

# Sterile Neutrinos

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## Standard Model: Massless Neutrinos

- ▶ Standard Model:  $\nu_L, \nu_R^c \implies$  no Dirac mass term

$$\mathcal{L}^D = m^D (\overline{\nu}_L \nu_R + \overline{\nu}_R \nu_L)$$

- ▶ Majorana Neutrino:  $\nu^c = \nu$

- ▶  $\nu_R^c = \nu_R \implies$  Majorana mass term

$$\mathcal{L}^M = \frac{1}{2} m^M (\overline{\nu}_L \nu_R^c + \overline{\nu}_R^c \nu_L)$$

- ▶ Standard Model: Majorana mass term **not** allowed by  $SU(2)_L \times U(1)_Y$

(no Higgs triplet)

# Extension of the SM: Massive Neutrinos

Standard Model can be extended with  $\nu_R$  ( $e_L, e_R; u_L, u_R; d_L, d_R; \dots$ )

$\nu_L + \nu_R \Rightarrow$  Dirac neutrino mass term  $\mathcal{L}^D \sim m^D \overline{\nu}_L \nu_R \Rightarrow m^D \lesssim 100 \text{ GeV}$

surprise: Majorana neutrino mass for  $\nu_R$  is allowed!  $\mathcal{L}_R^M \sim m_R^M \overline{(\nu^c)_L} \nu_R$

total neutrino mass term  $\mathcal{L}^{D+M} \sim \begin{pmatrix} \overline{\nu}_L & \overline{(\nu^c)_L} \end{pmatrix} \begin{pmatrix} 0 & m^D \\ m^D & m_R^M \end{pmatrix} \begin{pmatrix} (\nu^c)_R \\ \nu_R \end{pmatrix}$

$m_R^M$  can be arbitrarily large (not protected by SM symmetries)

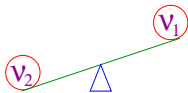
$m_R^M \sim$  scale of new physics beyond Standard Model  $\Rightarrow m_R^M \gg m^D$

diagonalization of  $\begin{pmatrix} 0 & m^D \\ m^D & m_R^M \end{pmatrix} \Rightarrow m_1 \simeq \frac{(m^D)^2}{m_R^M}, \quad m_2 \simeq m_R^M$

natural explanation of smallness  
of light neutrino masses

massive neutrinos are Majorana!

3-GEN  $\Rightarrow$  effective low-energy 3- $\nu$  mixing



see-saw mechanism

[Minkowski, PLB 67 (1977) 42]

[Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic, PRL 44 (1980) 912]

▶ Neutrinos are special in the Standard Model: the only **neutral fermions**

▶ In extensions of SM neutrinos can mix with non-SM fermions

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

▶  $\overline{L}_L \tilde{\Phi}$  can couple to new non-SM chiral fermion field  $f_R$

▶ 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**:  $f_R \rightarrow \nu_R$

▶ A light  $\nu_R$  is called **Sterile Neutrino**

# Sterile Neutrinos

- ▶ Sterile means No Standard Model Interactions
- ▶ Obviously no electromagnetic interactions as normal active neutrinos
- ▶ Thus Sterile means No Standard Weak Interactions
- ▶ But Sterile Neutrinos are not absolutely sterile:
  - ▶ Gravitational Interactions
  - ▶ New Non-Standard Interactions of the Physics Beyond the Standard Model which generates the masses of sterile neutrinos
- ▶ Extremely interesting and powerful window on Physics Beyond the SM
- ▶ Active Neutrinos ( $\nu_e, \nu_\mu, \nu_\tau$ ) can oscillate into Sterile Neutrinos ( $\nu_s$ )
- ▶ Observables:
  - ▶ disappearance of Active Neutrinos
  - ▶ indirect evidence through combined fit of data

## How many Sterile Neutrinos?

$e^+e^- \rightarrow Z \rightarrow \nu\bar{\nu} \Rightarrow \nu_e \nu_\mu \nu_\tau$  3 active flavor neutrinos

mixing  $\Rightarrow \nu_{\alpha L} = \sum_{k=1}^N U_{\alpha k} \nu_{kL} \quad \alpha = e, \mu, \tau$   $N \geq 3$   
no upper limit!

Mass Basis:	$\nu_1$	$\nu_2$	$\nu_3$	$\nu_4$	$\nu_5$	$\dots$
Flavor Basis:	$\nu_e$	$\nu_\mu$	$\nu_\tau$	$\nu_{s_1}$	$\nu_{s_2}$	$\dots$
	ACTIVE			STERILE		

# Solar and Atmospheric Neutrino Oscillations

$$\begin{array}{l}
 \text{Solar} \\
 \nu_e \rightarrow \nu_\mu, \nu_\tau \\
 \\
 \text{Reactor} \\
 \bar{\nu}_e \text{ disappearance}
 \end{array}
 \left( \begin{array}{c}
 \text{Homestake} \\
 \text{Kamiokande} \\
 \text{GALLEX/GNO \& SAGE} \\
 \text{Super-Kamiokande} \\
 \text{SNO} \\
 \text{BOREXino} \\
 \\
 \text{(KamLAND)}
 \end{array} \right)
 \rightarrow \left\{ \begin{array}{l}
 \Delta m_{\text{SOL}}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2 \\
 \sin^2 \vartheta_{\text{SOL}} \simeq 0.32
 \end{array} \right.$$

$$\begin{array}{l}
 \text{Atmospheric} \\
 \nu_\mu \rightarrow \nu_\tau \\
 \\
 \text{Accelerator} \\
 \nu_\mu \text{ disappearance}
 \end{array}
 \left( \begin{array}{c}
 \text{Kamiokande} \\
 \text{IMB} \\
 \text{Super-Kamiokande} \\
 \text{MACRO} \\
 \text{Soudan-2} \\
 \\
 \text{(K2K \& MINOS)}
 \end{array} \right)
 \rightarrow \left\{ \begin{array}{l}
 \Delta m_{\text{ATM}}^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2 \\
 \sin^2 \vartheta_{\text{ATM}} \simeq 0.50
 \end{array} \right.$$

