Recent MiniBooNE Results and the Status of Sterile Neutrinos

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Fermilab Theory Seminar
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Outline

- Introduction
- Motivation for sterile neutrinos: LSND
- Sterile neutrino phenomenology
- MiniBooNE (arxiv:1207.4809)
- Other recent anomalies
- Constraints from other experiments
- Global Fits (arxiv:1207.4765)
- Future

Neutrinos in the standard model

- Only interact via the "weak force" (W and Z bosons)

- Three flavors:

  – Electron $\nu_e \rightarrow e$

  – Muon $\nu_\mu \rightarrow \mu$

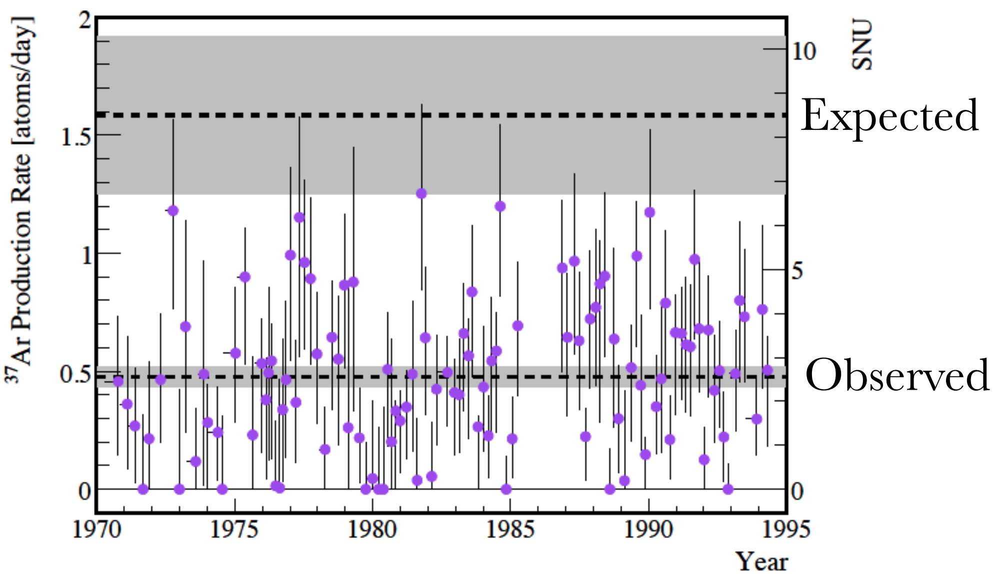
  – Tau $\nu_\tau \rightarrow \tau$

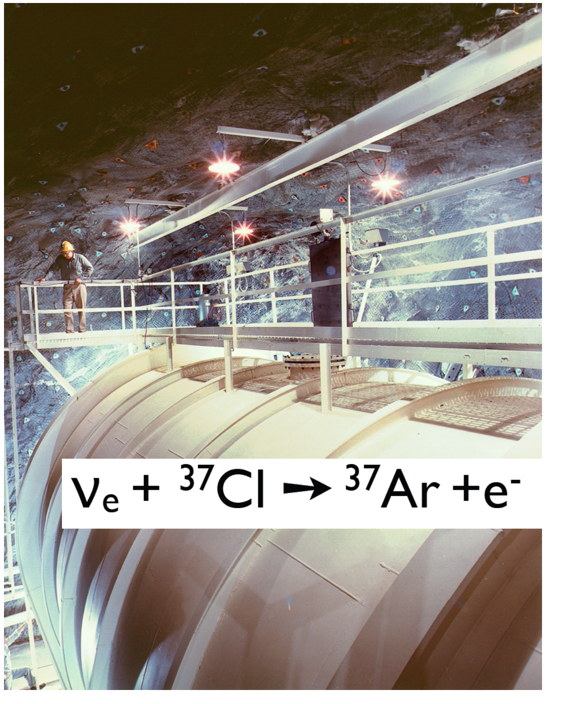
- Massless

http://www.particlezoo.net/

Anomaly in the neutrino sector

"Solar neutrino problem"





Missing neutrinos!

Neutrino Oscillations

Maybe neutrinos "oscillate" like in the quark sector

Two neutrino Oscillations:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} \\ U_{\mu 1} & U_{\mu 2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_\mu(t)\rangle = -\sin\theta e^{-iE_1 t}\,|\nu_1\rangle + \cos\theta e^{-iE_2 t}\,|\nu_2\rangle \qquad E \approx p + \frac{m^2}{2E}$$

$$|\,\langle \nu_e\,|\,\nu_\mu(t)\rangle\,|^2 = \sin^2 2\theta(1 - \cos(E_2 - E_1)t) \qquad v \approx c = \frac{L}{t}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(\underbrace{1.27}_{\text{Not unitless}}\Delta m^2 \frac{L}{E})$$

in m (km)

Not unitless

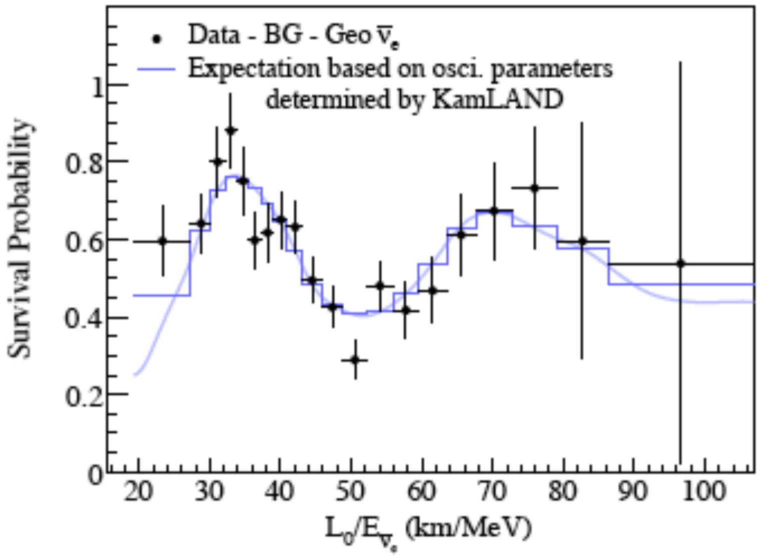
in MeV (GeV)

Neutrino Oscillations

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

Distance from source (chosen)

Energy (measured by detector)



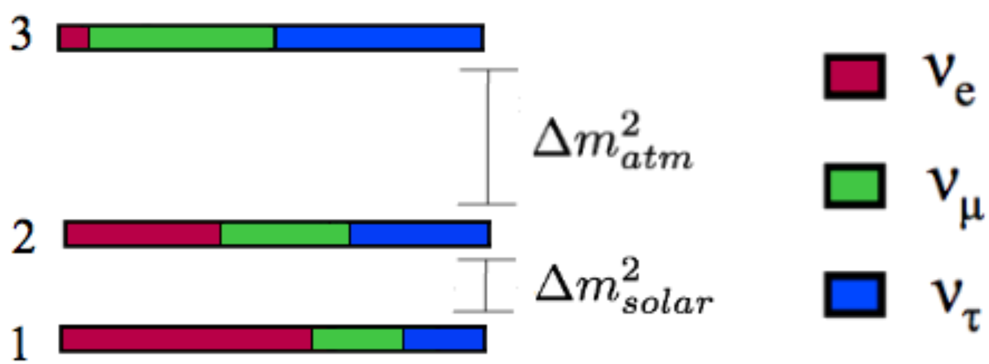
Neutrino Oscillations

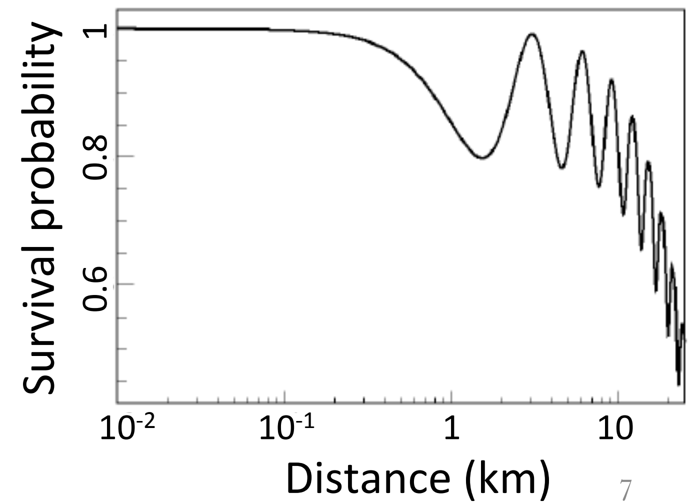
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3x3 rotation matrix

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

phase which may be non-zero (cp-violation)





Great, now we have a "nu" standard model!

So what's the problem?

