin^2 2\vartheta_{\mu\mu}$	0.048	0.049	0.054	0.03
	$(\chi^2_{\text{min}})_{\text{APP}}$	99.3	77.0	50.9	91.8
	$(\chi^2_{\text{min}})_{\text{DIS}}$	180.1	180.1	180.1	180.1
	$\Delta\chi^2_{\text{PG}}$	12.7	4.8	5.1	6.4
	NDF_{PG}	2	2	2	2
	GoF_{PG}	0.2 %	9 %	8 %	4 %
	$\text{p-val}_{\text{No Osc.}}$	3×10^{-10}	5×10^{-10}	3×10^{-10}	4×10^{-2}
	$n\sigma_{\text{No Osc.}}$	6.3σ	6.2σ	6.3σ	2.1σ

[Giunti, Laveder, Y.F. Li, H.W. Long, arXiv:1308.5288]

MiniBooNE Low-Energy Excess?





- No fit of low-energy excess for realistic

$$\Delta m^2_{41} \gtrsim 0.8\,\text{eV}^2 \text{ and } \sin^2 2\vartheta_{e\mu} \lesssim 5 \times 10^{-3}$$

- APP-DIS PGoF $= 0.1\%$
- Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

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

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

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

[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, JHEP 07 (2012) 161; Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, AHEP 2013 (2013) 163897; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

  4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu 4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu 5}|^2, \eta$

3+2

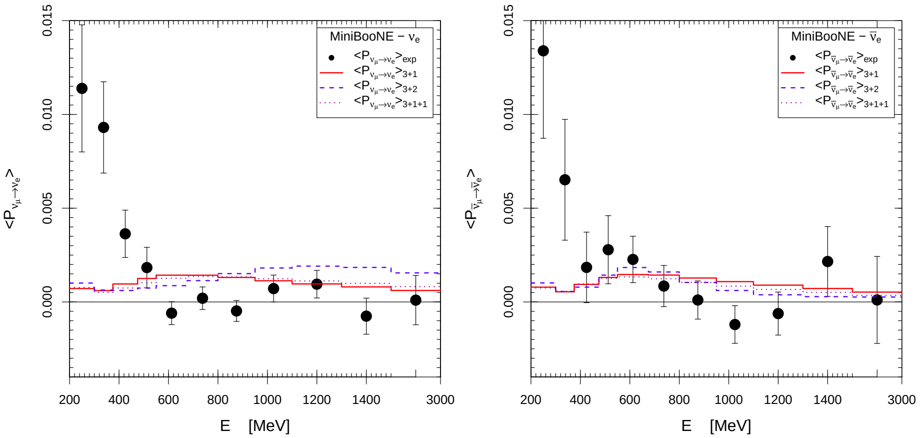
- 3+2 should be preferred to 3+1 only if
  - there is evidence of two peaks of the probability corresponding to two Δm^2's

    or
  - there is CP-violating difference of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions
- 2008 ν + 2010 $\bar{\nu}$ MiniBooNE data indicated ν–$\bar{\nu}$ difference

  $\Downarrow$

  reasonable and useful to consider 3+2
- ν–$\bar{\nu}$ difference almost disappeared with 2012 $\bar{\nu}$ data
- Okkam razor: 3+1 is enough!
- Different approach and conclusions:
  - Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050:
    Use all MiniBooNE data. No 3+1 global fit. 3+2 slightly preferred? Small allowed region.
  - Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, AHEP 2013 (2013) 163897:
    Use all MiniBooNE data. 3+2 strongly preferred. Very small allowed regions.

MiniBooNE Low-Energy Excess?



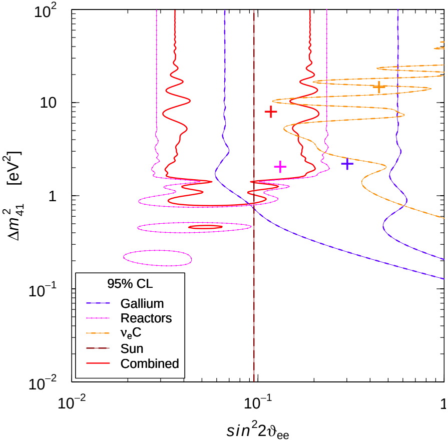
- 3+1: GoF = 6% PGoF = 0.2%
- 3+2: GoF = 8% PGoF = 0.1%
- 3+1+1: GoF = 6% PGoF = 0.2%