Two scales of  $\Delta m^2 \iff$  Three-Neutrino Mixing

$$\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.4 \times 10^{-3} \text{ eV}^2$$

- ▶ New Short-BaseLine Oscillations:  $\frac{L}{E} \lesssim 1 \frac{\text{m}}{\text{MeV}} \implies \Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2$
- ▶ Necessary introduction of at least one new massive neutrino:  $4\nu$  Mixing

$$\Delta m_{\text{SBL}}^2 = \Delta m_{41}^2$$

Mass Basis:  $\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4$

Flavor Basis:  $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_s$

- ▶ Effective SBL Oscillation Probabilities:

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

$$\text{▶ } P_{\nu_\alpha \rightarrow \nu_\alpha}^{\text{SBL}} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left( \frac{\Delta m_{\text{SBL}}^2 L}{4E} \right)$$



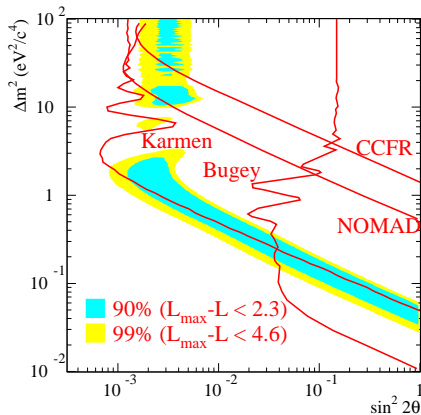
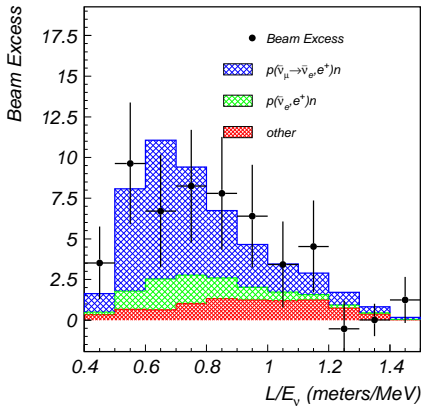
# LSND

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

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

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

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

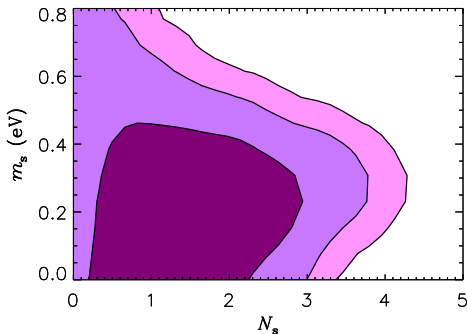


$$\Delta m_{\text{LSND}}^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SOL}}^2)$$

# Cosmology

- CMB and LLS in  $\Lambda$ CDM:

[Hamann, Hannestad, Raffelt, Tamborra, Wong, arXiv:1006.5276]

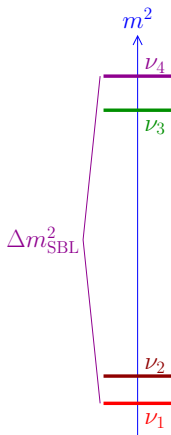


- BBN:

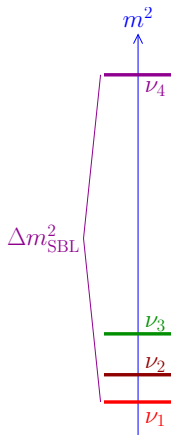
$$N_\nu = 3.68^{+0.80}_{-0.70}$$

[Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

# Four-Neutrino Schemes: 2+2 and 3+1

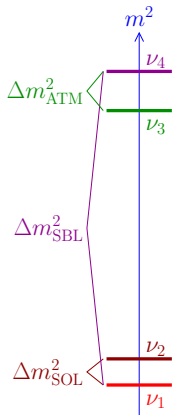


"2+2"

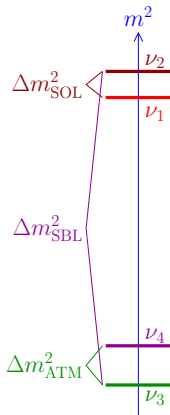


"3+1"

## 2+2 Four-Neutrino Schemes

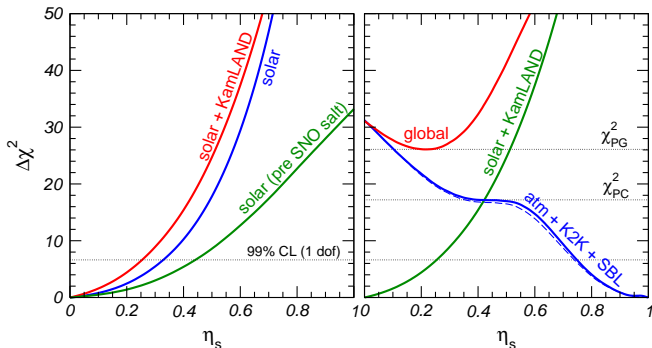


"normal"



"inverted"