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- Motivation for sterile neutrinos: LSND
- Sterile neutrino phenomenology
- MiniBooNE (arxiv:1207.4809)
- Other recent anomalies
- Constraints from other experiments
- Global Fits (arxiv:1207.4765)
- Future

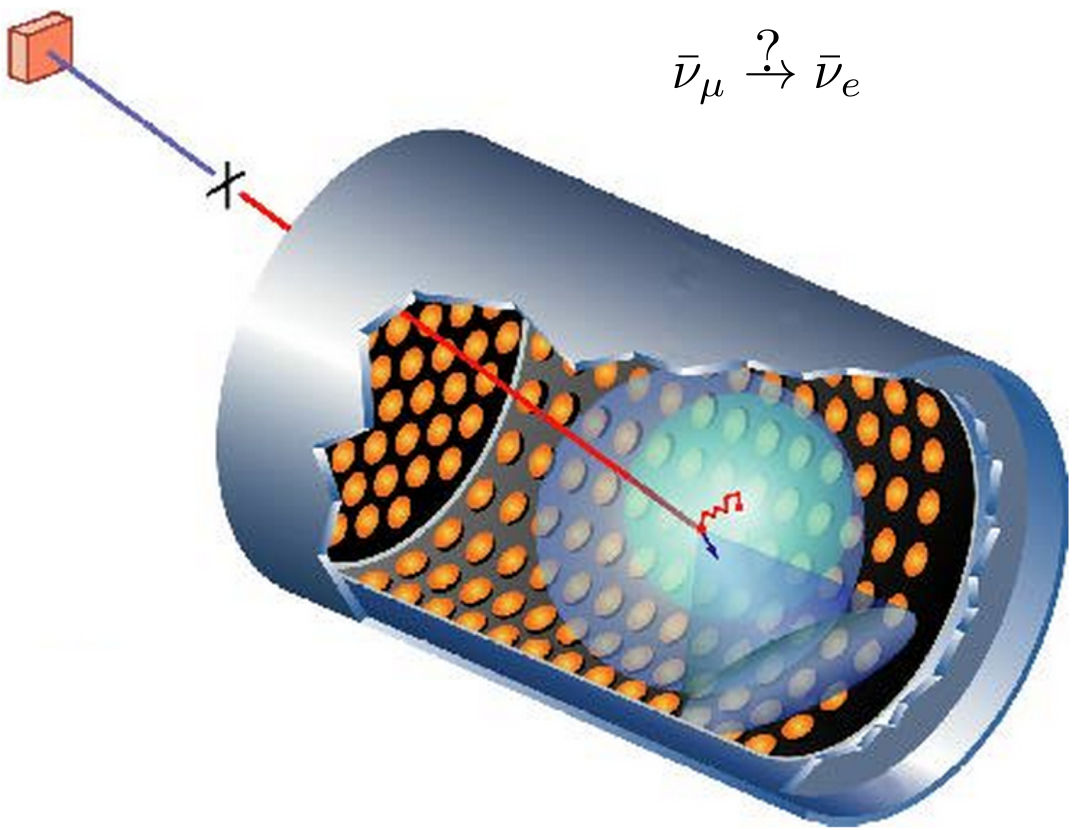
LSND Anomaly

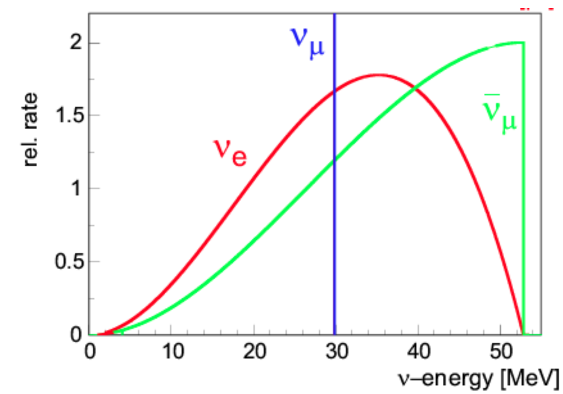
Liquid scintillator detector using stopped pion beam

$$\pi^+ \to \mu^+ + \nu_\mu \ ,$$

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

$$\bar{\nu}_\mu \xrightarrow{?} \bar{\nu}_e$$



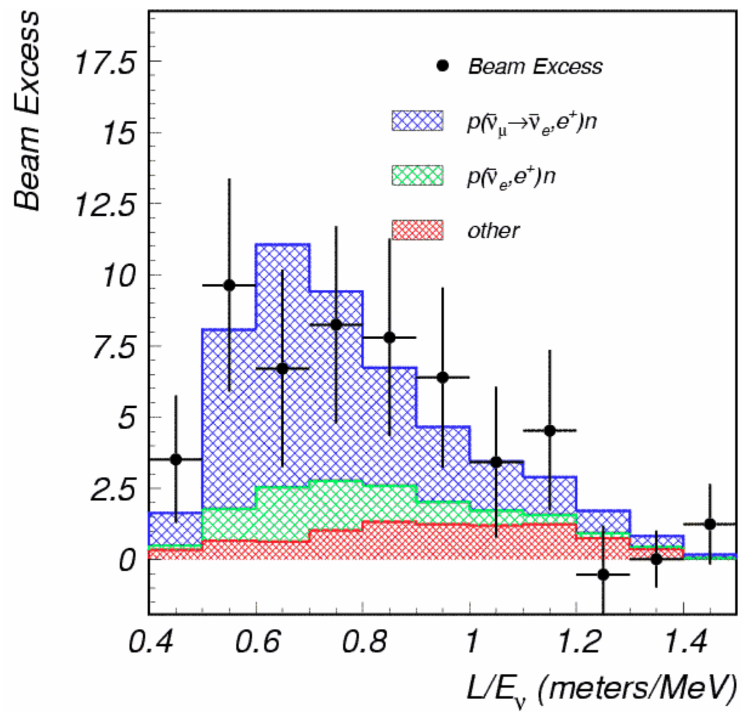


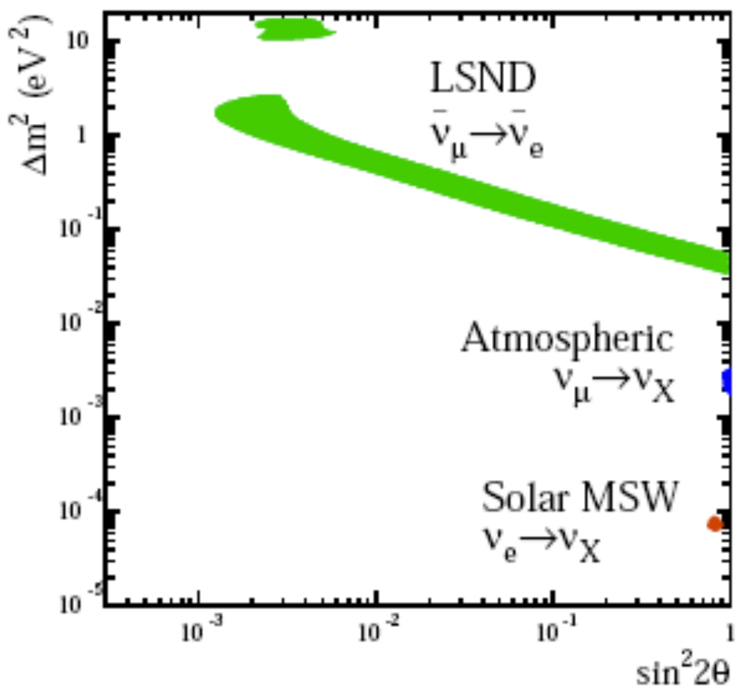
$$\bar{\nu}_e + p \to e^+ + n$$

LSND Anomaly

Observed excess of $\bar{\nu}_e$'s, which corresponds to oscillations (for 2 neutrino fit) on the order of $\Delta m^2 \sim 1\ eV^2$ (3.8 σ)

- Not consistent with known mass splittings!





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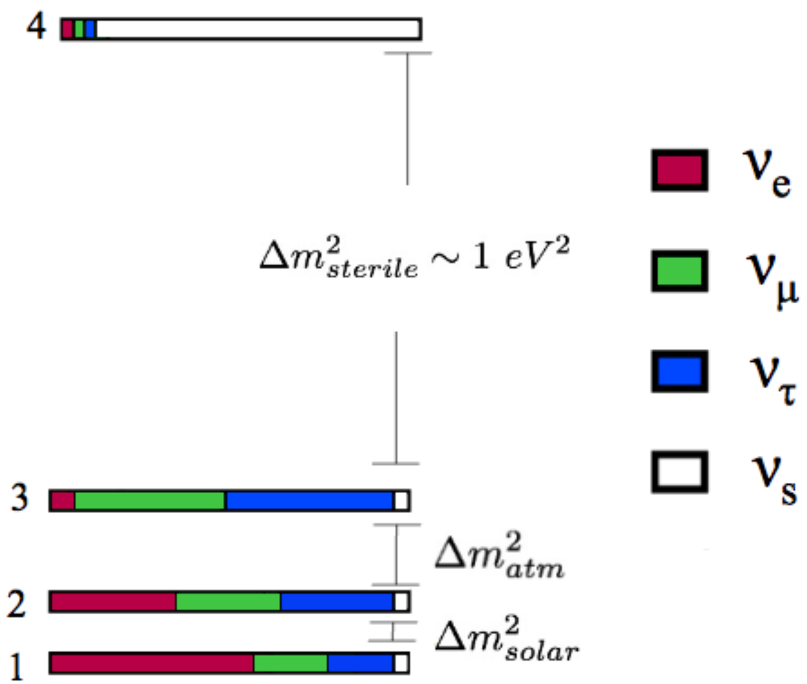
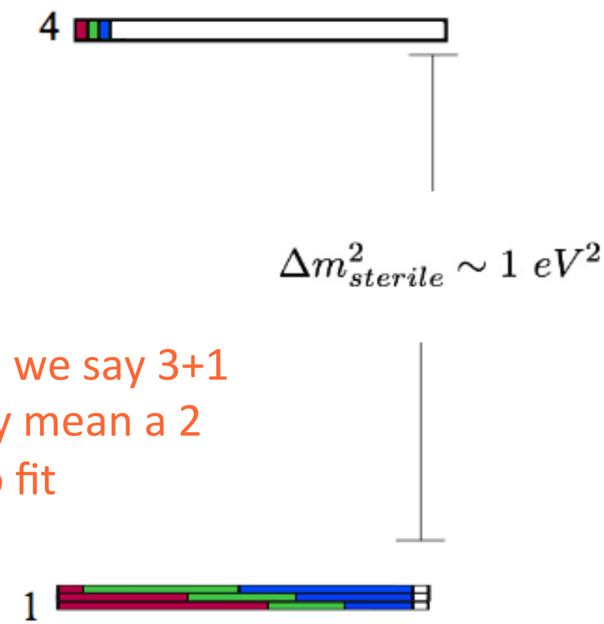
3+1 Model

