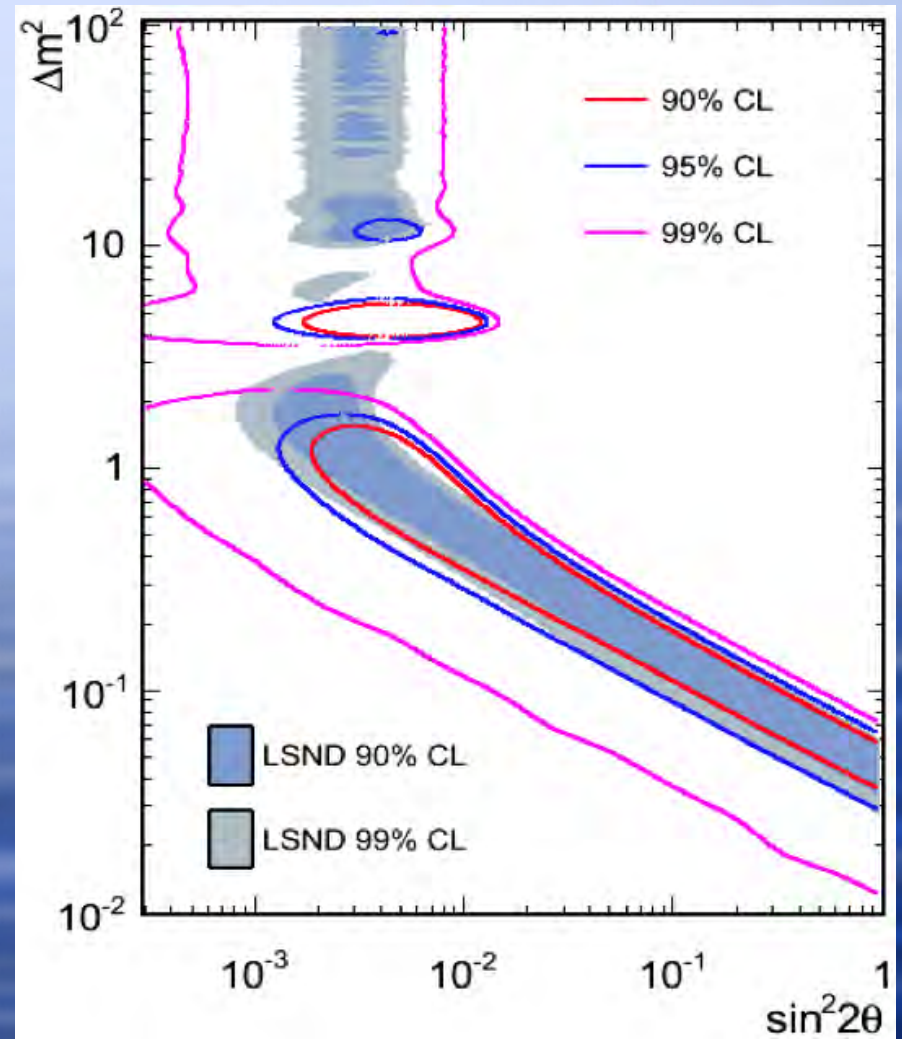


# Tensions With the $3 - \nu$ Paradigm

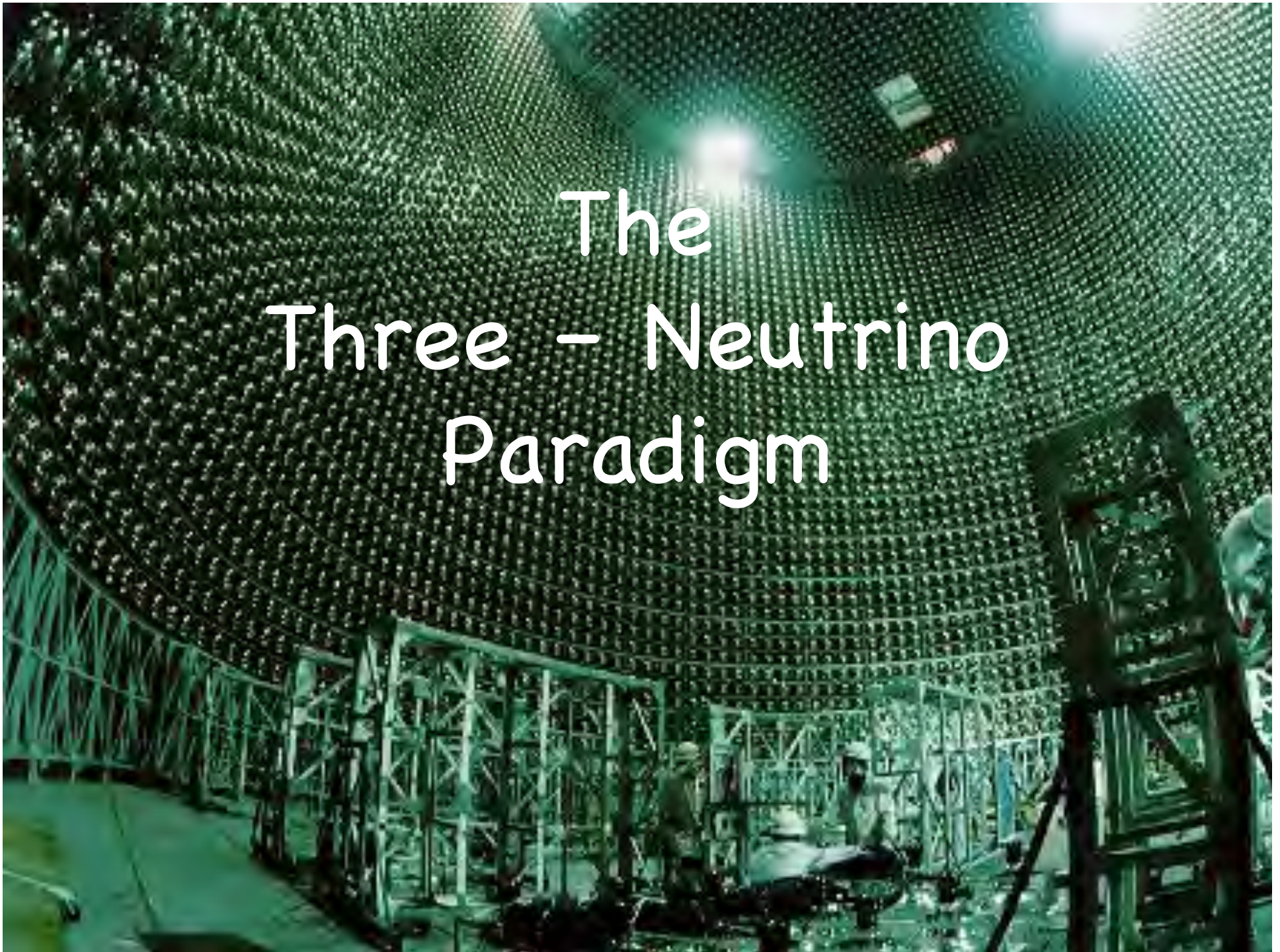


Boris Kayser, Fermilab  
EW Moriond 2012

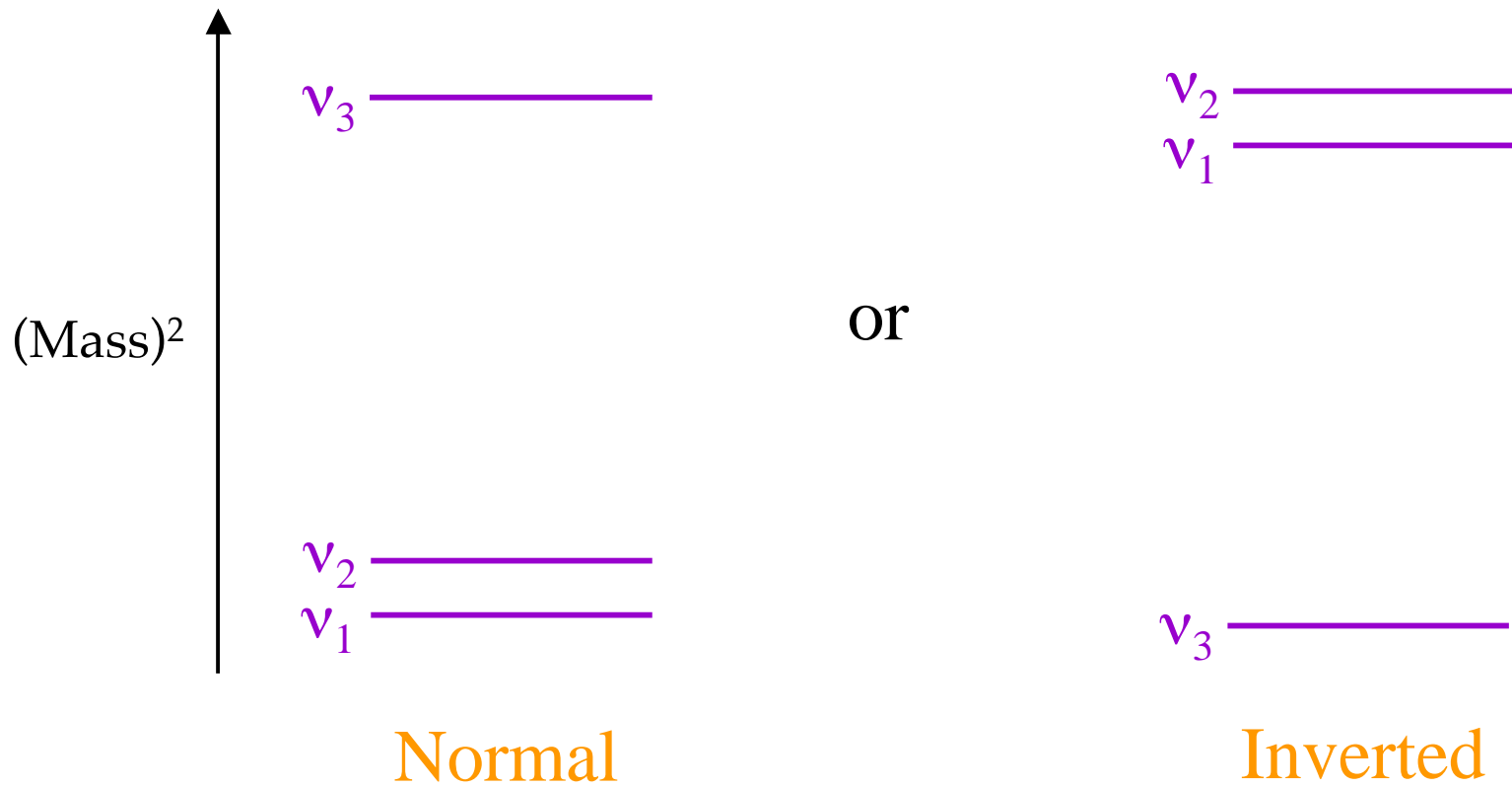
Thanks to the Moriond organizers  
for quite a few things ...