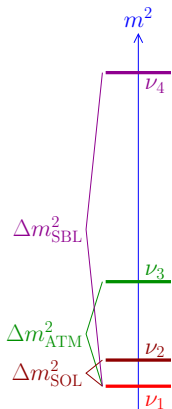
## 2+2 Schemes are strongly disfavored by solar and atmospheric data



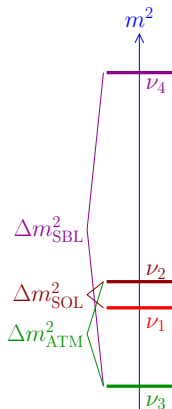
[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2 \quad 99\% \text{ CL: } \begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$$

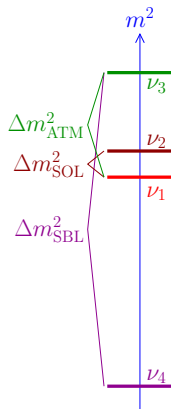
# 3+1 Four-Neutrino Schemes



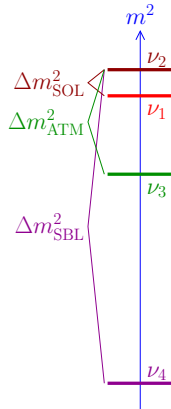
"normal"



"3 $\nu$ -inverted"



"4 $\nu$ -inverted"



"fully-inverted"

Perturbation of 3- $\nu$  Mixing

$$|U_{e4}|^2 \ll 1$$

$$|U_{\mu 4}|^2 \ll 1$$

$$|U_{\tau 4}|^2 \ll 1$$

$$|U_{S4}|^2 \simeq 1$$

## Effective SBL Oscillation Probability in 3+1 Schemes

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

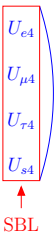
$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$$

No CP Violation!

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

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

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


  
 SBL

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



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

- ▶  $\nu_e$  disappearance experiments:

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

- ▶  $\nu_\mu$  disappearance experiments:

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

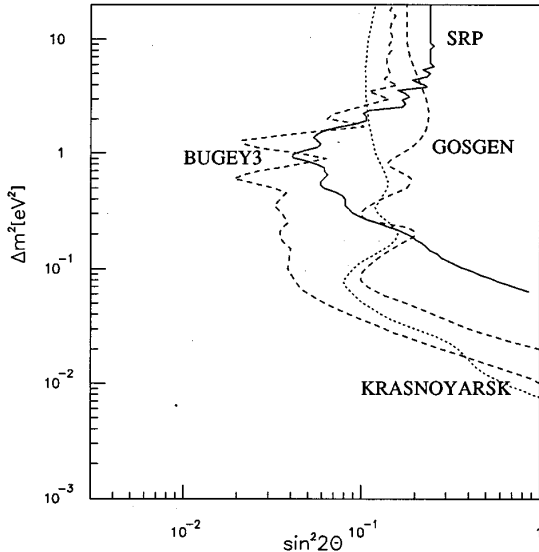
- ▶  $\nu_\mu \rightarrow \nu_e$  experiments:

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

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

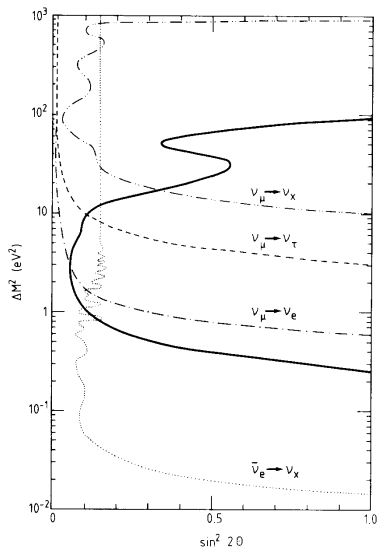


# $\bar{\nu}_e$ Disappearance

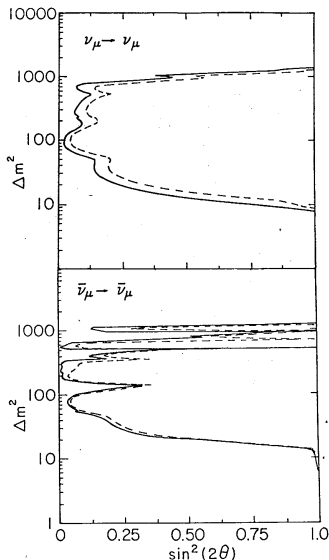


[Savannah River (SRP), PRD 53 (1996) 6054]

# $\nu_\mu$ and $\bar{\nu}_\mu$ Disappearance

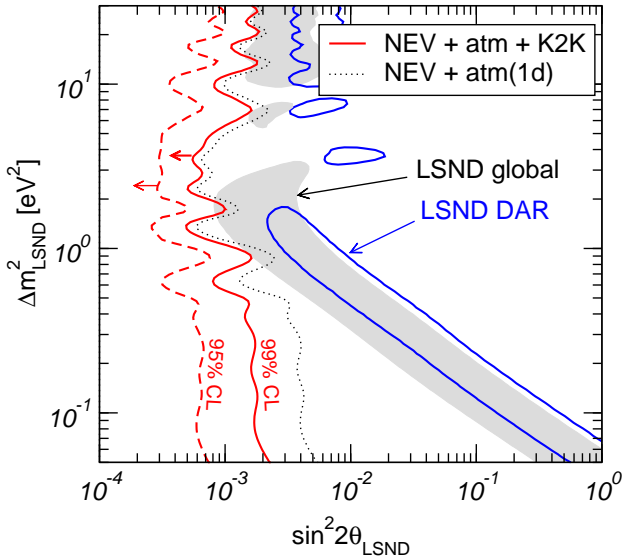


[CDHSW, PLB 134 (1984) 281]