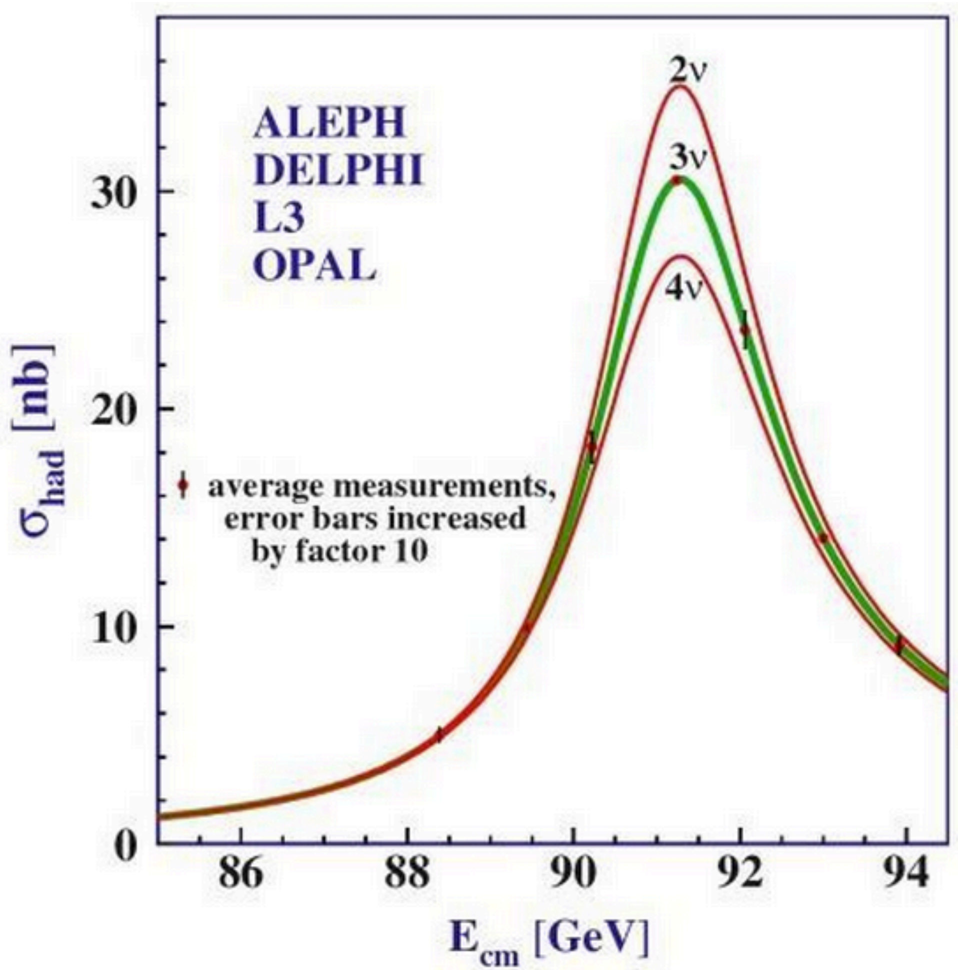
- Assume one more neutrino that doesn't interact through the weak force but can still oscillate with other neutrinos
- Assume $\Delta m^2_{sterile} \gg \Delta m^2_{atm}$ and Δm^2_{solar} so only fit to one Δm^2 and one mixing parameter per experiment.



So when we say 3+1 we really mean a 2 neutrino fit



Why "Sterile"?



$$e^+ + e^- \to Z \to f\bar{f}$$

$$N_\nu = 2.9840 \pm 0.0082$$

# of weakly interacting neutrino flavors

3+1 Model Fit Parameters:

Oscillation Probabilities:

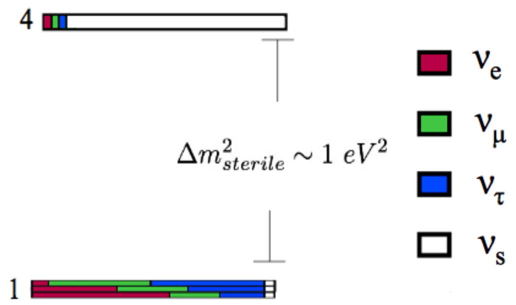
Appearance: $P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\theta_{\alpha\beta} \sin^2(1.27\Delta m^2 \frac{L}{E})$

Disappearance: $P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2(1.27\Delta m^2 \frac{L}{E})$

$$\sin^2 2\theta_{\mu e} = 4U_{e4}^2 U_{\mu 4}^2$$

$$\sin^2 2\theta_{\mu\mu} = 4U_{\mu 4}^2(1 - U_{\mu 4}^2)$$

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



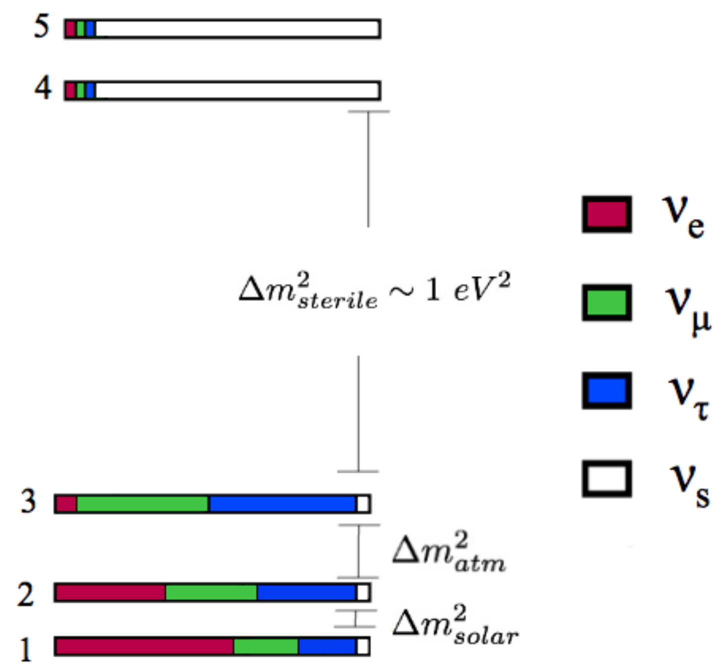
3+1 Fit parameters: $\Delta m^2_{41}, |U_{\mu 4}|,$ and $|U_{e4}|$

3+2 model

$$\Delta m^2_{51} \geq \Delta m^2_{41} \gg \Delta m^2_{atm}$$

The 3 original mass eigenstates remain degenerate so now we are doing a 3 neutrino fit

7 parameters: $\Delta m^2_{41}, \Delta m^2_{51}, U_{\mu 4}, U_{e4}, U_{\mu 5}, U_{e5}, \Phi_{45}$



Disappearance: $$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \frac{1.27\Delta m^2_{41} L}{E} + |U_{\alpha 5}|^2 \sin^2 \frac{1.27\Delta m^2_{51} L}{E}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \frac{1.27\Delta m^2_{54} L}{E}]$$

"- " for $\bar{\nu}$

Appearance: $$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \frac{1.27\Delta m^2_{41} L}{E} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 \frac{1.27\Delta m^2_{51} L}{E} + 8|U_{\alpha 4}||U_{\beta 4}||U_{\alpha 5}||U_{\beta 5}| \sin \frac{1.27\Delta m^2_{41} L}{E} \sin \frac{1.27\Delta m^2_{51} L}{E} \cos(\frac{1.27\Delta m^2_{54} L}{E} + \phi_{45})$$

3+3 Model (new for arxiv:1207.4765)

- 3rd mostly sterile state, Introduce $\Delta m^2_{61}, U_{\mu 6}, U_{e6}, \Phi_{46}, \Phi_{56}$
- 12 total parameters

Appearance:

$$\begin{aligned}
P(\nu_\alpha \to \nu_\beta) \simeq & -4|U_{\alpha5}||U_{\beta5}||U_{\alpha4}||U_{\beta4}|\cos\phi_{54}\sin^2(1.27\Delta m^2_{54}L/E) \\
& -4|U_{\alpha6}||U_{\beta6}||U_{\alpha4}||U_{\beta4}|\cos\phi_{64}\sin^2(1.27\Delta m^2_{64}L/E) \\
& -4|U_{\alpha5}||U_{\beta5}||U_{\alpha6}||U_{\beta6}|\cos\phi_{65}\sin^2(1.27\Delta m^2_{65}L/E) \\
& +4(|U_{\alpha4}||U_{\beta4}| + |U_{\alpha5}||U_{\beta5}|\cos\phi_{54} + |U_{\alpha6}||U_{\beta6}|\cos\phi_{64})|U_{\alpha4}||U_{\beta4}|\sin^2(1.27\Delta m^2_{41}L/E) \\
& +4(|U_{\alpha4}||U_{\beta4}|\cos\phi_{54} + |U_{\alpha5}||U_{\beta5}| + |U_{\alpha6}||U_{\beta6}|\cos\phi_{65})|U_{\alpha5}||U_{\beta5}|\sin^2(1.27\Delta m^2_{51}L/E) \\
& +4(|U_{\alpha4}||U_{\beta4}|\cos\phi_{64} + |U_{\alpha5}||U_{\beta5}|\cos\phi_{65} + |U_{\alpha6}||U_{\beta6}|)|U_{\alpha6}||U_{\beta6}|\sin^2(1.27\Delta m^2_{61}L/E) \\
& +2|U_{\beta5}||U_{\alpha5}||U_{\beta4}||U_{\alpha4}|\sin\phi_{54}\sin(2.53\Delta m^2_{54}L/E) \\
& +2|U_{\beta6}||U_{\alpha6}||U_{\beta4}||U_{\alpha4}|\sin\phi_{64}\sin(2.53\Delta m^2_{64}L/E) \\
& +2|U_{\beta6}||U_{\alpha6}||U_{\beta5}||U_{\alpha5}|\sin\phi_{65}\sin(2.53\Delta m^2_{65}L/E) \\
& +2(|U_{\alpha5}||U_{\beta5}|\sin\phi_{54} + |U_{\alpha6}||U_{\beta6}|\sin\phi_{64})|U_{\alpha4}||U_{\beta4}|\sin(2.53\Delta m^2_{41}L/E) \\
& +2(-|U_{\alpha4}||U_{\beta4}|\sin\phi_{54} + |U_{\alpha6}||U_{\beta6}|\sin\phi_{65})|U_{\alpha5}||U_{\beta5}|\sin(2.53\Delta m^2_{51}L/E) \\
& +2(-|U_{\alpha4}||U_{\beta4}|\sin\phi_{64} - |U_{\alpha5}||U_{\beta5}|\sin\phi_{65})|U_{\alpha6}||U_{\beta6}|\sin(2.53\Delta m^2_{61}L/E)\ .
\end{aligned}$$

Disappearance:

$$\begin{aligned}
P(\nu_\alpha \to \nu_\alpha) \simeq & \ 1 - 4|U_{\alpha4}|^2|U_{\alpha5}|^2\sin^2(1.27\Delta m^2_{54}L/E) \\
& -4|U_{\alpha4}|^2|U_{\alpha6}|^2\sin^2(1.27\Delta m^2_{64}L/E) - 4|U_{\alpha5}|^2|U_{\alpha6}|^2\sin^2(1.27\Delta m^2_{65}L/E) \\
& -4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2 - |U_{\alpha6}|^2)(|U_{\alpha4}|^2\sin^2(1.27\Delta m^2_{41}L/E) \\
& +|U_{\alpha5}|^2\sin^2(1.27\Delta m^2_{51}L/E) + |U_{\alpha6}|^2\sin^2(1.27\Delta m^2_{61}L/E))\ .
\end{aligned}$$

Other Recent Anomalies

OK, LSND motivated introducing sterile neutrinos… is there any other data to back this up?