Thanks to Alan Bross, Patrick Huber,  
Georgia Karagiorgi, and Joachim Kopp  
for inputs.

# The Three – Neutrino Paradigm



# The (Mass)<sup>2</sup> Spectrum

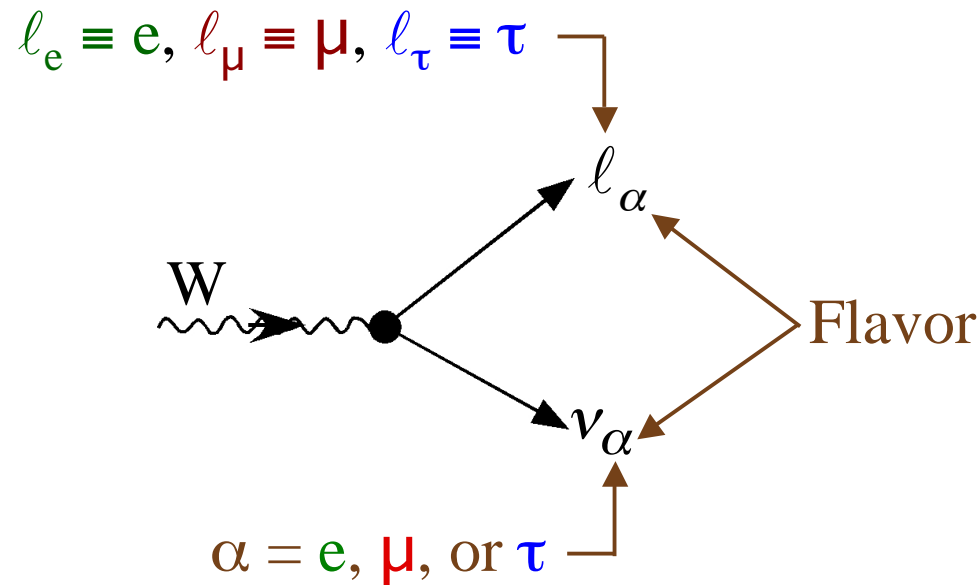


$$\Delta m_{21}^2 \cong 7.4 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{32}^2 \cong 2.3 \times 10^{-3} \text{ eV}^2$$

# The Interactions

The interactions of the neutrinos are assumed to be those of the Standard Model (SM), modified to incorporate leptonic mixing.

The neutrino couplings to the W:



But the neutrinos  $\nu_{e,\mu,\tau}$  of definite flavor are **superpositions** of the neutrinos of definite mass:

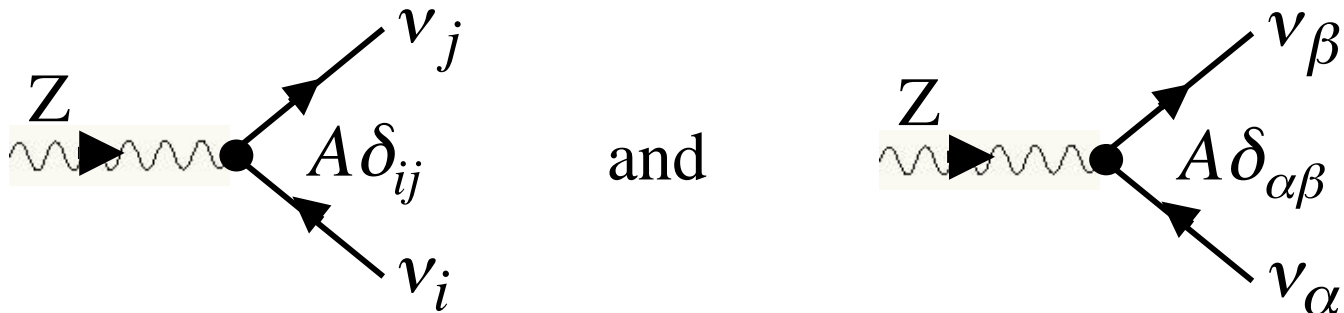
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

↑  
 Neutrino of flavor  
 $\alpha = e, \mu, \text{ or } \tau$

↑  
 Unitary leptonic mixing matrix

↑  
 Neutrino of definite mass

The neutrino couplings to the Z:



*Oscillation among  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$   
does not change the Neutral Current event rate.*

# The Mixing Matrix $U$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \underbrace{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Doesn't affect oscillation}}$$

$c_{ij} \equiv \cos \theta_{ij}$   
 $s_{ij} \equiv \sin \theta_{ij}$

$$\theta_{12} \approx 34^\circ, \quad \theta_{23} \approx 39-51^\circ,$$

$$\sin^2 2\theta_{13} = 0.092 \pm 0.023 \text{ (stat)} \pm 0.005 \text{ (syst)} \quad (\text{Daya Bay})$$

$\delta$  **and**  $\theta_{13} \neq 0$  would lead to  $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$ . *CP violation*

# The Implications of the Value of $\theta_{13}$

With  $\sin^2 2\theta_{13}$  not much below 0.1, NOvA has a good shot at determining whether the neutrino mass spectrum looks like  $\overline{\overline{\quad}}$  or  $\overline{\quad}$ .

(Mark Messier's talk)

The evidence now seems quite strong that  $\sin^2 2\theta_{13} > 0.01$ .

This is very encouraging for experiments that propose to look for CP violation in neutrino oscillation by comparing  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  with  $\nu_\mu \rightarrow \nu_e$ .

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13}$$

A conventional accelerator neutrino beam from  $\pi$  and  $K$  decay is mostly  $\nu_\mu$ , but has a  $\sim 1\%$   $\nu_e$  contamination.

Studying  $\nu_\mu \rightarrow \nu_e$  with a conventional beam would have been difficult if  $\sin^2 2\theta_{13}$  had been less than 0.01.

# Why CP Violation (~~CP~~) In Neutrino Oscillation Would Be Very Interesting

It would establish that ~~CP~~ is not special to quarks.

A major motivation to look for it:

Its observation would make it more plausible that —  
— the baryon-antibaryon asymmetry of the universe —  
— arose, at least in part, through **Leptogenesis**.

## Leptogenesis

Explains the baryon-antibaryon asymmetry of the universe by CP-violating heavy neutrino decays.

Heavy ( $m_N > 10^9$  GeV)  
Majorana neutrino

SM lepton

SM BEH scalar boson

$$\Gamma(N \rightarrow \ell^- + H^+) \neq \Gamma(N \rightarrow \ell^+ + H^-)$$

This ~~CP~~ creates a *lepton-antilepton* asymmetry.

The SM Sphaleron process converts part of this asymmetry into the observed *baryon-antibaryon* asymmetry.

*Generically, leptogenesis and light-neutrino ~~CP~~ imply each other.*

( B.K.  
1012.4469 )

*The 3- $v$  paradigm successfully  
describes many experimental results,*

*but not all.*

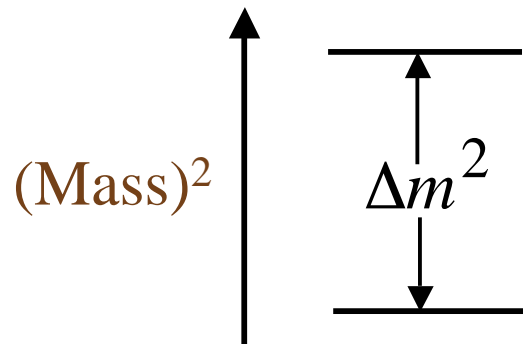
# The Non-SM

$$P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}) \neq P(\nu_{\mu} \rightarrow \nu_{\mu})$$

Possibility

# Oscillation

When the neutrino spectrum has effectively only 2 levels



Travel distance

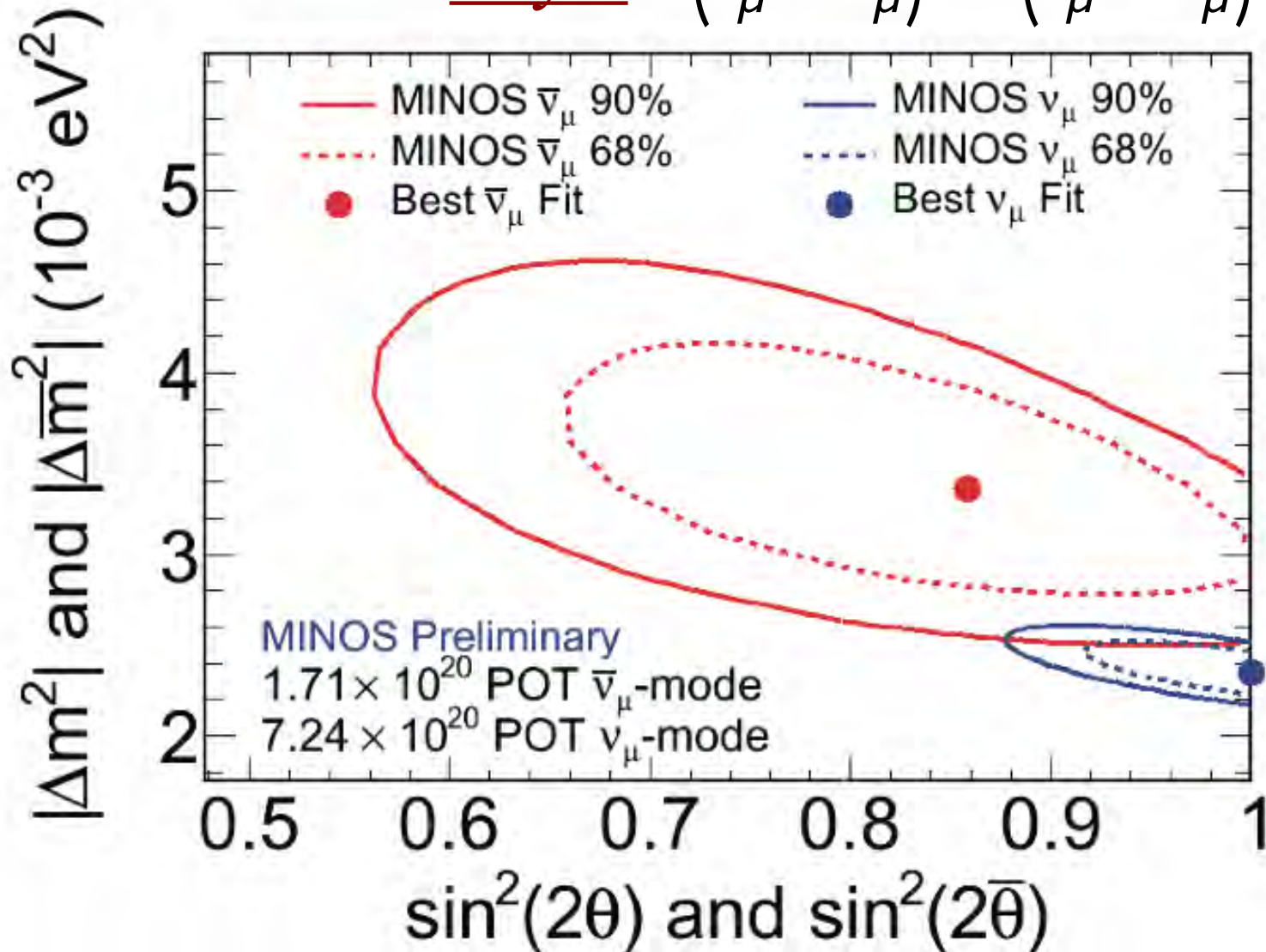
$$P(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}) = \underbrace{\sin^2 2\theta_{\alpha\beta}}_{\text{Parameters that are } \leq 1} \sin^2 \left[ 1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)} \right]$$