[CCFR, Z. Phys. C 27 (1985) 53]

# $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in 3+1 Schemes



[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

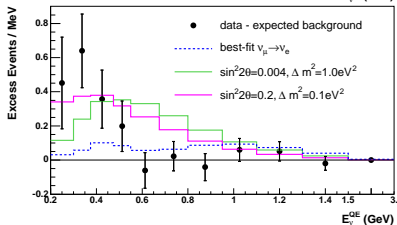
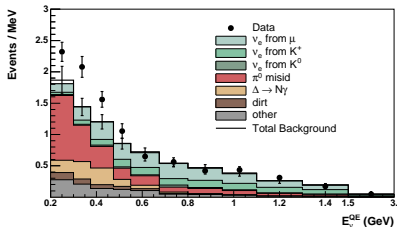
# MiniBooNE Neutrinos

[PRL 98 (2007) 231801]

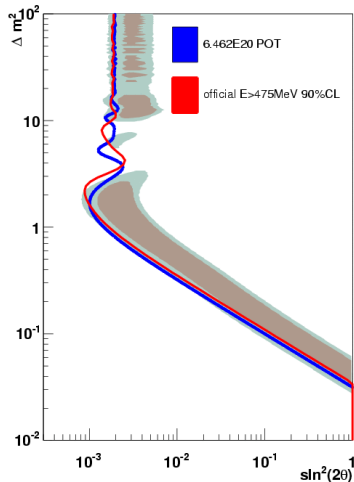
$$\nu_{\mu} \rightarrow \nu_e$$

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

$$475 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$$



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



[arXiv:0901.1648]

## Low-Energy Anomaly!

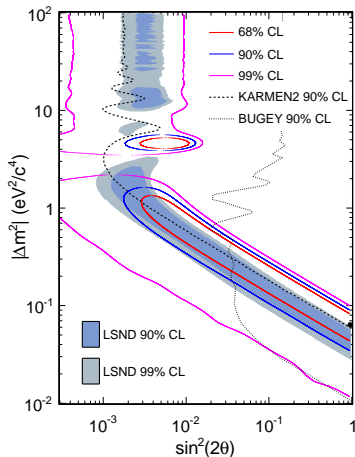
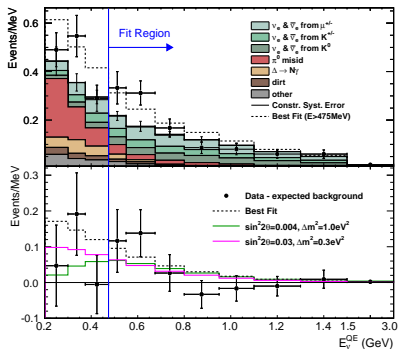
# MiniBooNE Antineutrinos

[arXiv:1007.1150]

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

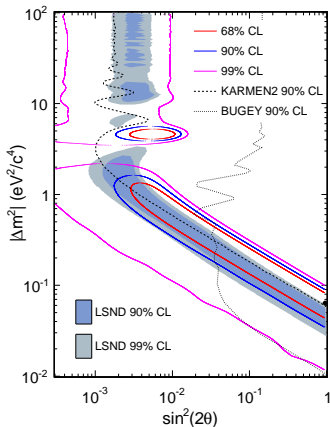
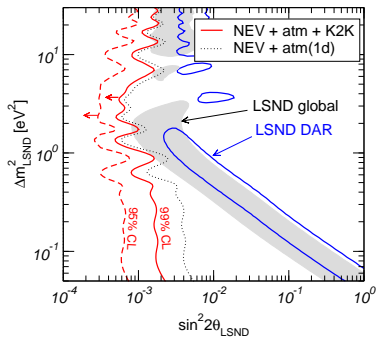
$$L \simeq 541 \text{ m}$$

$$475 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$$



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

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



- ▶ Most of LSND and MiniBooNE  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  allowed region is disfavored by KARMEN  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  and MiniBooNE  $\nu_\mu \rightarrow \nu_e$
- ▶ 3+1 Schemes: tension between LSND and MiniBooNE  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  appearance and  $\bar{\nu}_e$  (Bugey) +  $\bar{\nu}_\mu^{(-)}$  (CDHSW+CCFR) disappearance limits
- ▶ Marginally allowed:  $\Delta m_{\text{SBL}}^2 \simeq 0.9 \text{ eV}^2$   $\sin^2 2\vartheta_{e\mu} \simeq 2 \times 10^{-3}$

## 3+2 Five-Neutrino Mixing?

### *Implications of new antineutrino results from MiniBooNE*

New antineutrino results from MiniBooNE support conclusions in previous sterile neutrino fits:

In a (3+1) fit, antineutrino experiments are still compatible at 20% (from 30%), and still strongly exclude the no oscillations hypothesis.