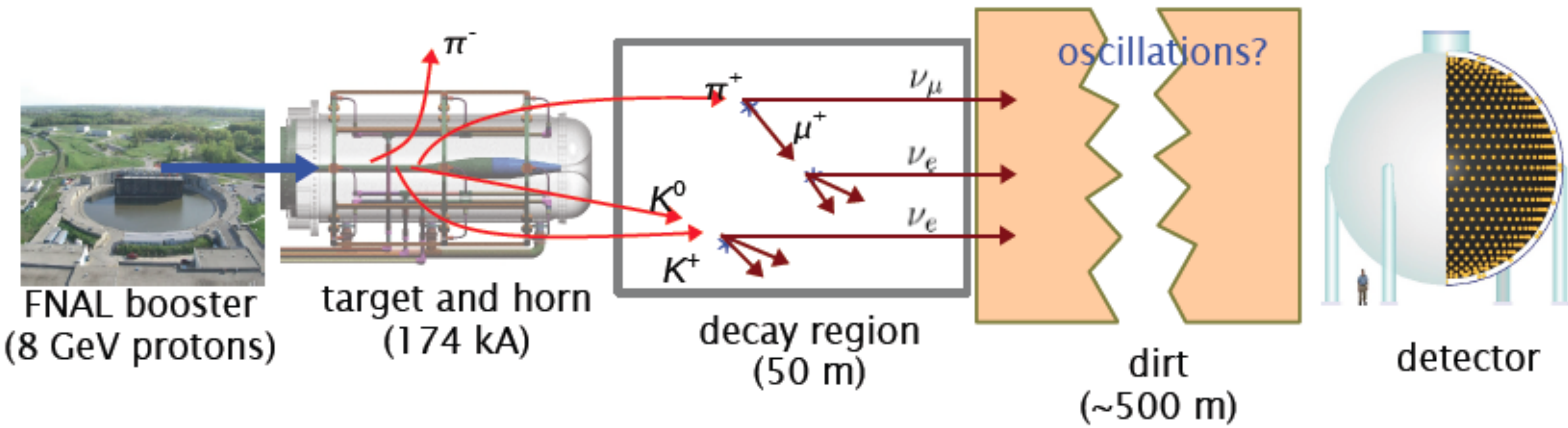
Lets especially look at:

- MiniBooNE
- Reactor antineutrino anomaly
- Gallium

- Constraints from other experiments
  (not everyone sees an anomaly!)

MiniBooNE

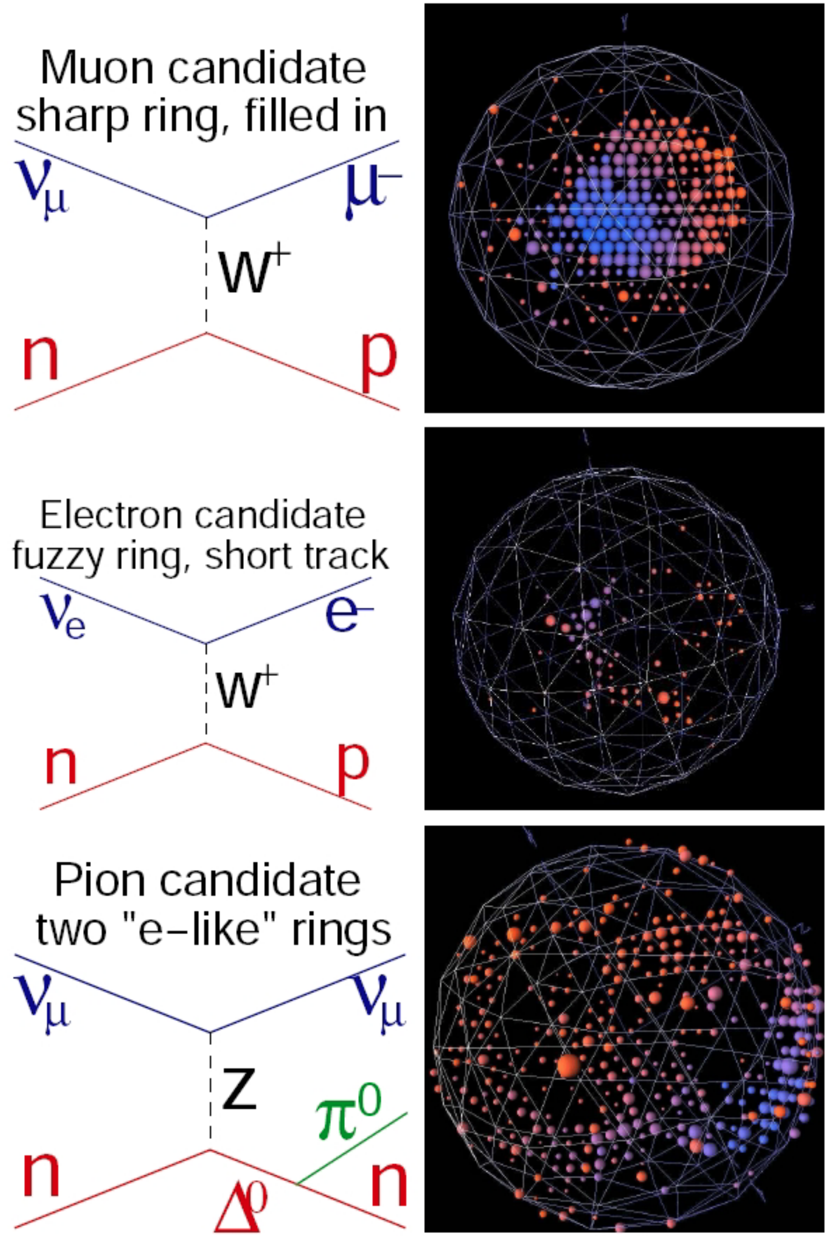
- Designed to explore LSND anomaly (similar L/E)
  - Different detector design and systematics
  - Can run in neutrino or antineutrino mode by choosing positive or negative mesons with a focusing horn



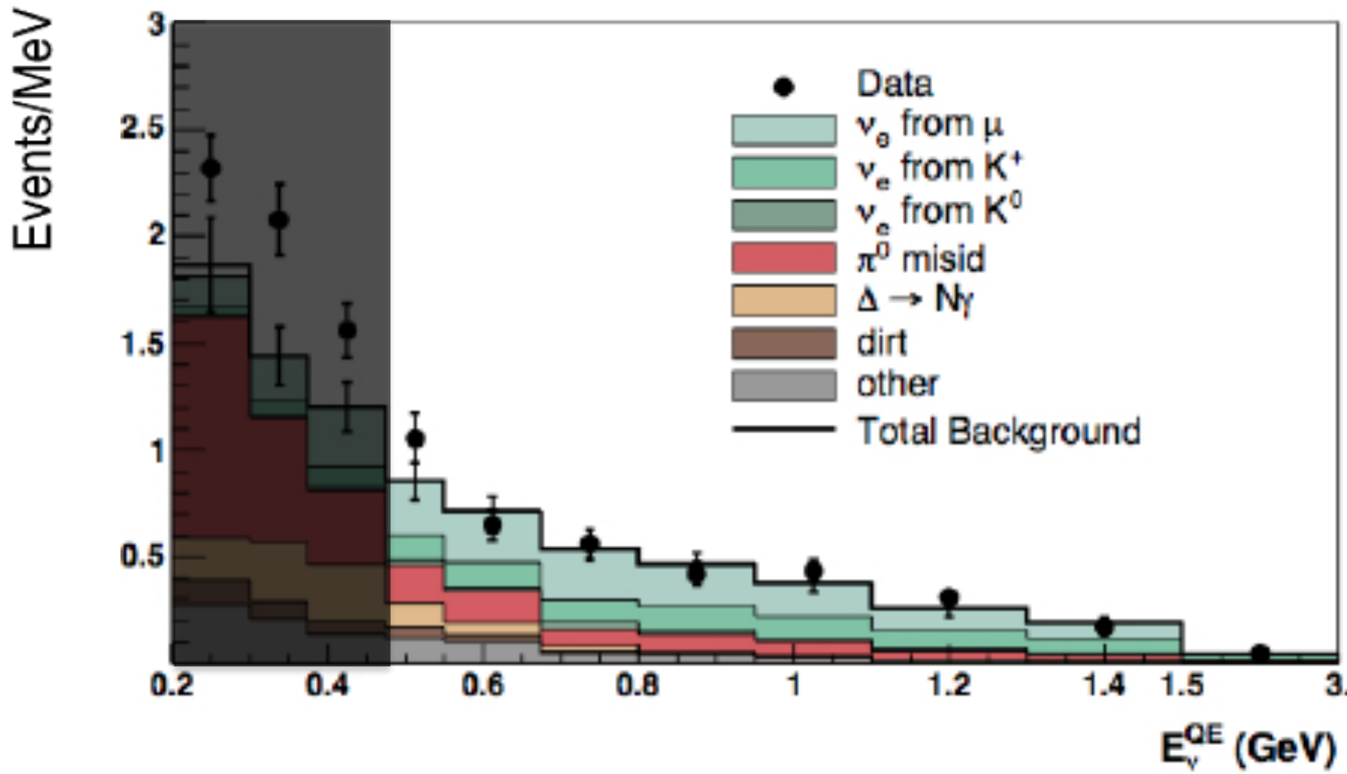
MiniBooNE

- Cherenkov Detector
  - Detects Cherenkov rings created by charged particles

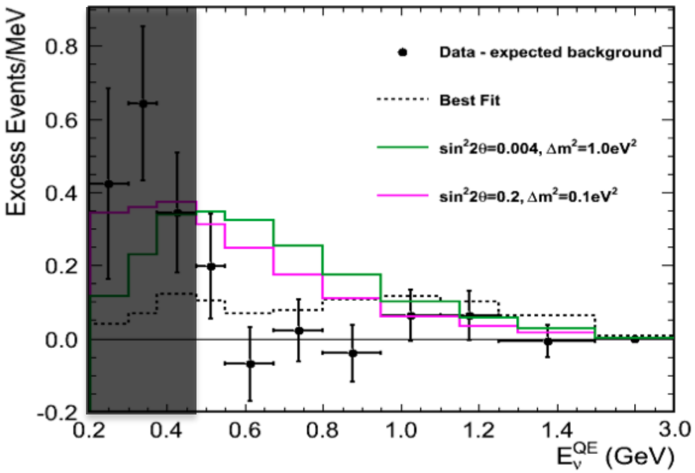
- Main sources of background from intrinsic ν_e in the beam and mis ID $(\gamma \to e^+e^-)$ from $\pi^0 \to \gamma\gamma, \Delta \to N\gamma$