Energy

Parameters that are  $\leq 1$

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \underbrace{\sin^2 2\theta_{\alpha\alpha}}_{\text{Parameters that are } \leq 1} \sin^2 \left[ 1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)} \right]$$

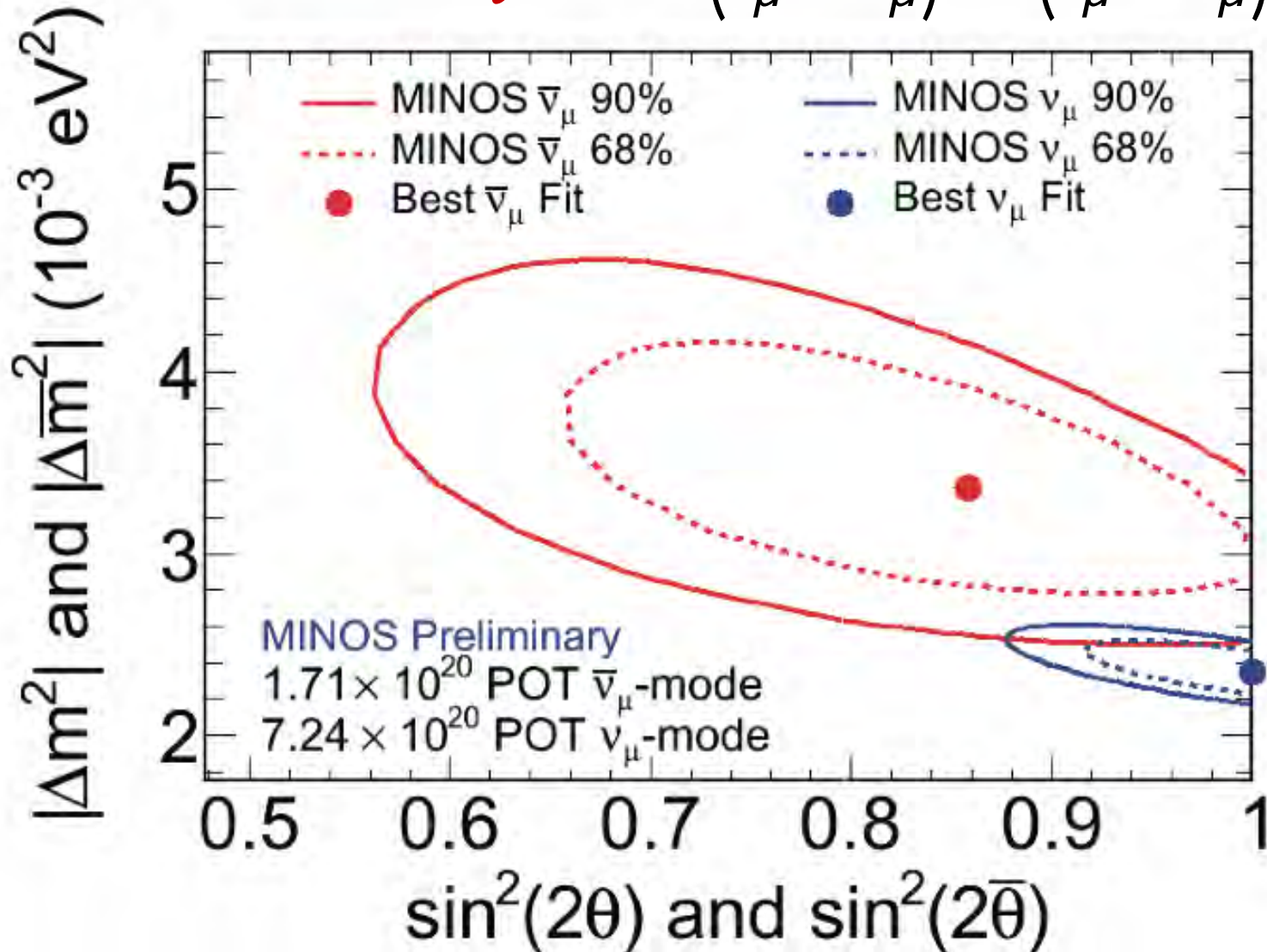
MINOS: *Maybe*  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \neq P(\nu_\mu \rightarrow \nu_\mu)$



P. Vahle, Neutrino 2010

Non-SM neutrino interactions?? (Kopp, Machado, Parke)

MINOS *may* find  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \neq P(\nu_\mu \rightarrow \nu_\mu)$

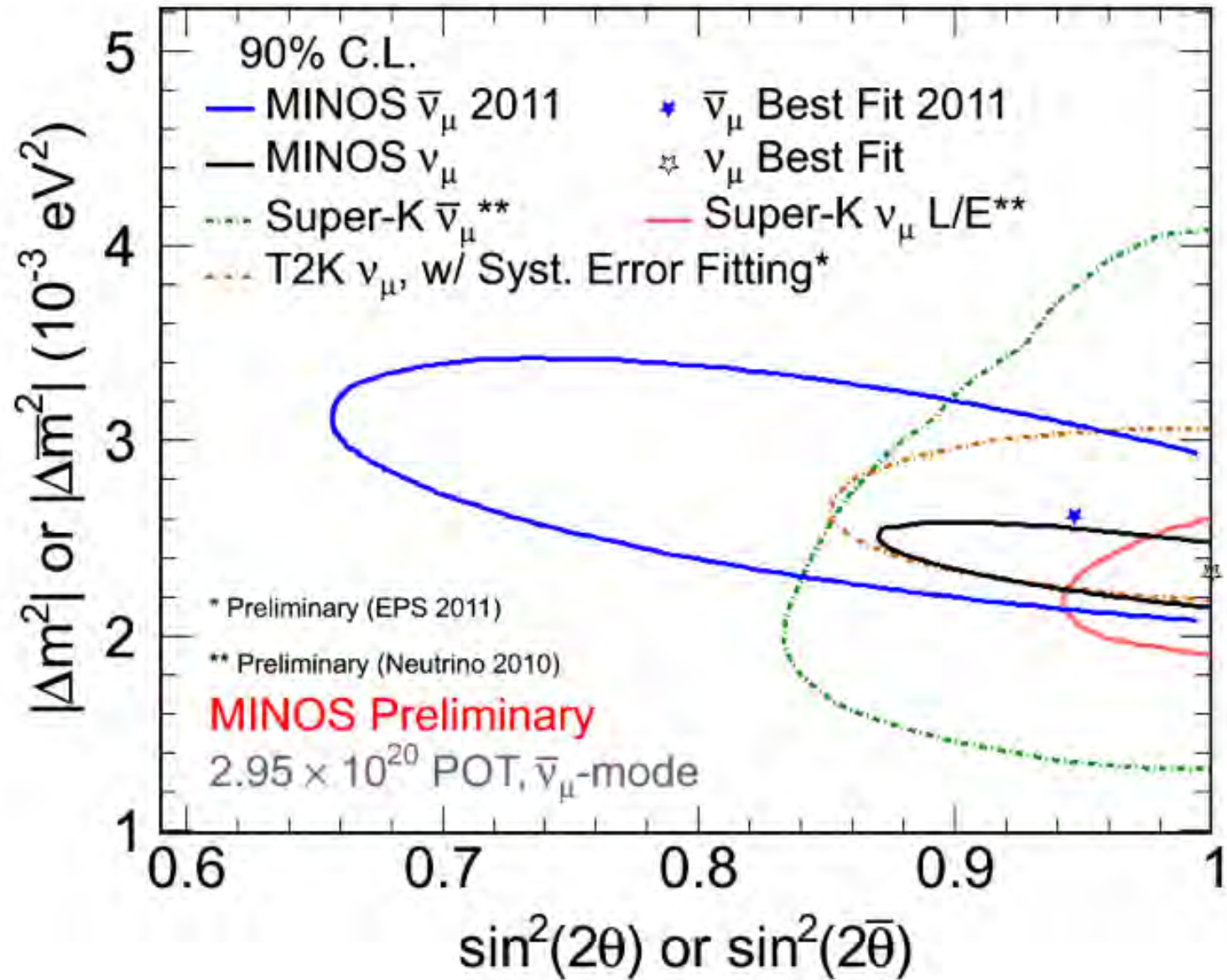


P. Vahle, Neutrino 2010

$$\nu_\tau + N \rightarrow X + \mu$$

(Kopp, Machado, Parke)

# MINOS: *With 70% More $\bar{\nu}$ Data*



Are There  
*More* Than 3  
Mass Eigenstates?

Are There  
*Sterile* Neutrinos?