Compatibility among **all datasets (SBL+atm)** decreases further:

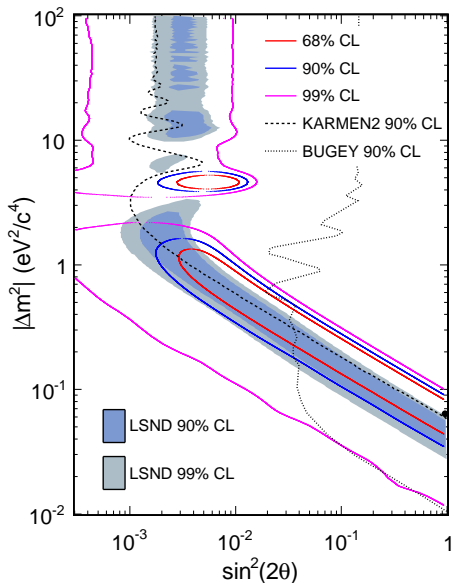
0.11% → <b>0.04%</b>	in a (3+1) hypothesis
7% → <b>3%</b>	in a (3+2) CPV hypothesis

Preliminary

[Georgia Karagiorgi, Neutrino 2010, 14 June 2010]

# CPT Violation?

- ▶ Masses and mixing of neutrinos and antineutrinos may be different
- ▶ In CDHSW mainly  $\nu_\mu$ 's
- ▶ No limit on SBL  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  transitions from disappearance experiments
- [Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
- ▶ LSND and MiniBooNE allowed regions are limited only by KARMEN and Bugey





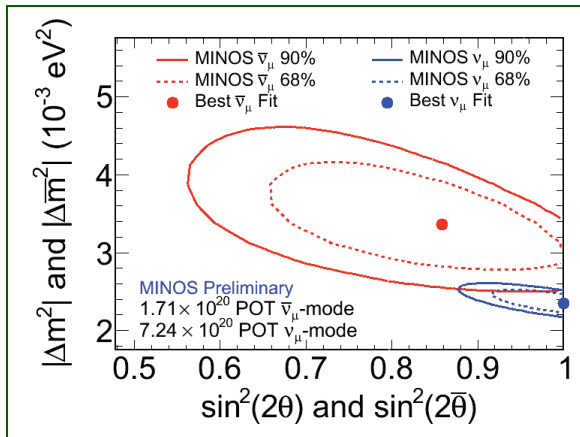
# MINOS Hint of CPT Violation

LBL  $\nu_\mu$  disappearance

$E \sim 3$  GeV

Near Detector at 1.04 km

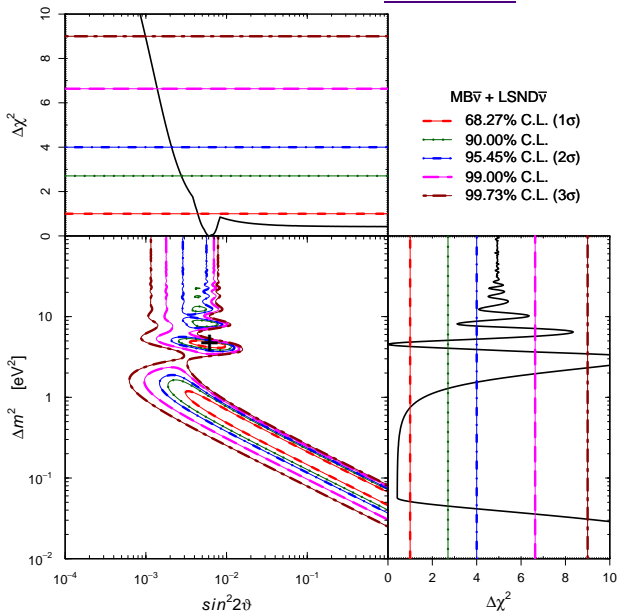
Far Detector at 734 km



[MINOS, Neutrino 2010, 14 June 2010]

## Phenomenological Approach: Consider $\bar{\nu}$ 's Only

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



$$\chi_{\min}^2 = 14.6$$

$$\text{NdF} = 18$$

$$\text{GoF} = 69\%$$

$$\sin^2 2\vartheta = 0.0062$$

$$\Delta m^2 = 4.57 \text{ eV}^2$$

Parameter  
Goodness-of-Fit

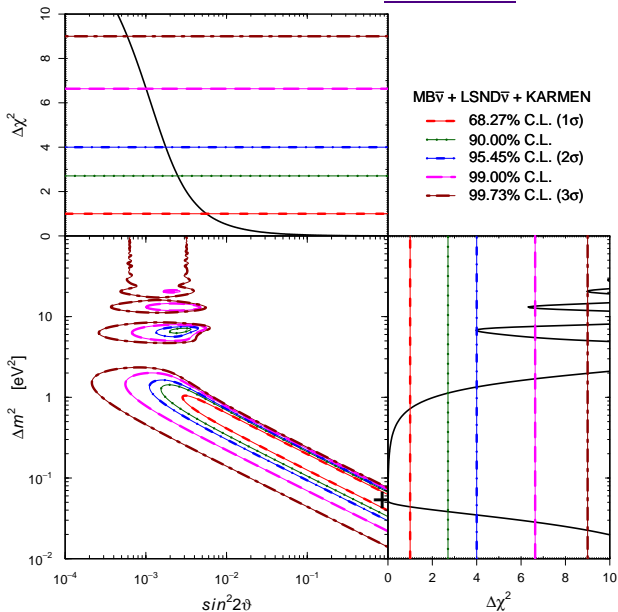
$$\Delta \chi_{\min}^2 = 2.6$$

$$\text{NdF} = 2$$

$$\text{GoF} = 27\%$$

[Giunti, Laveder, in preparation]

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



$$\chi_{\min}^2 = 25.9$$

$$\text{NdF} = 26$$

$$\text{GoF} = 47\%$$

$$\sin^2 2\theta = 0.98$$

$$\Delta m^2 = 0.052 \text{ eV}^2$$

Parameter

Goodness-of-Fit

$$\Delta\chi_{\min}^2 = 7.5$$

$$\text{NdF} = 4$$

$$\text{GoF} = 11\%$$

[Giunti, Laveder, in preparation]

## Conservation of Probability

$$\sum_{\alpha} P_{\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_e} = 1$$