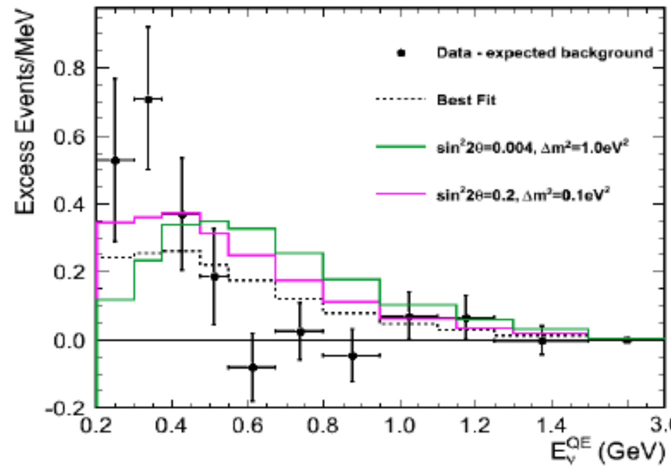


MiniBooNE ν mode

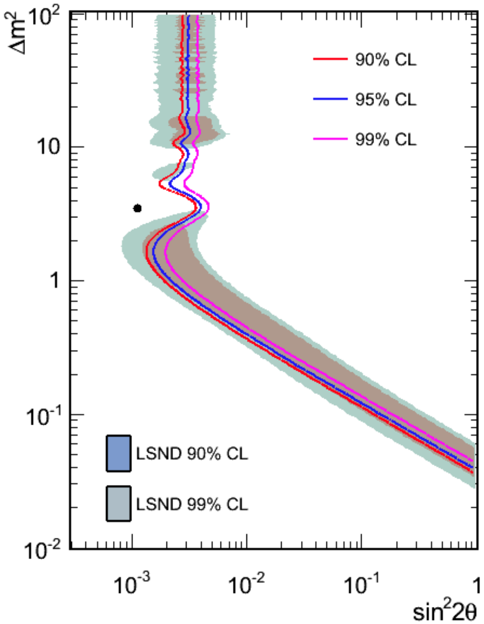


MiniBooNE ν mode

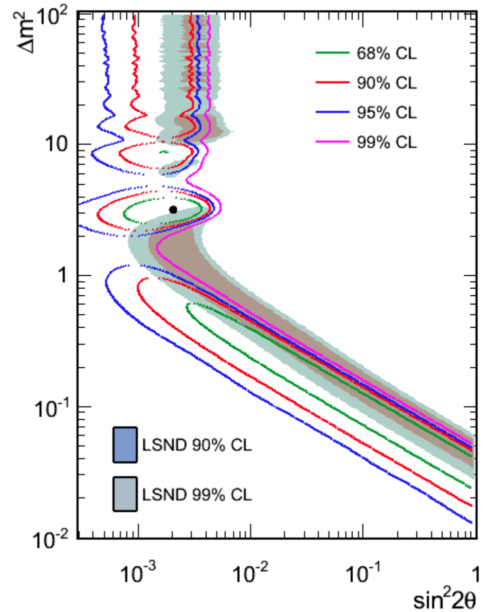




E > 475 MeV



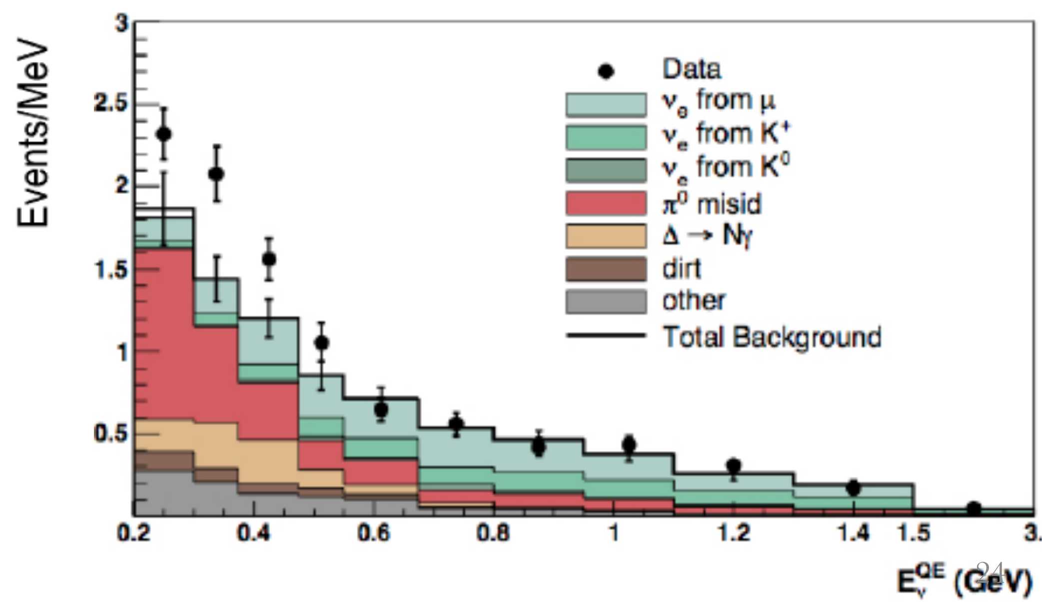
E > 200 MeV



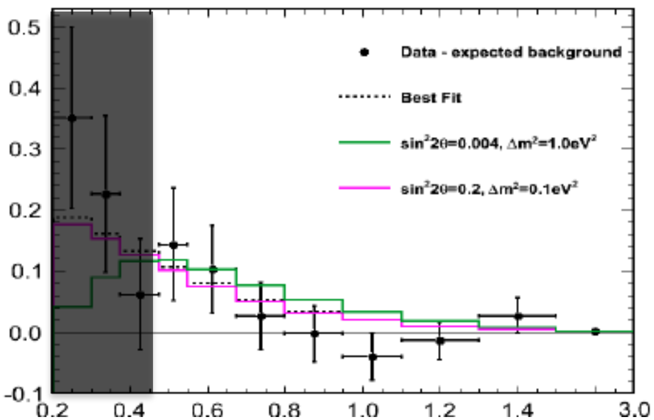
	E > 475	E > 200
χ^2 (null)	6.35	22.81
P (null)	36.6%	0.5%
χ^2 (bf)	3.73	13.24
P (bf)	42.0%	6.12%

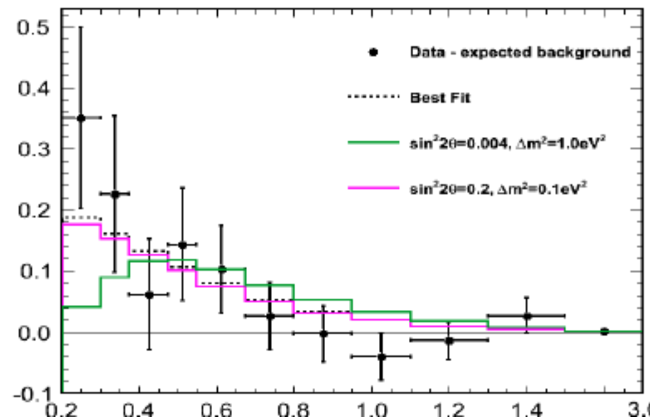
Low energy excess

- Still unexplained
- Not a statistical fluctuation (6σ)
- Unlikely intrinsic ν_e (low bg here)
- NC π_0 bg dominates
  - Constrained by NC π_0 direct measurements
- Δ-> Nγ rate tied to NC π_0 rate
  - Theoretical calculations agree within 20%