## *Sterile Neutrino*

One that does not couple  
to the SM  $W$  or  $Z$  boson

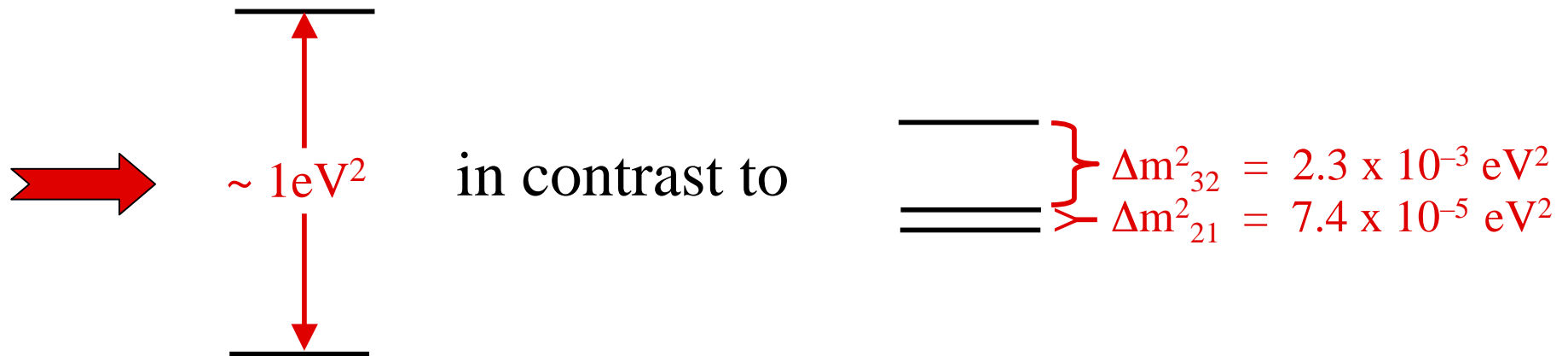
A “sterile” neutrino may well  
couple to some non-SM particles.  
These particles could perhaps be  
found at LHC or elsewhere.

# The Hint From LSND

The **LSND** experiment at Los Alamos reported a *rapid*  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillation at  $L(km)/E(GeV) \sim 1$ .

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2 \left[ 1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)} \right] \sim 0.26\%$$

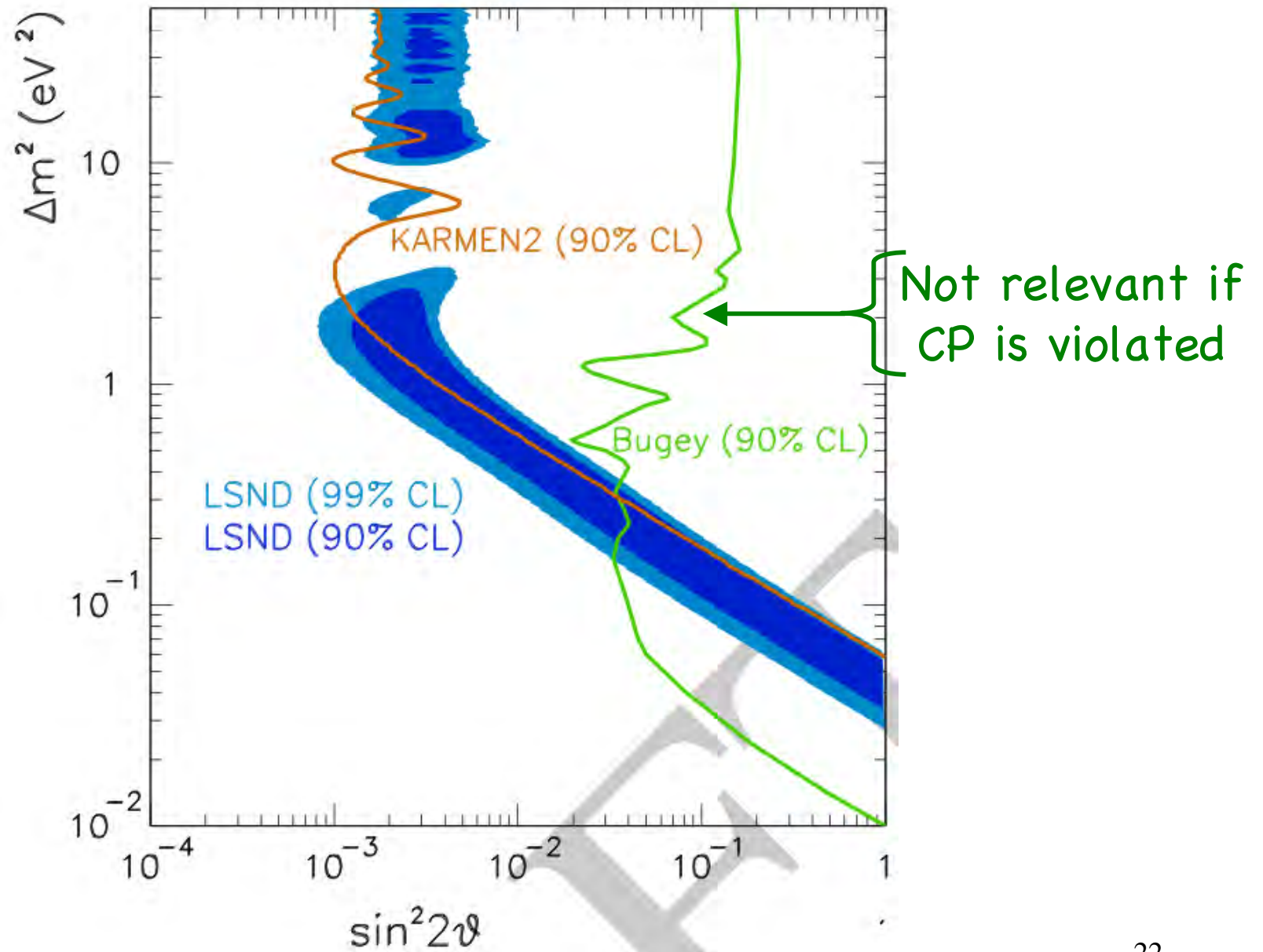
From  $\mu^+$  decay at rest;  $E \sim 30$  MeV



At least **4** mass eigenstates

{ from measured  $\Gamma(Z \rightarrow \nu\bar{\nu})$  } At least **1** sterile neutrino

# The LSND-favored region

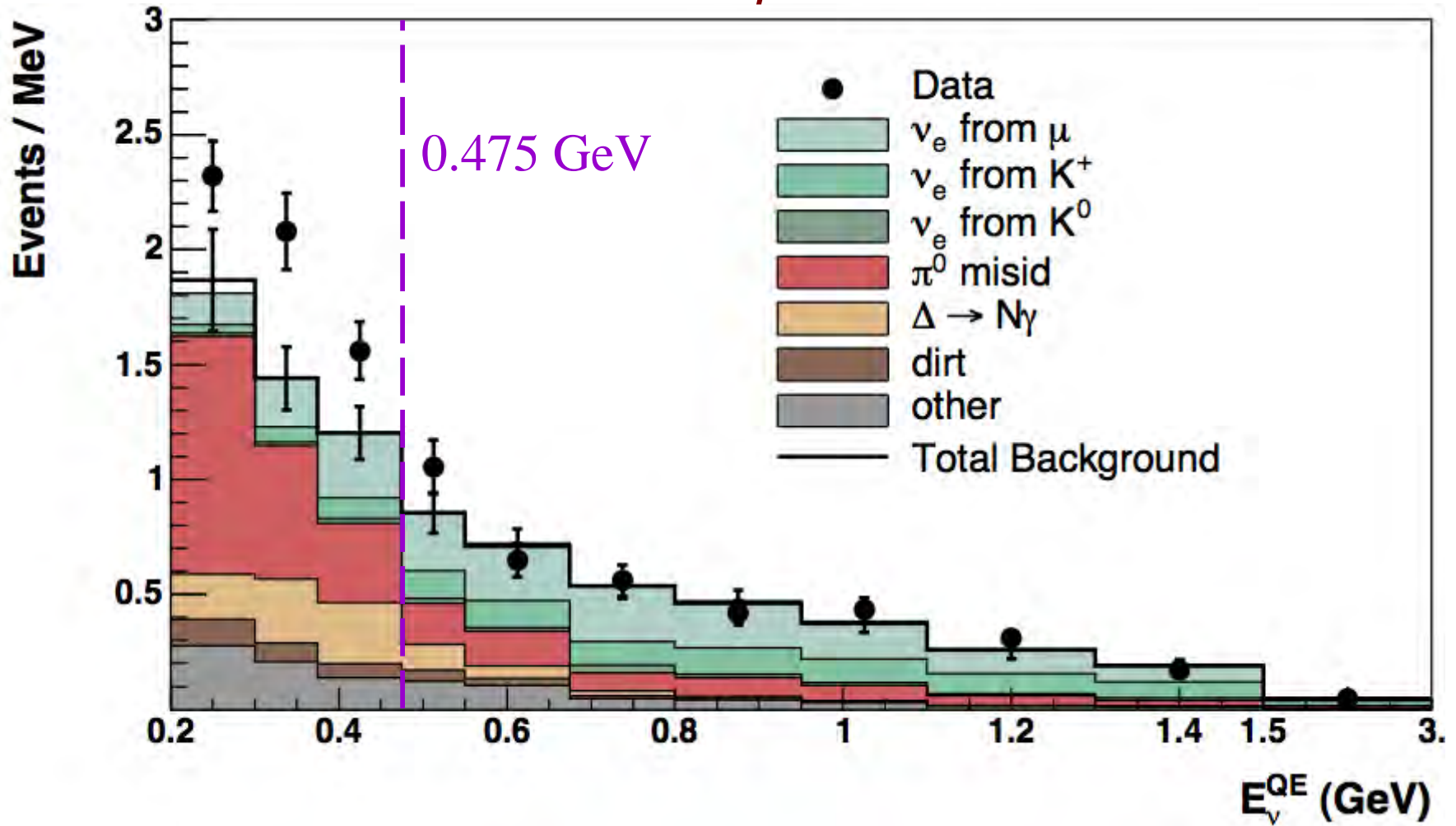


# The Hint From MiniBooNE

In **MiniBooNE**, both L and E are  $\sim 17$  times larger than they were in **LSND**, and L/E is comparable.