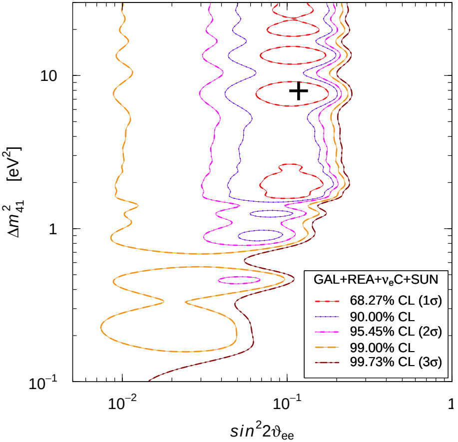
	3+2 LOW	3+2 HIG	3+1+1 LOW	3+1+1 HIG
χ^2_{min}	284.4	256.4	289.8	259.0
NDF	252	246	253	247
GoF	8 %	31 %	6 %	29 %
$\Delta m^2_{41}[\text{eV}^2]$	1.9	0.93	1.6	1.6
$\lvert U_{e4}\rvert^2$	0.03	0.015	0.026	0.023
$\lvert U_{\mu 4}\rvert^2$	0.012	0.0097	0.011	0.012
$\Delta m^2_{51}[\text{eV}^2]$	4.1	1.6		
$\lvert U_{e5}\rvert^2$	0.013	0.018	0.0088	0.0092
$\lvert U_{\mu 5}\rvert^2$	0.0065	0.0091	0.0049	0.0052
η/π	0.51	1.6	0.4	0.45
$(\chi^2_{\text{min}})_{\text{APP}}$	87.7	69.8	94.8	75.5
$(\chi^2_{\text{min}})_{\text{DIS}}$	179.1	179.1	180.1	180.1
$\Delta\chi^2_{\text{PG}}$	17.7	7.5	14.9	3.4
NDF_{PG}	4	4	3	3
GoF_{PG}	0.1 %	11 %	0.2 %	34 %
p-val_{3+1}	0.12	0.25	0.59	0.42
$n\sigma_{3+1}$	1.6σ	1.2σ	0.54σ	0.81σ

[Giunti, Laveder, Y.F. Li, H.W. Long, arXiv:1308.5288]

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

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





$\nu_e + {}^{12}C \to {}^{12}N_{g.s.} + e^-$

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; PRD 85 (2012) 077301]

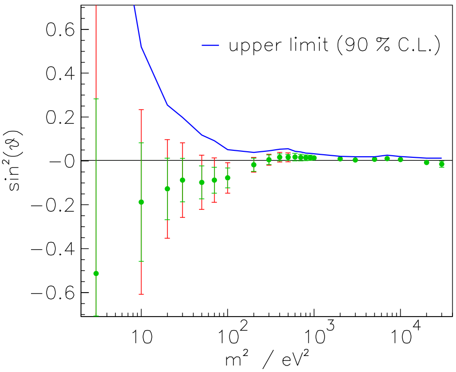
GoF = 62% PGoF = 4%

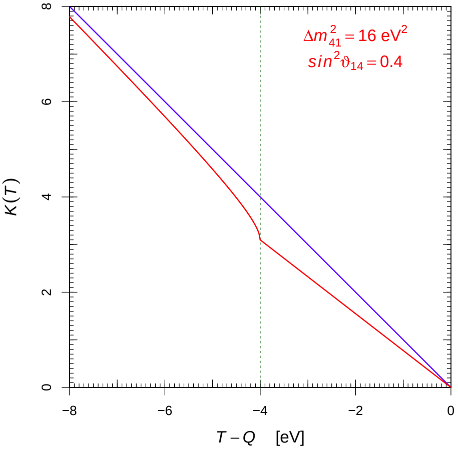
No Osc. excluded at 2.7σ

$\Delta\chi^2/\mathrm{NDF} = 10.1/2$

Mainz Limit on m_4^2

[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]