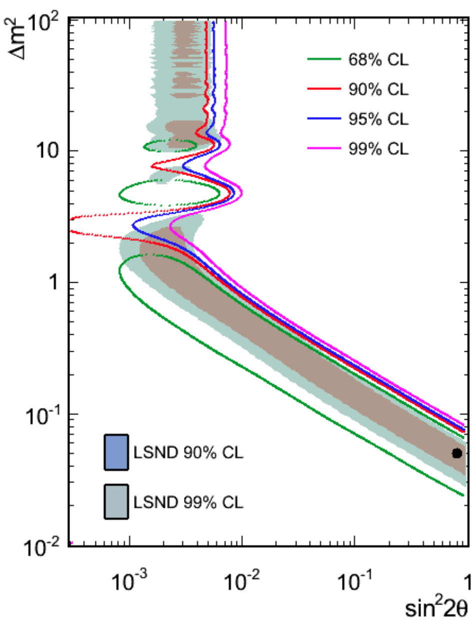


MiniBooNE $\bar{\nu}$ mode



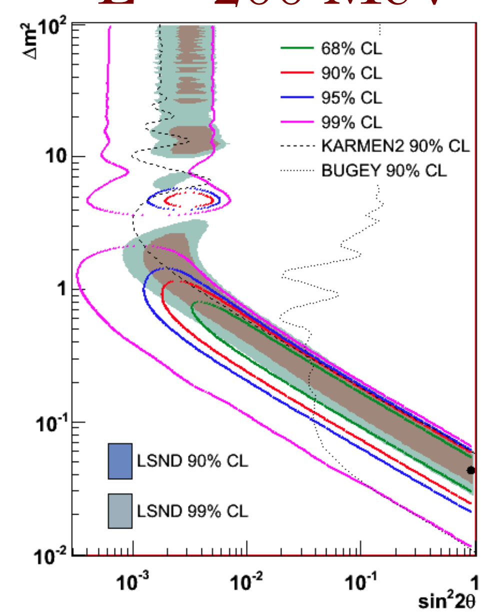


E > 475 MeV

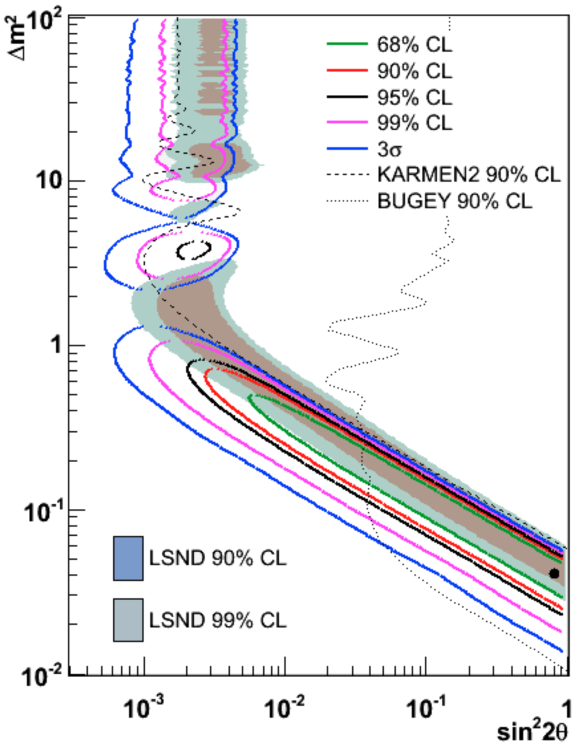


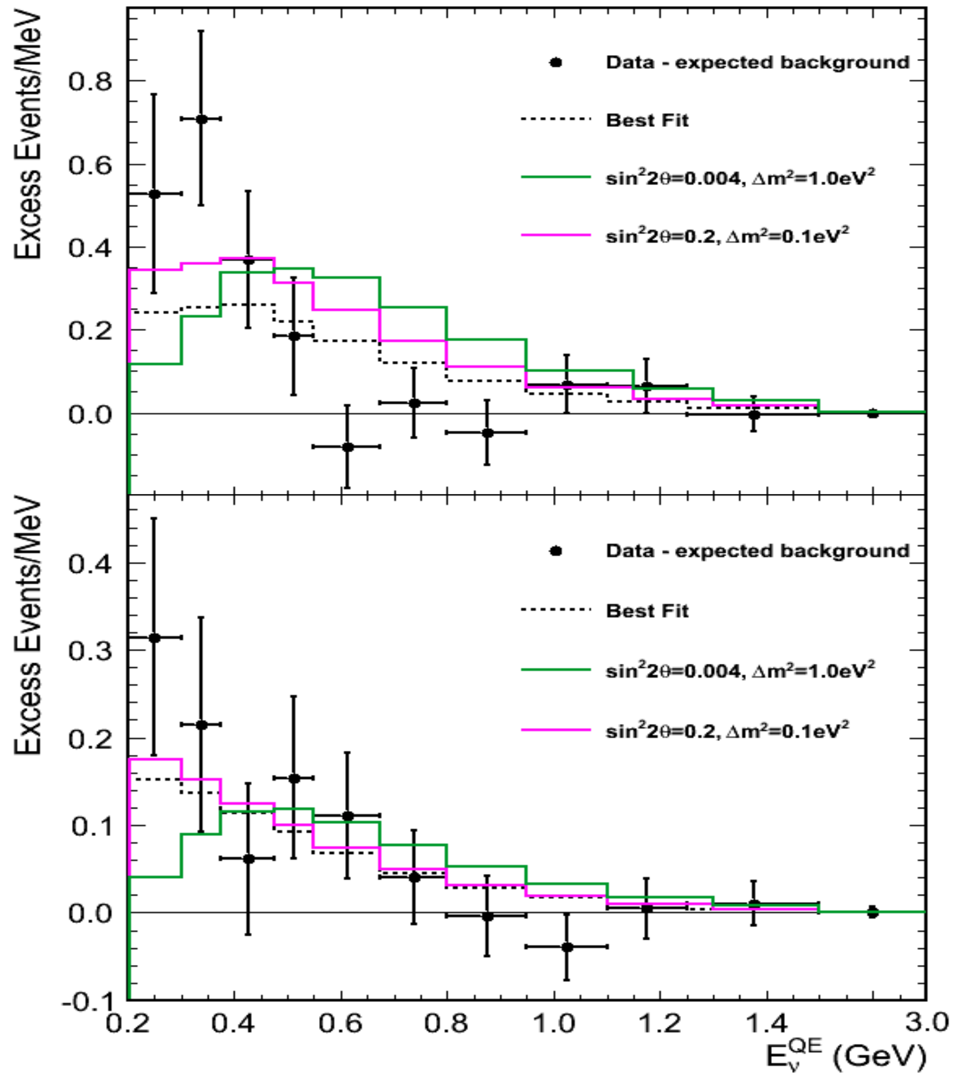
	E > 475	E > 200
χ^2 (null)	7.59	16.3
P (null)	26.4%	5.8%
χ^2 (bf)	3.23	4.76
P (bf)	50.2%	67.5%

E > 200 MeV



MiniBooNE Combined Fit

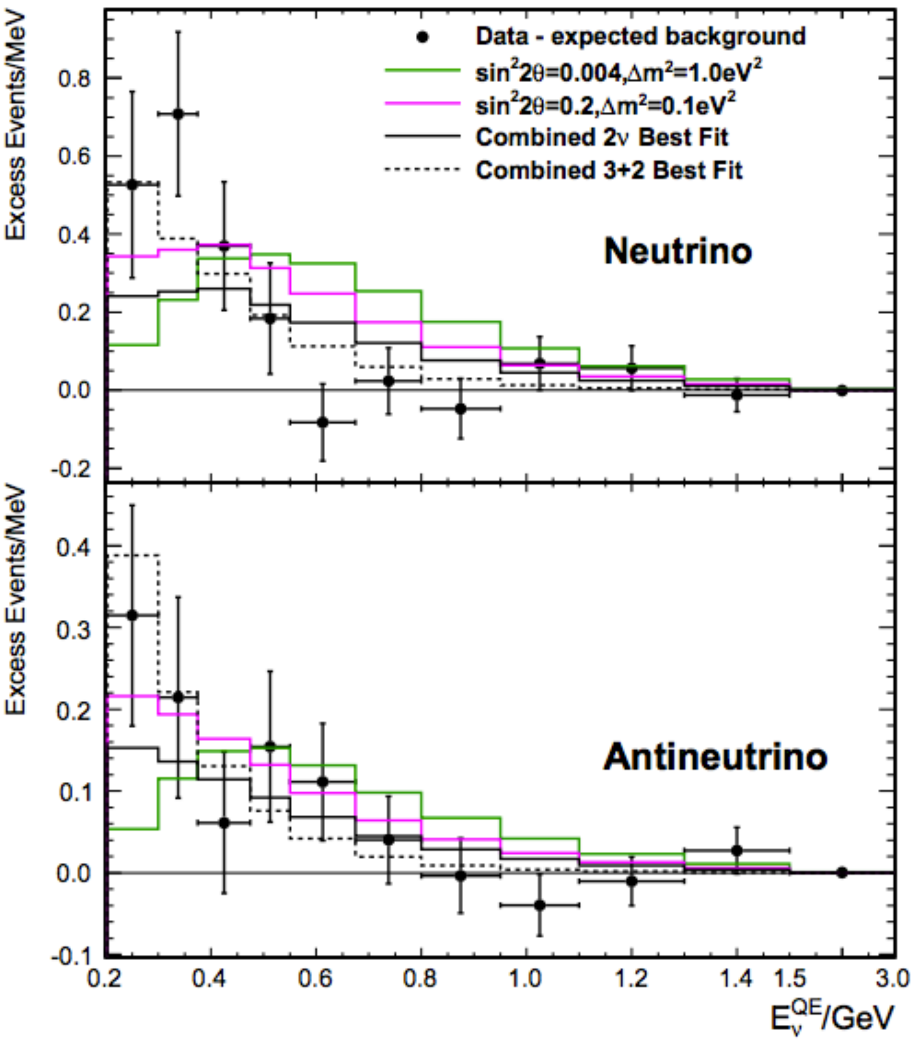




	E > 475	E > 200
χ^2 (null)	12.87	42.53
P (null)	35.8%	0.1%
χ^2 (bf)	10.67	24.72
P (bf)	35.8%	6.7%

3+2 combined fit

- CP violation allows for difference between neutrinos and antineutrinos
- Much better fit than 3+1
- No ν_e or ν_μ disappearance constraints
  - Limited value outside of a global picture



Only Antineutrinos need to match LSND!
(LSND was $\bar{\nu}$ only)