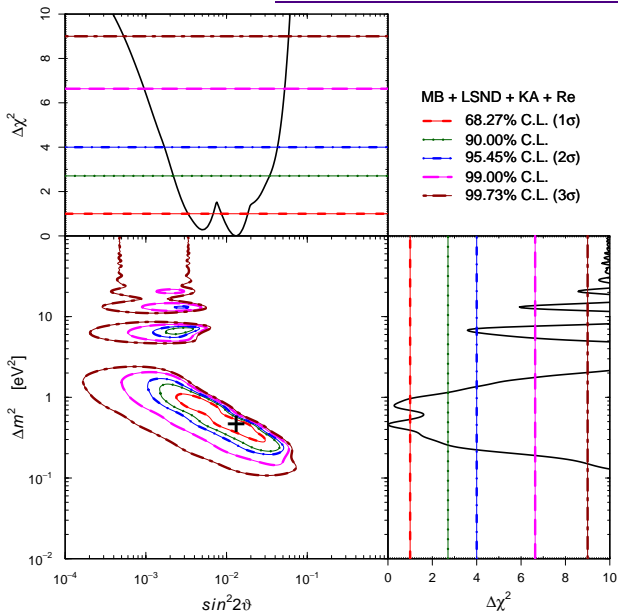
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} + P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e} + P_{\bar{\nu}_{\tau} \rightarrow \bar{\nu}_e} + P_{\bar{\nu}_s \rightarrow \bar{\nu}_e} = 1$$

$$P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e} = 1 - P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} - P_{\bar{\nu}_{\tau} \rightarrow \bar{\nu}_e} - P_{\bar{\nu}_s \rightarrow \bar{\nu}_e}$$

$$P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e} \leq 1 - P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$$

Reactor  $\bar{\nu}_e$  disappearance bound is unavoidable!

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



$$\chi^2_{\min} = 77.3$$

$$\text{NdF} = 82$$

$$\text{GoF} = 63\%$$

$$\sin^2 2\theta = 0.013$$

$$\Delta m^2 = 0.46 \text{ eV}^2$$

Parameter

Goodness-of-Fit

$$\Delta\chi^2_{\min} = 10.4$$

$$\text{NdF} = 6$$

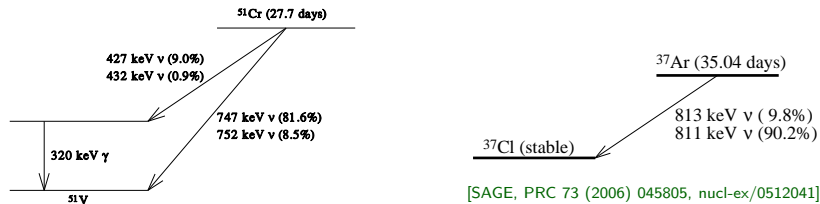
$$\text{GoF} = 11\%$$

[Giunti, Laveder, in preparation]

# Gallium Anomaly

## Gallium Radioactive Source Experiments

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



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

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

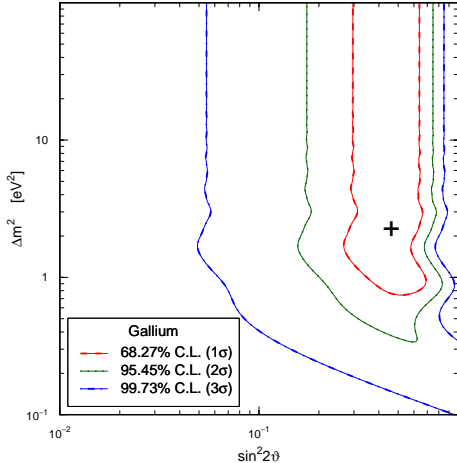


[Giunti, Laveder, arXiv:1006.3244]

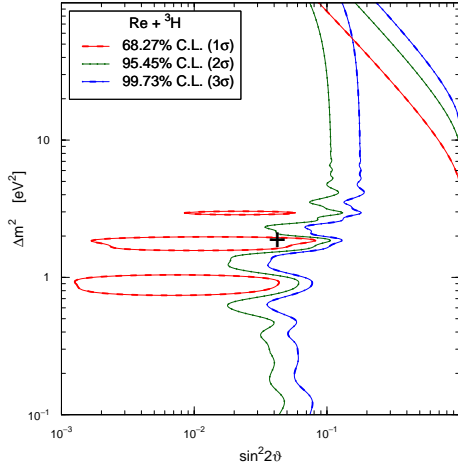
$$R_{\text{Ga}} = 0.76^{+0.09}_{-0.08}$$

Haxton cross section and uncertainty

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



[Giunti, Laveder, arXiv:1006.3244]



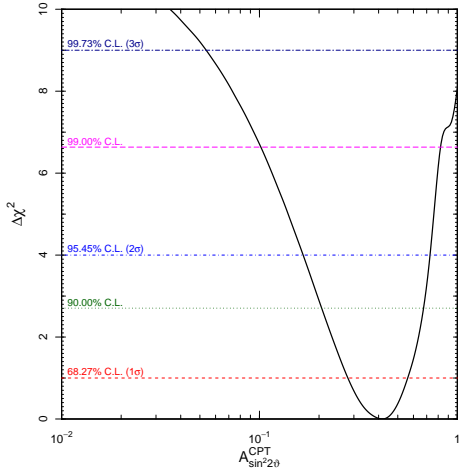
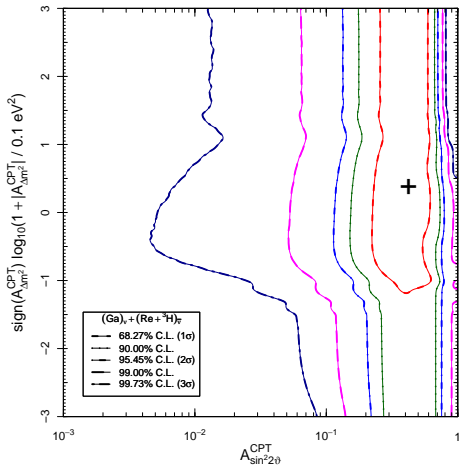
[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

$$\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2 \quad \text{is OK}$$

$$\sin^2 2\vartheta_\nu > \sin^2 2\vartheta_{\bar{\nu}} \quad \text{CPT violation?}$$