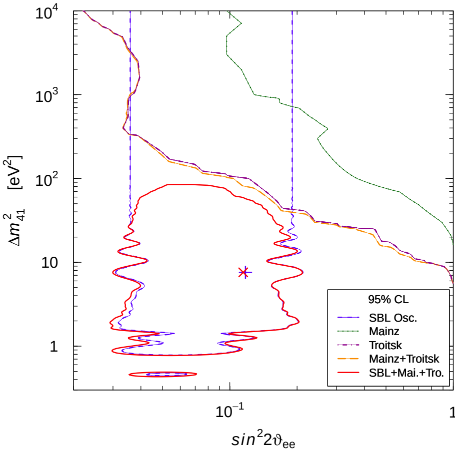


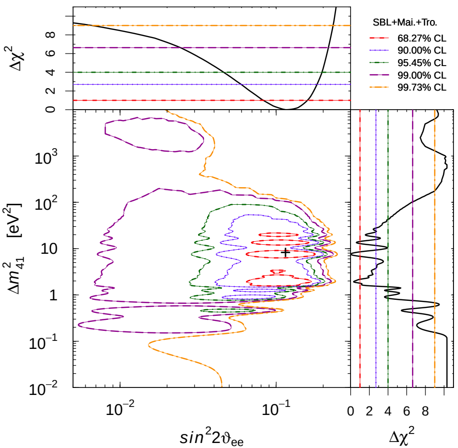


$$m_4 \gg m_1, m_2, m_3 \quad \Longrightarrow \quad \Delta m_{41}^2 \equiv m_4^2 - m_1^2 \simeq m_4^2$$

Troitsk: Surprising Much Better Limit on m_4^2

[Belesev et al, JETP Lett. 97 (2013) 67; arXiv:1307.5687]

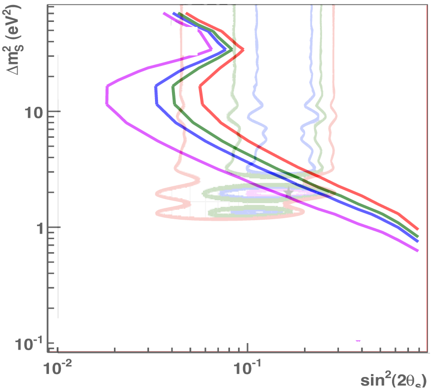




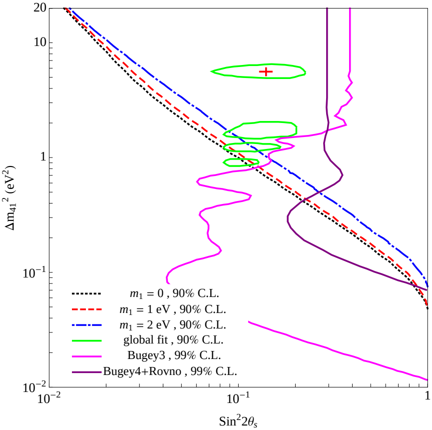
$$2\sigma: \quad 0.85 \lesssim \Delta m^2_{41} \lesssim 43\,\text{eV}^2 \quad \Longrightarrow \quad 6\,\text{cm} \lesssim \frac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 3\,\text{m}$$

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

KATRIN Sensitivity



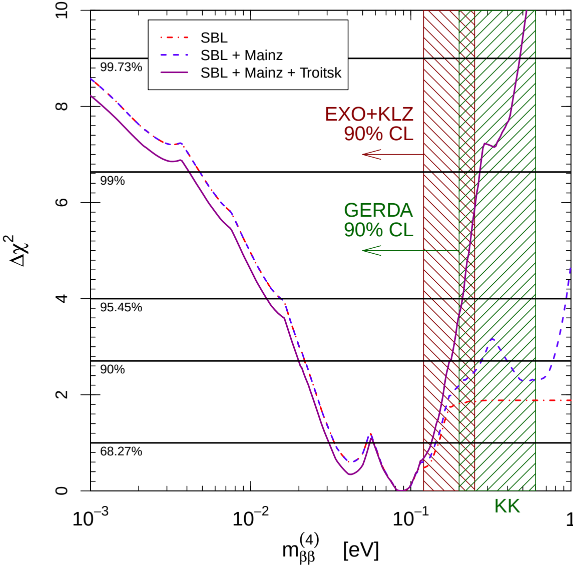
[Formaggio, Barrett, PLB 706 (2011) 68]



[Esmaili, Peres, PRD 85 (2012) 117301]

[see also Sejersen Riis, Hannestad, JCAP (2011) 1475; Sejersen Riis, Hannestad, Weinheimer, PRC 84 (2011) 045503]

Neutrinoless Double-β Decay



$$|m_{\beta\beta}| = \left|\sum_{k=1}^{4} U_{ek}^2\, m_k\right|$$

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

caveat:
possible cancellation
with $m_{\beta\beta}^{(3\nu-IH)}$

[Barry et al, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]