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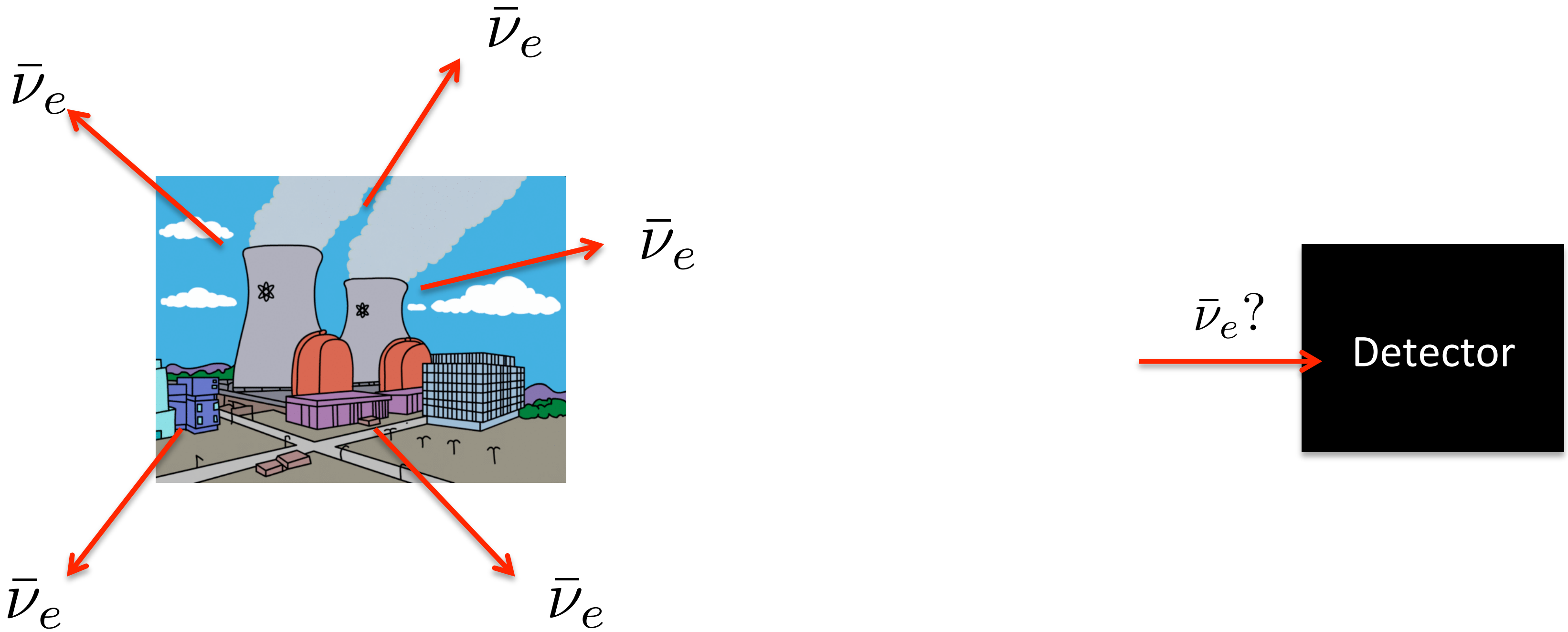
Reactor Anomaly

- Reactor experiments often used to measure neutrino mixing in a 3 neutrino scenario



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{ee} \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

Reactor Anomaly

How do you get the expected flux without a near detector?

Monte Carlo simulations: 2 components

- Fission rates

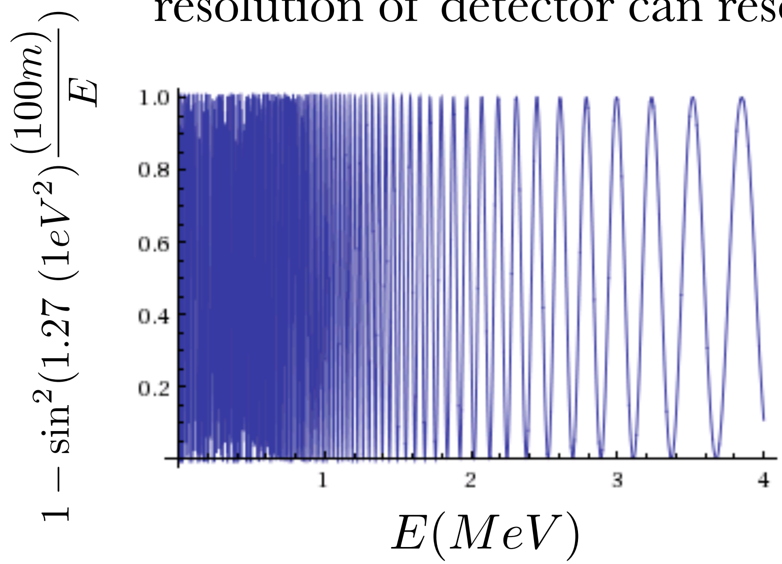
(which we know very well)

- Predicting neutrinos from fissions
  - This has changed recently! (arxiv:1101.2663) We have more information than we did ~30 years ago
- Raised the expected value of neutrino events
  - So now there is a deficit!

Reactor Anomaly

- What do oscillations look like in an experiment designed to look for much smaller mass splittings?

- Get fast oscillations: oscillations occur much more rapidly than energy resolution of detector can resolve

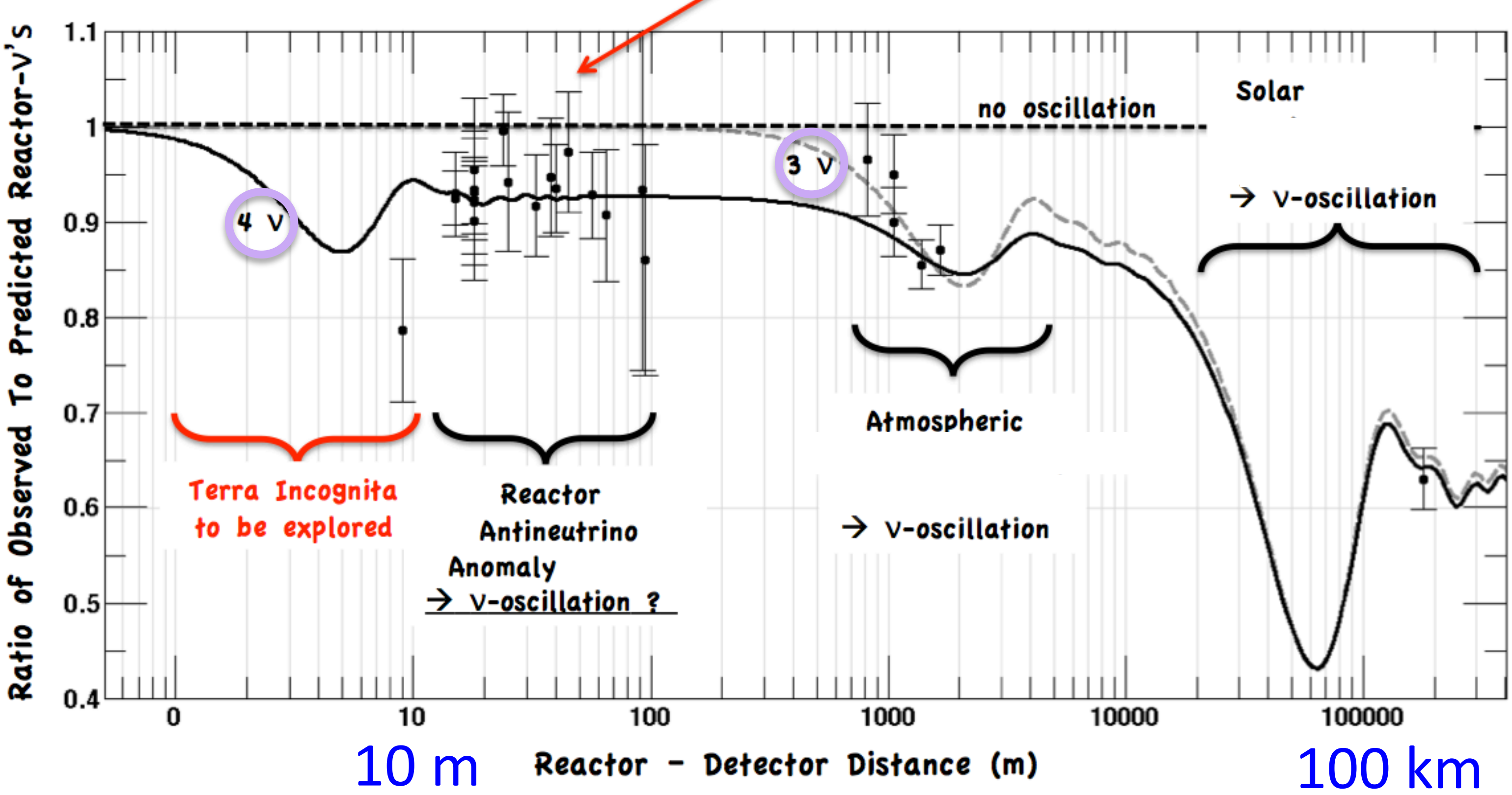


$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \underbrace{\sin^2(1.27\Delta m^2 \frac{L}{E})}_{1/2}$$