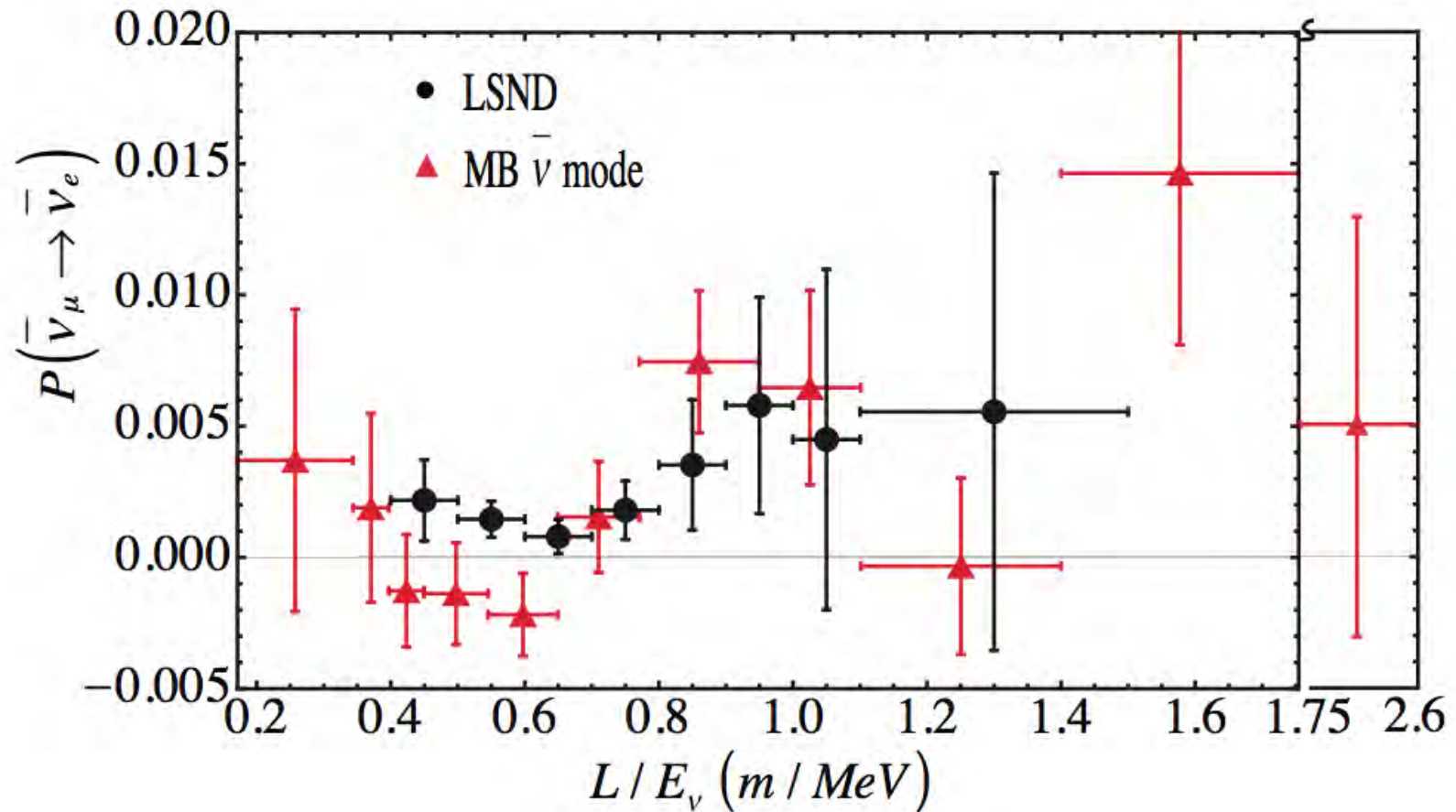
**MiniBooNE** has reported both  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  results.

# MiniBooNE $\nu_\mu \rightarrow \nu_e$ Search



*No excess above background above 0.475 GeV.*

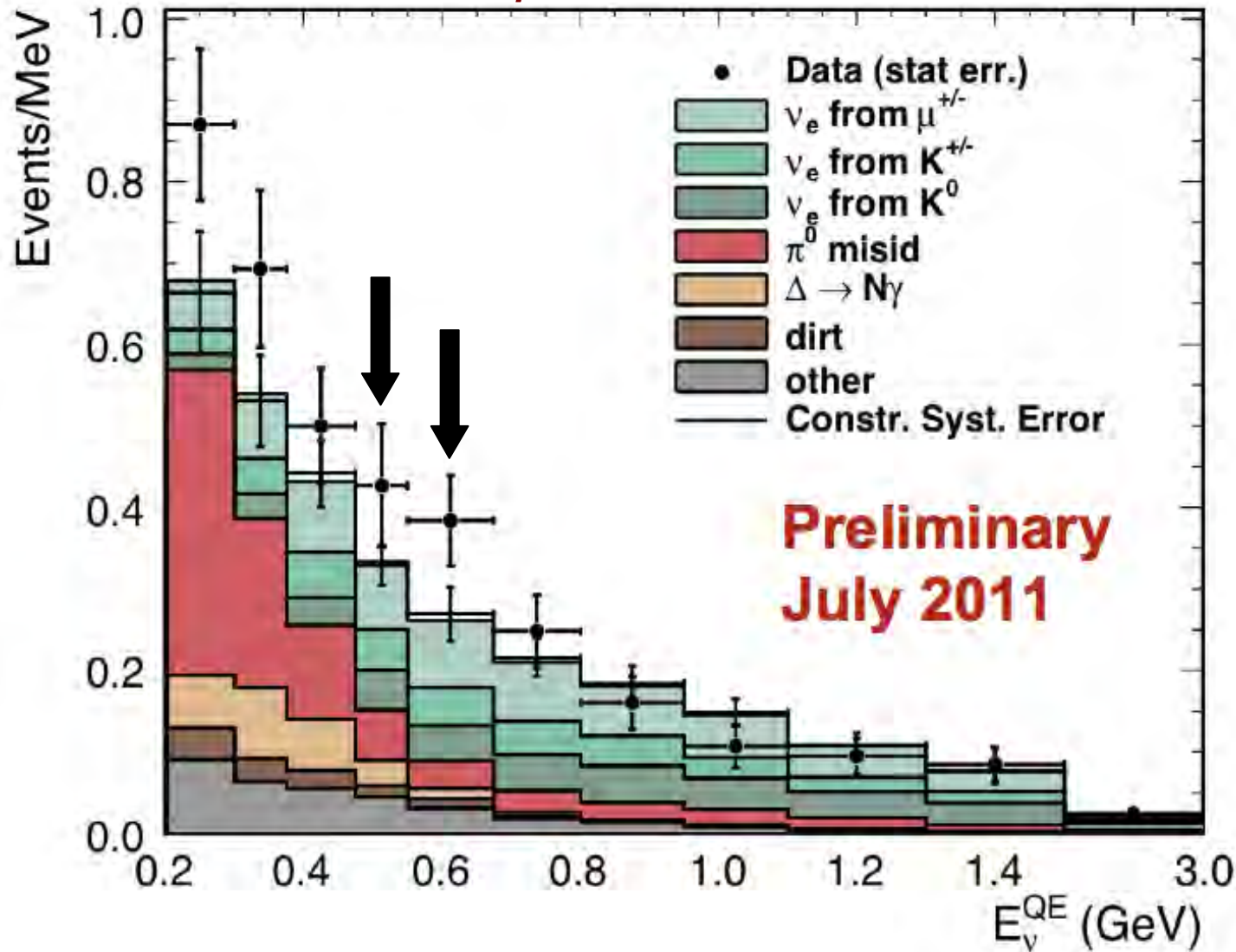
# MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Search; 2010 Results



(Phys.Rev.Lett.105:181801, 2010)

*The  $\nu$  and  $\bar{\nu}$  results can differ due to CP violation.*

# MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Search; 2011 Results



*Any  
excess  
is  
small.*

E. Zimmerman and M. Shaevitz at PANIC 2011

# The Hint From Reactors

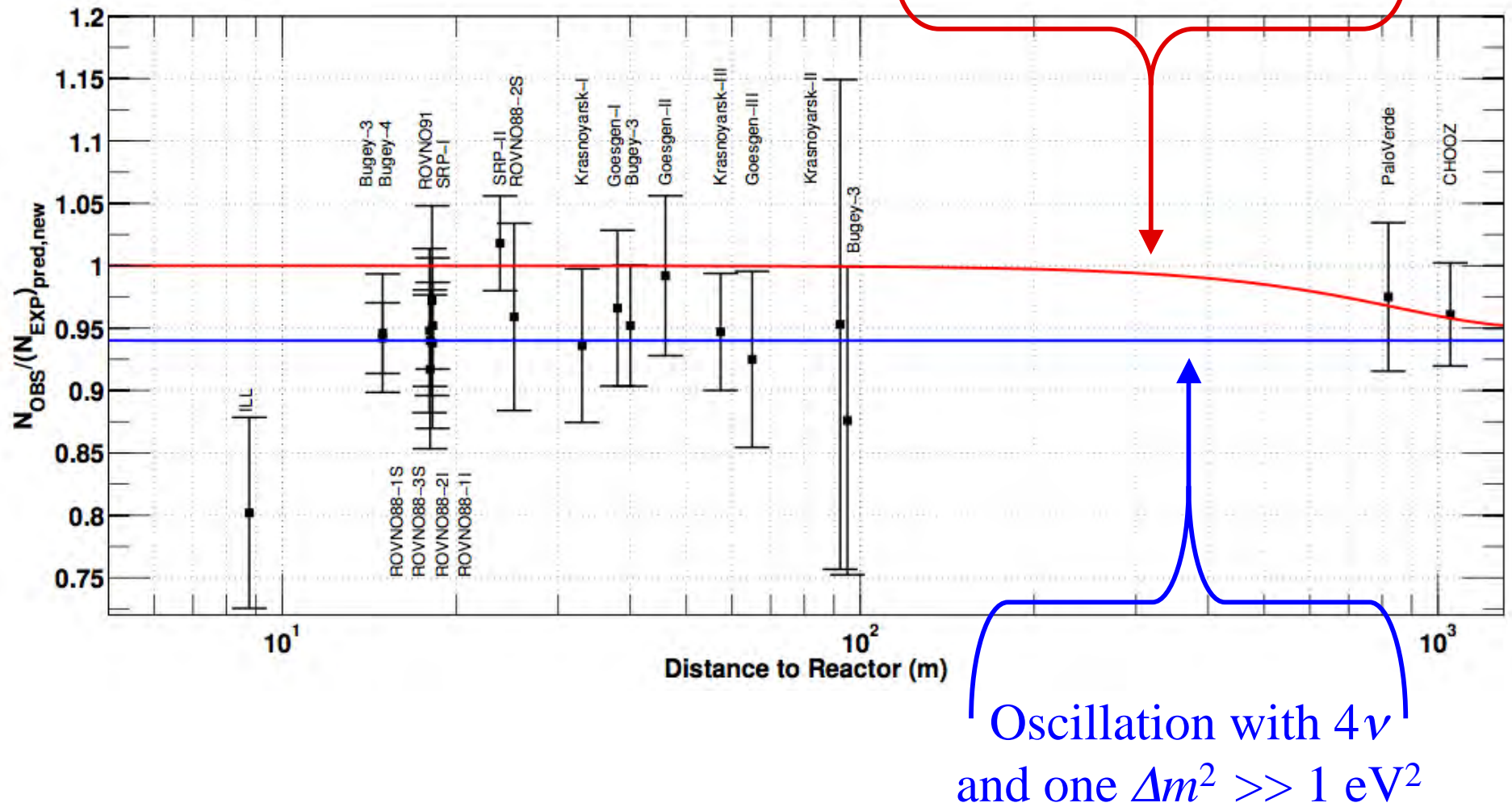
The prediction for the un-oscillated  $\bar{\nu}_e$  flux from reactors, which has  $\langle E \rangle \sim 3$  MeV, has increased by about 3%.