Parameter Goodness-of-Fit:  $\Delta\chi_{\text{min}}^2 = 12.1$ , NDF = 2, GoF = 0.2%





[Giunti, Laveder, arXiv:1008.4750]

$$A_{\sin^2 2\theta}^{\text{CPT}} = \sin^2 2\theta_{\nu} - \sin^2 2\theta_{\bar{\nu}}$$

$$(A_{\sin^2 2\theta}^{\text{CPT}})_{\text{bf}} = 0.42$$

$$A_{\Delta m^2}^{\text{CPT}} = \Delta m_{\nu}^2 - \Delta m_{\bar{\nu}}^2$$

$$(A_{\Delta m^2}^{\text{CPT}})_{\text{bf}} = 0.37 \text{ eV}^2$$

$$A_{\sin^2 2\theta}^{\text{CPT}} > 0.055 \text{ at } 3\sigma$$

$$A_{\sin^2 2\theta}^{\text{CPT}} > 0 \text{ at } 3.5\sigma.$$

# Conclusions

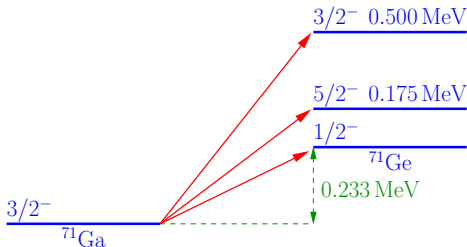
- ▶ Existence of sterile neutrinos is possible
- ▶  $\Lambda$ CDM cosmology and BBN hint at  $N_s > 0$
- ▶ Impressive LSND and MiniBooNE agreement on  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  signal
- ▶ Three experimental tensions:
  - ▶ LSND and MiniBooNE  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  vs MiniBooNE  $\nu_\mu \rightarrow \nu_e$
  - ▶ LSND and MiniBooNE  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  vs  $\bar{\nu}_e$  and  $\nu_\mu$  disappearance limits
  - ▶ Gallium Anomaly ( $\nu_e$  disappearance) vs Bugey ( $\bar{\nu}_e$  disappearance)
- ▶ Interpretation of experimental results is difficult:
  - ▶ 3+1 Four-Neutrino Mixing or more?
  - ▶ CPT violation?
  - ▶ ...?
- ▶ New short-baseline neutrino oscillation experiments are needed!

# Backup Slides

- ▶ Gallium Anomaly could be due to overestimate of

$$\sigma(\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-)$$

- ▶ Calculation: Bahcall, PRC 56 (1997) 3391, hep-ph/9710491



- ▶  $\sigma_{\text{G.S.}}$  related to measured  $\sigma(e^- + {}^{71}\text{Ge} \rightarrow {}^{71}\text{Ga} + \nu_e)$ :

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

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

- ▶ Contribution of Excited States only 5%!

► Bahcall:

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

from  $p + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + n$  measurements [Krofccheck et al., PRL 55 (1985) 1051]

$$\frac{\text{BGT}_{175\text{ keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \Rightarrow \frac{\text{BGT}_{175\text{ keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{0.056}{2} \quad \frac{\text{BGT}_{500\text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146$$

$$3\sigma \text{ lower limit: } \frac{\text{BGT}_{175\text{ keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{\text{BGT}_{500\text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0$$

$$3\sigma \text{ upper limit: } \frac{\text{BGT}_{175\text{ keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \quad \frac{\text{BGT}_{500\text{ keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2$$

$$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46} \text{ cm}^2 \left( 1_{-0.028}^{+0.036} \right)_{1\sigma}$$

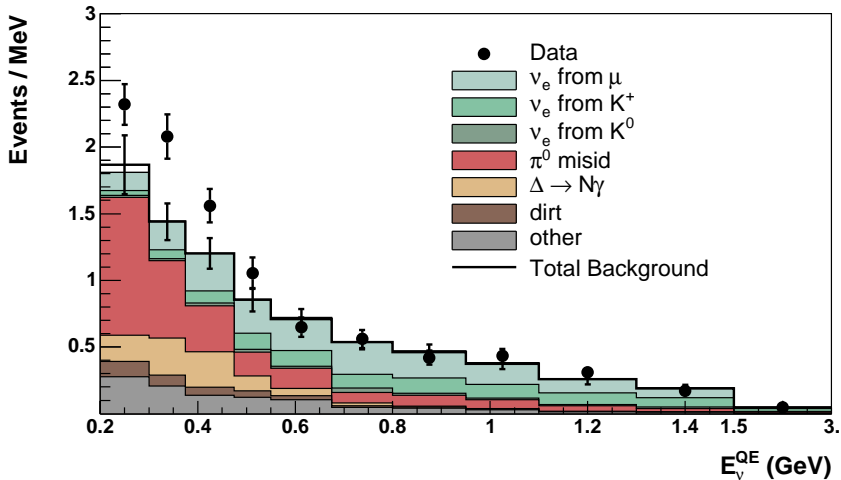
► Haxton:

[Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

“a sophisticated shell model calculation is performed ... for the transition to the first excited state in  ${}^{71}\text{Ge}$ . The calculation predicts destructive interference between the  $(p, n)$  spin and spin-tensor matrix elements.”

$$\sigma({}^{51}\text{Cr}) = 63.9 \times 10^{-46} \text{ cm}^2 (1 \pm 0.106)_{1\sigma}$$

# MiniBooNE Low-Energy Anomaly



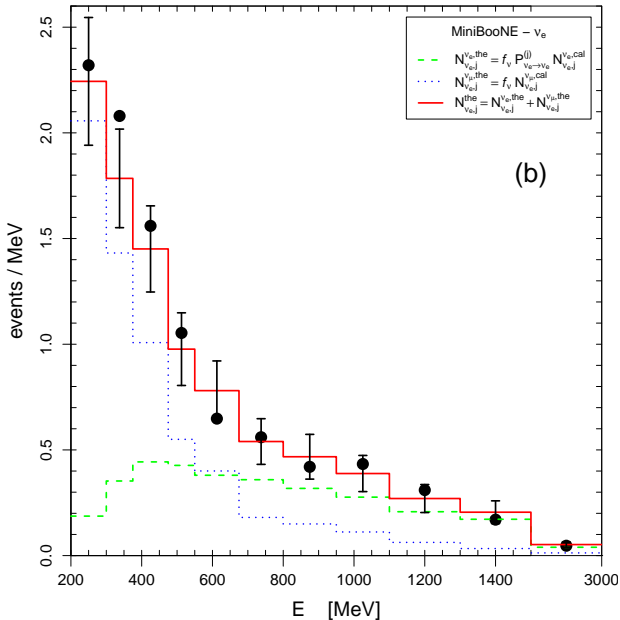
[PRL 102 (2009) 101802, arXiv:0812.2243]

Our Hypothesis: 
$$N_{\nu_j}^{\text{the}} = f_\nu \left( P_{\nu_e \rightarrow \nu_e} N_{\nu_{e,j}}^{\text{cal}} + N_{\nu_{\mu,j}}^{\text{cal}} \right)$$

[Giunti, Laveder, PRD 77 (2008) 093002, arXiv:0707.4593; PRD 80 (2009) 013005, arXiv:0902.1992]

$$N_{\nu,j}^{\text{the}} = f_{\nu} \left( P_{\nu_e \rightarrow \nu_e} N_{\nu_e,j}^{\text{cal}} + N_{\nu_{\mu},j}^{\text{cal}} \right)$$

- ▶ Estimated 15% uncertainty of the calculated neutrino flux [MiniBooNE, PRD 79 (2009) 072002, arXiv:0806.1449] is consistent with measured ratio  $1.21 \pm 0.24$  of detected and predicted charged-current quasi-elastic  $\nu_{\mu}$  events [MiniBooNE, PRL 100 (2008) 032301, arXiv:0706.0926]
- ▶ We fit MiniBooNE  $\nu_e$  and  $\nu_{\mu}$  data using the info at [http://www-boone.fnal.gov/for\\_physicists/data\\_release/lowe/](http://www-boone.fnal.gov/for_physicists/data_release/lowe/)



[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

No Osc. &  $f_\nu = 1$

$\chi_{\min}^2 = 14.3 + 5.4$

NdF = 3 + 16

GoF = 41%

Our Hypothesis

$\chi_{\min}^2 = 2.0 + 7.6$

NdF = 16

GoF = 89%

$f_\nu = 1.26$

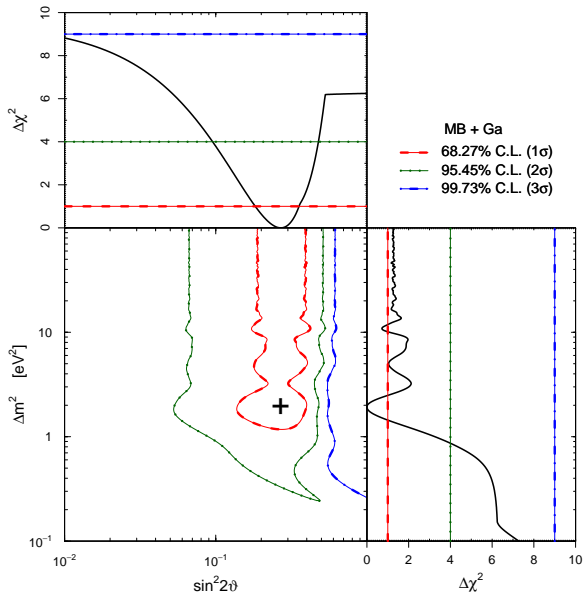
$\sin^2 2\vartheta = 0.32$

$\Delta m^2 = 1.84 \text{ eV}^2$



- ▶ Note similar best-fit values of  $\sin^2 2\vartheta$  and  $\Delta m^2$
- ▶ Gallium best fit:  $\sin^2 2\vartheta = 0.27$  and  $\Delta m^2 = 2.09 \text{ eV}^2$
- ▶ MiniBooNE best fit:  $\sin^2 2\vartheta = 0.32$  and  $\Delta m^2 = 1.84 \text{ eV}^2$
- ▶ Parameter Goodness-of-Fit of combined analysis:  
 $\Delta\chi_{\min}^2 = 0.14$     NDF = 2    GoF = 93%

# MiniBooNE + Gallium



$$\chi^2_{\min} = 2.3 + 9.2$$

$$N_{dF} = 20$$

$$\text{GoF} = 93\%$$

$$\sin^2 2\theta = 0.27$$

$$\Delta m^2 = 1.92 \text{ eV}^2$$

[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]