(Mueller et al., Huber)

Measurements of the  $\bar{\nu}_e$  flux at (10 – 100)m from reactor cores now show a  $\sim 6\%$  disappearance.

(Mention et al.)

Oscillation with only  $3\nu$   
and  $\sin^2 2\theta_{13} = 0.06$



Disappearance at  $L(\text{m})/E(\text{MeV}) \gtrsim 1$  suggests oscillation  
with  $\Delta m^2 \gtrsim 1 \text{ eV}^2$ , like LSND and MiniBooNE.

# The Hint From $^{51}\text{Cr}$ and $^{37}\text{Ar}$ Sources

These radioactive sources were used  
to test gallium solar  $\nu_e$  detectors.

$$\frac{\text{Measured event rate}}{\text{Expected event rate}} = 0.86 \pm 0.05$$

(Giunti, Laveder)

Rapid disappearance of  $\nu_e$  flux  
due to oscillation with a large  $\Delta m^2$ ??

# The Hint From Cosmology

Big Bang Nucleosynthesis (BBN) and CMB anisotropies count the effective number of relativistic degrees of freedom,  $N_{\text{eff}}$ , at early times.

Light sterile neutrinos mixed with the active ones as required by the terrestrial anomalies would very likely have thermalized in the early universe.

Then  $N_{\text{eff}}$  grows by 1 for each sterile species.

The evidence suggests that perhaps  $N_{\text{eff}} > 3$ .

# $N_{\text{eff}}$ From BBN

Model	Data	$N_{\text{eff}}$	Ref.
$\eta + N_{\text{eff}}$	$\eta_{\text{CMB}} + Y_{\text{p}} + \text{D/H}$	$3.8^{(+0.8)}_{(-0.7)}$	[10]
	$\eta_{\text{CMB}} + Y_{\text{p}} + \text{D/H} < (4.05)$		[11]
	$Y_{\text{p}} + \text{D/H}$ {	$3.85 \pm 0.26$	[13]
		$3.82 \pm 0.35$	[13]
		$3.13 \pm 0.21$	[13]
$\eta + N_{\text{eff}}, (\Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 \geq 0)$	$\eta_{\text{CMB}} + \text{D/H}$	$3.8 \pm 0.6$	[12]
	$\eta_{\text{CMB}} + Y_{\text{p}}$	$3.90^{+0.21}_{-0.58}$	[12]
	$Y_{\text{p}} + \text{D/H}$	$3.91^{+0.22}_{-0.55}$	[12]

# $N_{\text{eff}}$ From CMB

Model	Data	$N_{\text{eff}}$	Ref.
$N_{\text{eff}}$	W-5+BAO+SN+ $H_0$	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[26]
	W-5+LRG+ $H_0$	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[26]
	W-5+CMB+BAO+XLF+ $f_{\text{gas}}+H_0$	$3.4^{+0.6}_{-0.5}$	[29]
	W-5+LRG+maxBCG+ $H_0$	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[26]
	W-7+BAO+ $H_0$	$4.34^{+0.86}_{-0.88}$	[18]
	W-7+LRG+ $H_0$	$4.25^{+0.76}_{-0.80}$	[18]
	W-7+ACT	$5.3 \pm 1.3$	[23]
	W-7+ACT+BAO+ $H_0$	$4.56 \pm 0.75$	[23]
	W-7+SPT	$3.85 \pm 0.62$	[24]
	W-7+SPT+BAO+ $H_0$	$3.85 \pm 0.42$	[24]
	W-7+ACT+SPT+LRG+ $H_0$	$4.08^{(+0.71)}_{(-0.68)}$	[30]
	W-7+ACT+SPT+BAO+ $H_0$	$3.89 \pm 0.41$	[31]
$N_{\text{eff}}+f_\nu$	W-7+CMB+BAO+ $H_0$	$4.47^{(+1.82)}_{(-1.74)}$	[32]
	W-7+CMB+LRG+ $H_0$	$4.87^{(+1.86)}_{(-1.75)}$	[32]
$N_{\text{eff}}+\Omega_k$	W-7+BAO+ $H_0$	$4.61 \pm 0.96$	[31]
	W-7+ACT+SPT+BAO+ $H_0$	$4.03 \pm 0.45$	[32]
$N_{\text{eff}}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+ $H_0$	$4.00 \pm 0.43$	[31]
$N_{\text{eff}}+f_\nu+w$	W-7+CMB+BAO+ $H_0$	$3.68^{(+1.90)}_{(-1.84)}$	[32]
	W-7+CMB+LRG+ $H_0$	$4.87^{(+2.02)}_{(-2.02)}$	[32]
$N_{\text{eff}}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+ $H_0$	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[33]
	W-7+CMB+LRG+SN+ $H_0$	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[33]

*More precise  
information will  
come from the  
Planck satellite.*

# $\sum_i m(\nu_i)$ In the Early Universe

Large Scale Structure in the universe and the CMB suggest that —

$$\sum_i m(\nu_i) < (0.17 - 1.0) \text{ eV}$$

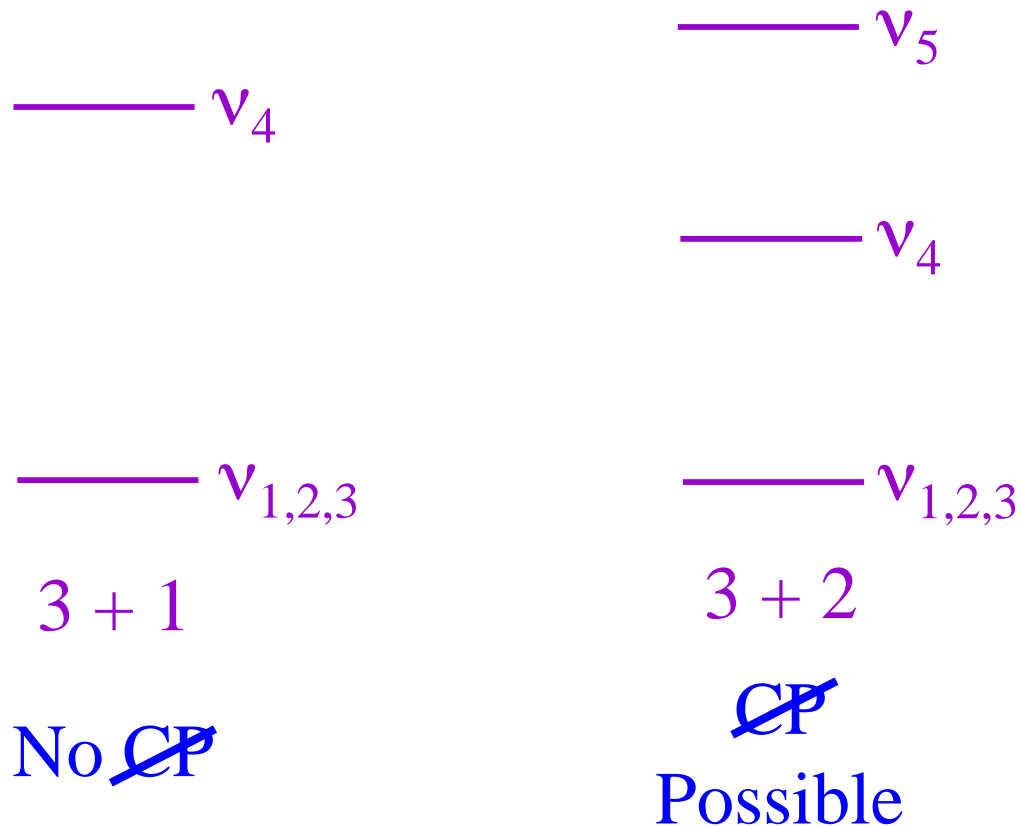
(Seljak, Slosar, McDonald)  
Hannestad; Pastor

Possible tension with terrestrial experiments if  $\Delta m^2 > 1 \text{ eV}^2$ .

However, in cosmology, there are parameter degeneracies.

# Global Fits To Short-Baseline Terrestrial Data

# The Spectra That Are Tried



Short-Baseline experiments  
have an  $L/E$  too small to see  
the splitting between  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$ .

# The Bottom Line

**3 + 1 spectra do not provide  
a good fit to all the data.**

**They do not violate CP.**

**They cannot accommodate the CP-violating  
simultaneous presence of a  $\bar{\nu}$  signal in LSND  
and MiniBooNE, and the absence  
of a  $\nu$  signal in MiniBooNE.**

(Karagiorgi; Kopp, Maltoni, and Schwetz)

**3 + 2 spectra can violate CP, so they do better,  
but there is still tension between  
appearance data and disappearance data.**

**Other phenomenological models  
are being tried ....**

# So, Are There Sterile Neutrinos?

**Not speaking for anybody else,**  
my personal impression is —

Individually or taken together,  
the hints are certainly not convincing.

**But —**

**They are interesting enough  
to call for further,  
hopefully definitive,  
investigation.**

# Fermilab Short Baseline Neutrino Focus Group

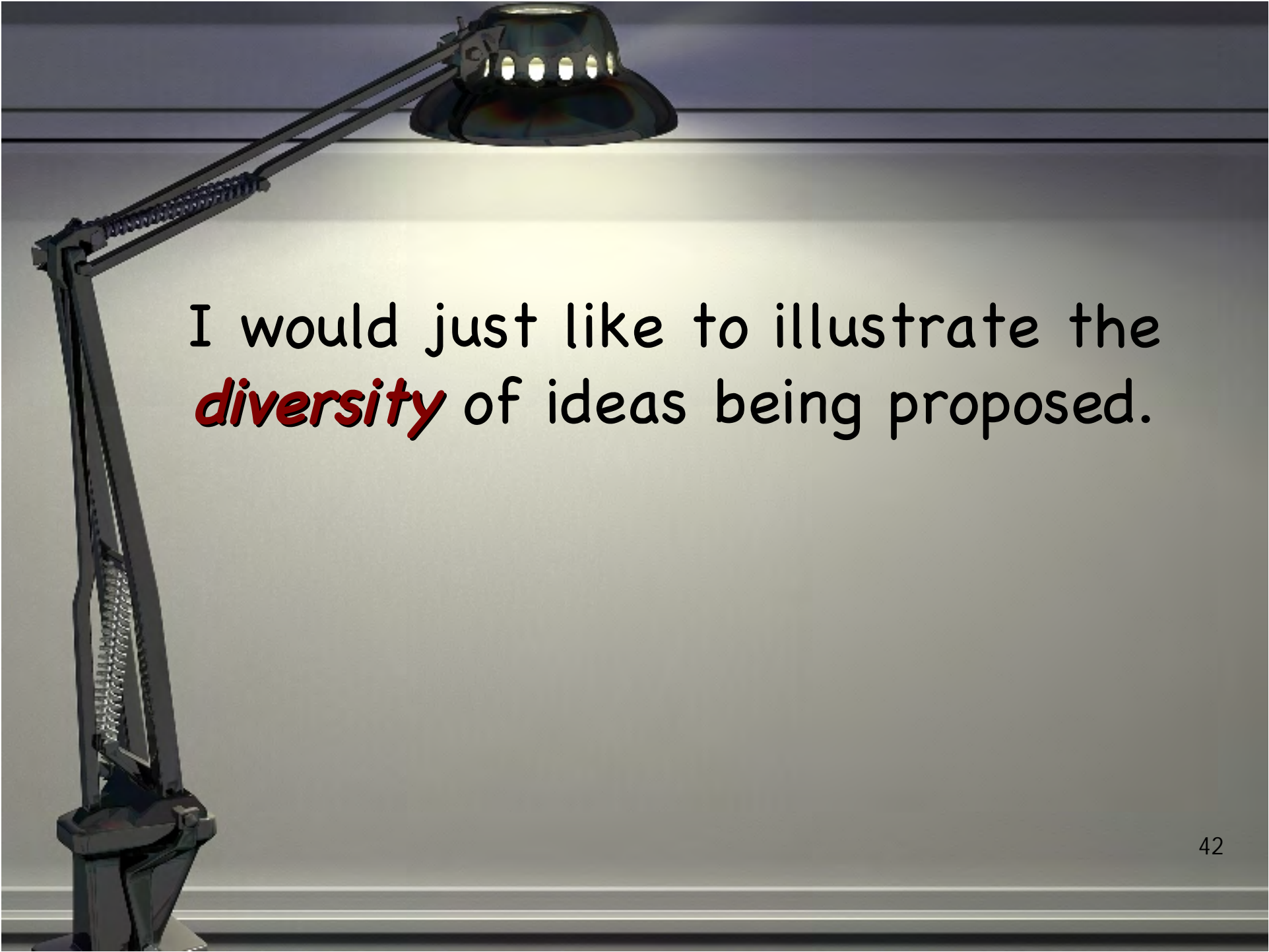
From the charge:

**“... consider new generation detectors and/or new types of neutrino sources that would lead to a definitive resolution of the existing anomalies.”**

Started ~ January, 2012

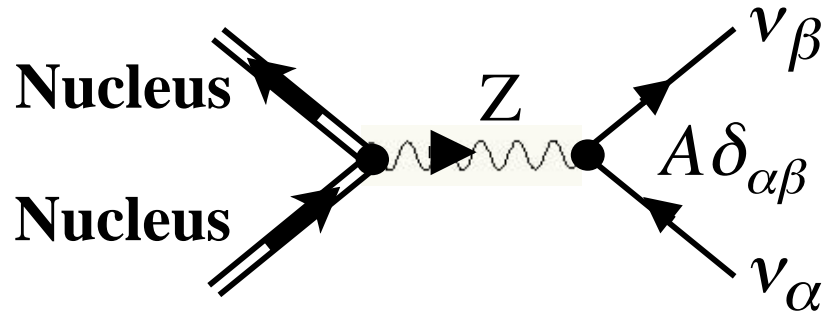
Report due ~ May, 2012

# Ideas For Future Experiments

A 3D-rendered desk lamp with a black adjustable arm and a silver-colored lamp head is positioned on the left side of the frame. The lamp is turned on, casting a warm, yellowish glow onto a large, white rectangular surface that resembles a whiteboard or a piece of paper. The surface is set against a dark, textured background. The text "I would just like to illustrate the *diversity* of ideas being proposed." is written on the white surface. The word "diversity" is written in a red, italicized font, while the rest of the text is in a black, sans-serif font.

I would just like to illustrate the  
*diversity* of ideas being proposed.

# Coherent Neutral-Current Scattering



This process has the same rate for any incoming *active* neutrino,  $\nu_e$ ,  $\nu_\mu$ , or  $\nu_\tau$ .

But the Z does not couple to  $\nu_{sterile}$ .

If  $\nu_{active} \rightarrow \nu_{sterile}$ , the coherent scattering event rate will oscillate with it.

## Ideas—

### Electron-capture monoenergetic $\nu_e$ source

Kinetic energy of nuclear recoil  $\sim$  Few  $\times$  10 eV.

Use bolometric cryogenic detector.

(Formaggio et al.)

### Cyclotron pion & muon decay-at-rest neutrino source

Two sources — one detector

Kinetic energy of nuclear recoil  $\sim$  keV.

Detection via DM-inspired detectors.

(Anderson et al.)

*Caveat: If  $\Delta m^2 \gg 1 \text{ eV}^2$ , the oscillation may be too fast to see.*

# Position Dependence Within One Detector



For  $E \sim 30$  MeV  $\bar{\nu}_\mu$  from  $\mu^+$  decay at rest, and  $\Delta m^2 \sim 1$  eV<sup>2</sup>, the oscillation maximum is at  $\sim 40$  m.

(Agarwalla et al.)

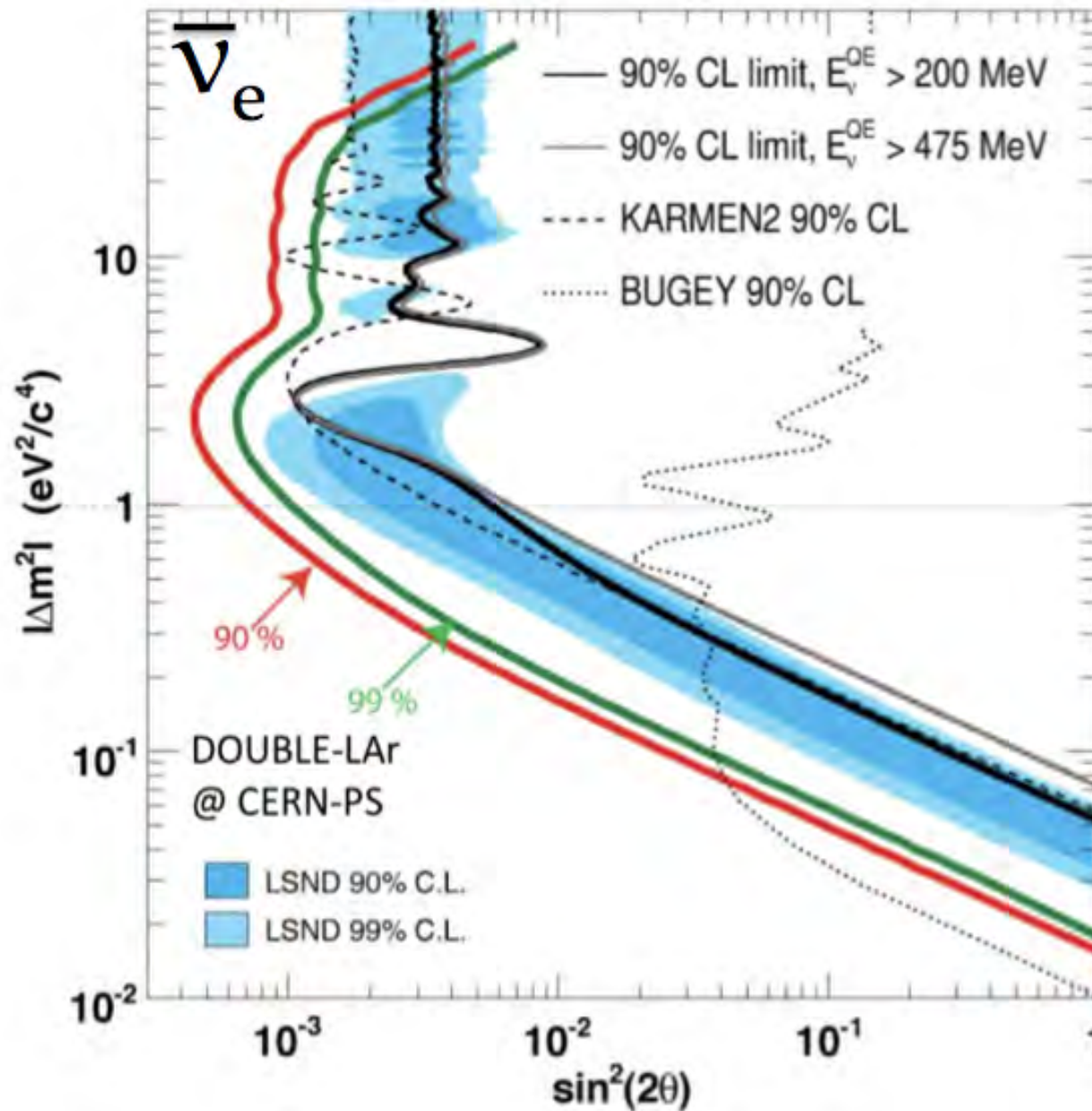
# Two-Detector Short Baseline Experiments At Accelerators

Compare event rates in a near and a far detector.

This is a good way to deal with flux uncertainties, so long as the neutrinos have not already oscillated before reaching the near detector..

**Ideas —**

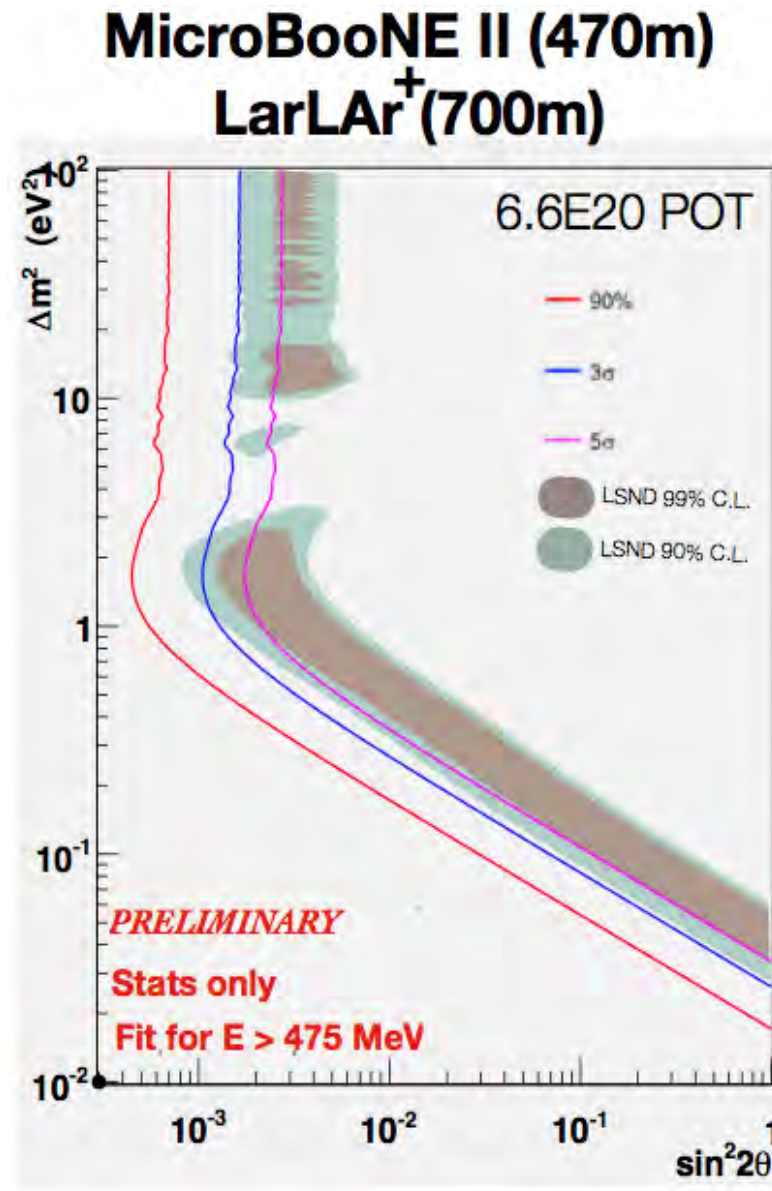
## Two ICARUS detectors in the CERN PS beam



$5 \times 10^{20}$  POT

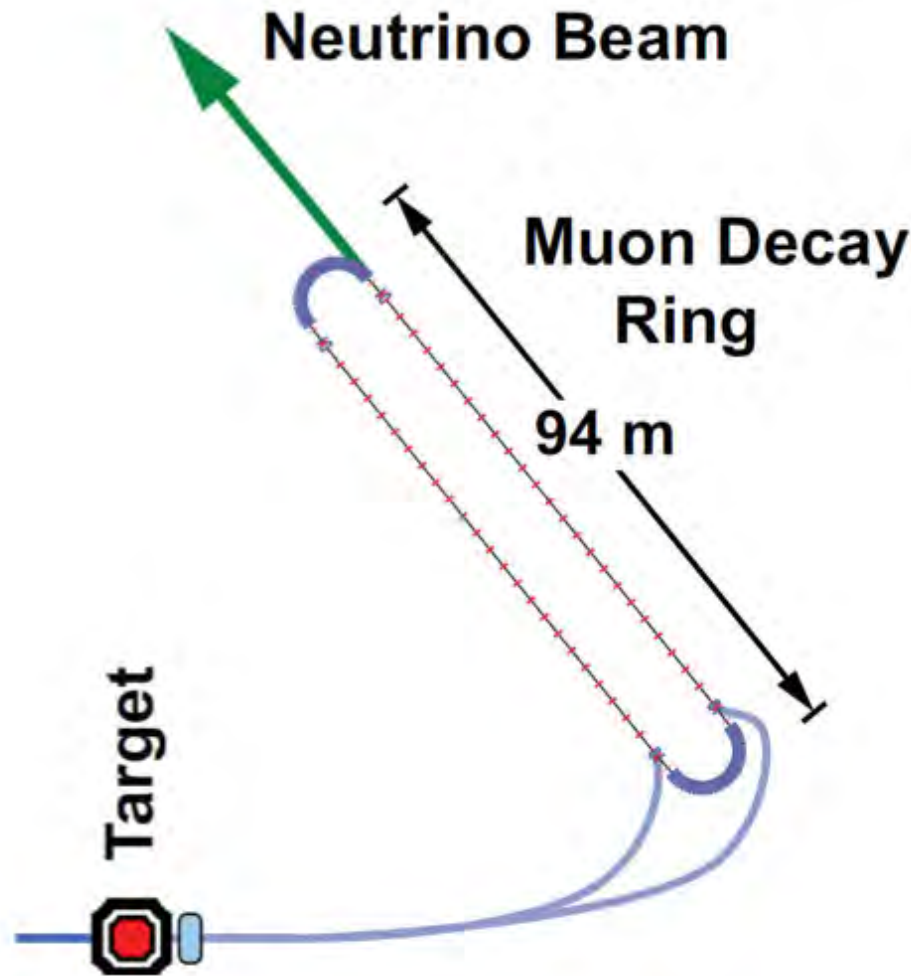
(ICARUS)

## Two LAr detectors in the FNAL Booster beam



(Guenette et al.)

# A Very Low Energy Neutrino Factory



$$E_{\mu} = (2 - 3) \text{ GeV}$$

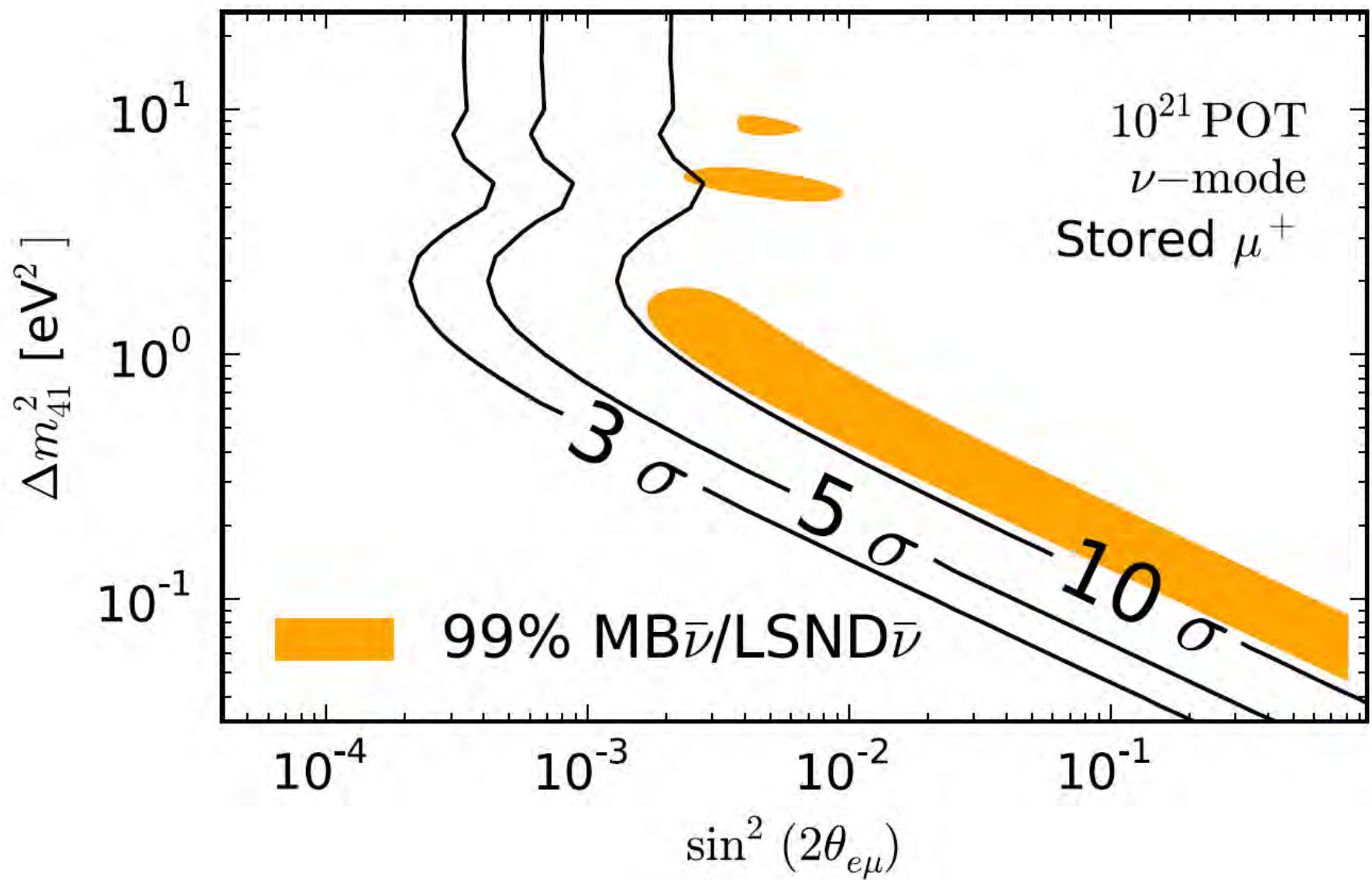
If store  $\mu^+$ ,  
can study—

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_{\mu}$$

followed by —

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

LSND reported  $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$ .  $P(\nu_e \rightarrow \nu_{\mu}) \stackrel{\text{CPT}}{=} P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e)$



(Bross et al.)

# Summary

---

There are interesting tensions  
with the  $3 - \nu$  paradigm.

Hopefully we will be able to  
determine what is behind them  
in the not too distant future.