Get Deficit of events corresponding to ½ oscillation amplitude

Reactor Anomaly

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

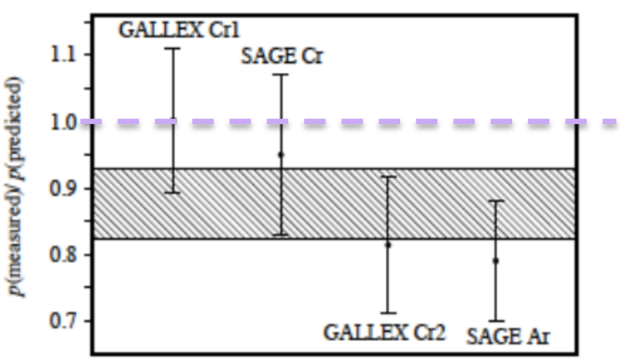


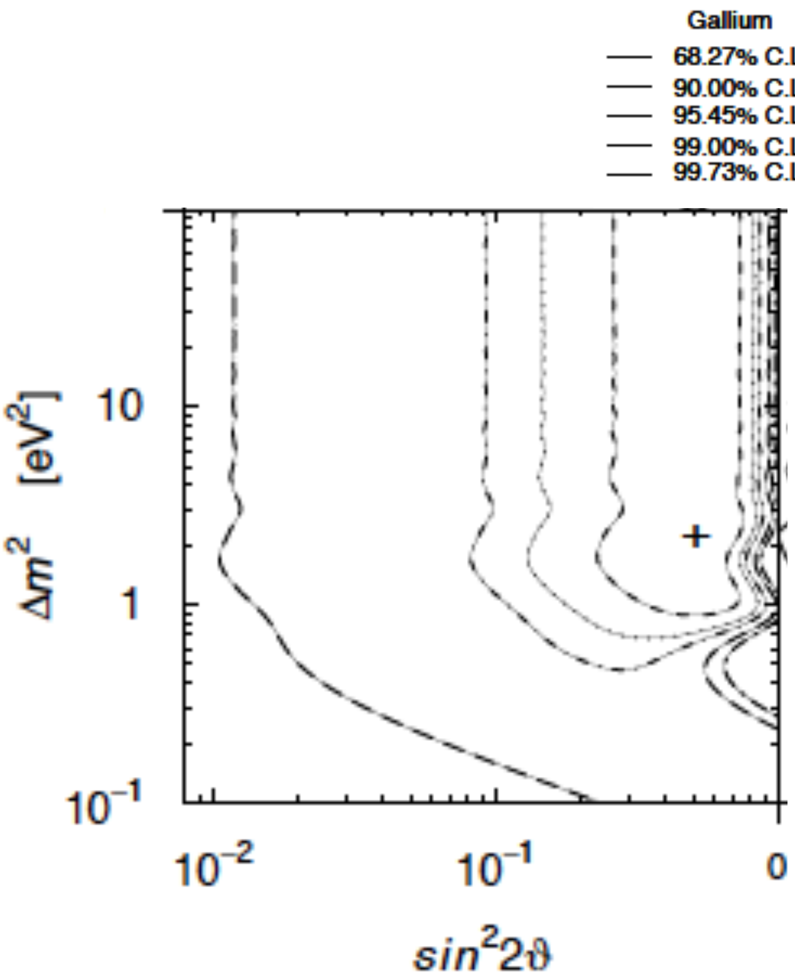
The addition of one or more sterile neutrinos could resolve this issue

Gallium anomaly

- Cr-51 and Ar-37 sources were used to calibrate the GALLEX and SAGE solar neutrino experiments
- Very short baseline (meter scale) so sensitive to ~1 eV^2 neutrino oscillation

$\nu_e \nrightarrow \nu_e$





arXiv:1006.3244

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Included data sets

ν_e and $\bar{\nu}_e$ Appearance:

LSND $\bar{\nu}_\mu \to \bar{\nu}_e$

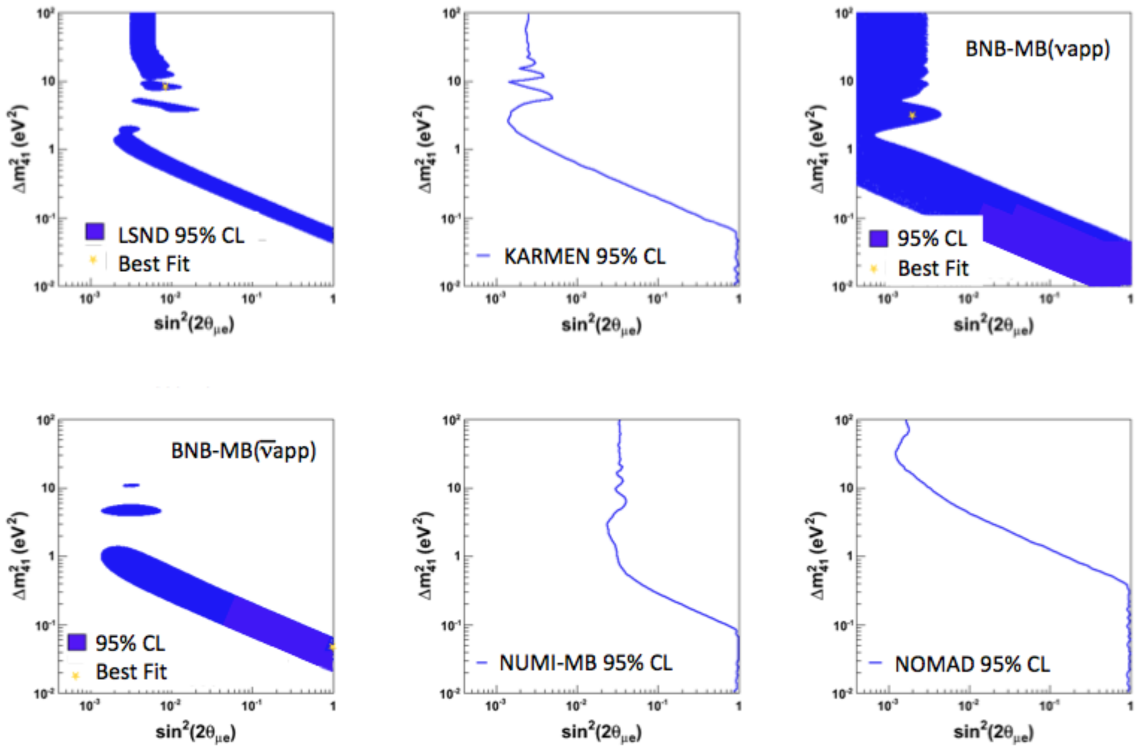
MiniBooNE $\nu_\mu \to \nu_e$

MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$

NOMAD $\nu_\mu \to \nu_e$

NuMI in MB $\nu_\mu \to \nu_e$

KARMEN $\bar{\nu}_\mu \to \bar{\nu}_e$



Included data sets

ν_μ and $\bar{\nu}_\mu$ Disappearance:

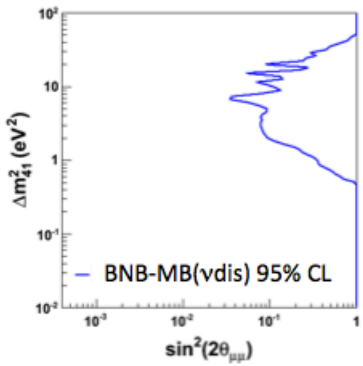
MiniBooNE $\nu_\mu \nrightarrow \nu_\mu$

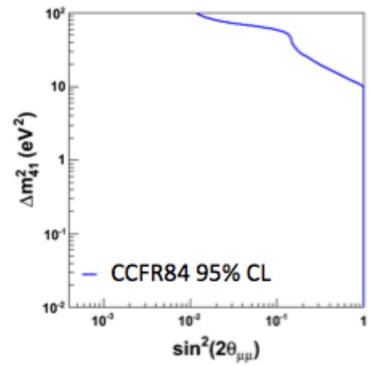
CCFR84 $\nu_\mu \nrightarrow \nu_\mu$

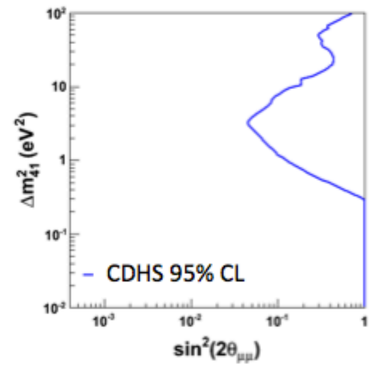
CDHS $\nu_\mu \nrightarrow \nu_\mu$

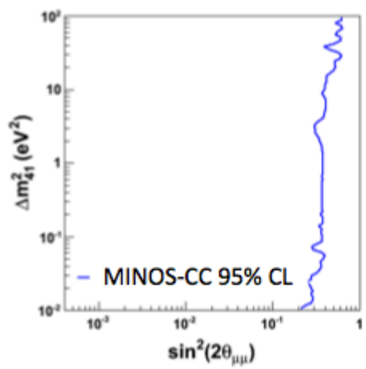
Atmospheric $\nu_\mu \nrightarrow \nu_\mu$

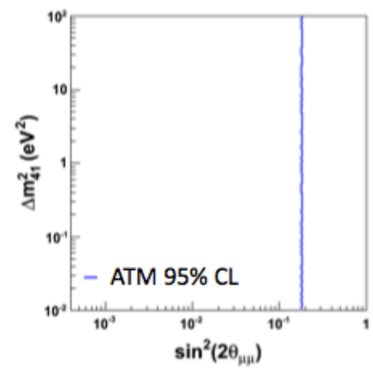
MINOS CC $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$











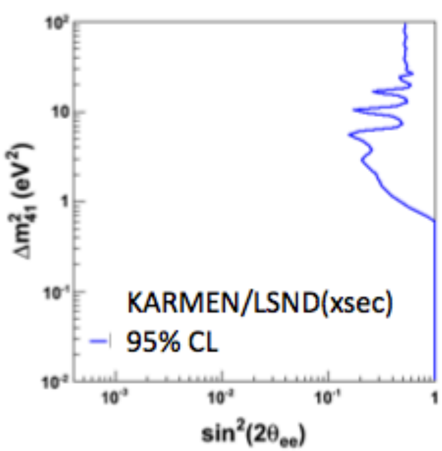
Included data sets

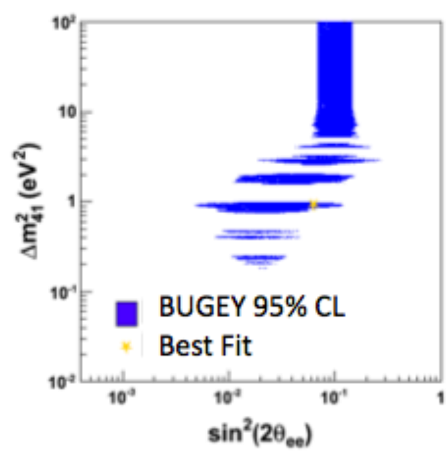
ν_e and $\bar{\nu}_e$ Disappearance:

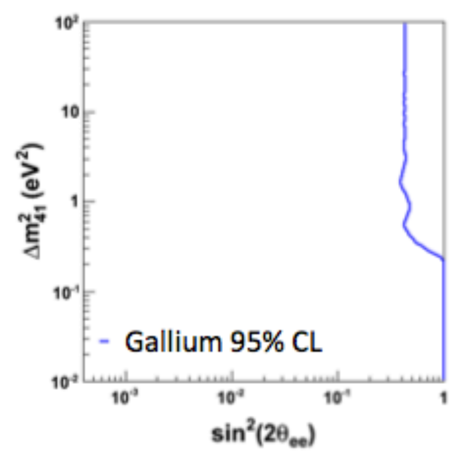
Bugey $\bar{\nu}_e \not\to \bar{\nu}_e$ (with new reactor fluxes)

Gallium $\nu_e \not\to \nu_e$

Karmen/LSND xsec $\nu_e \not\to \nu_e$



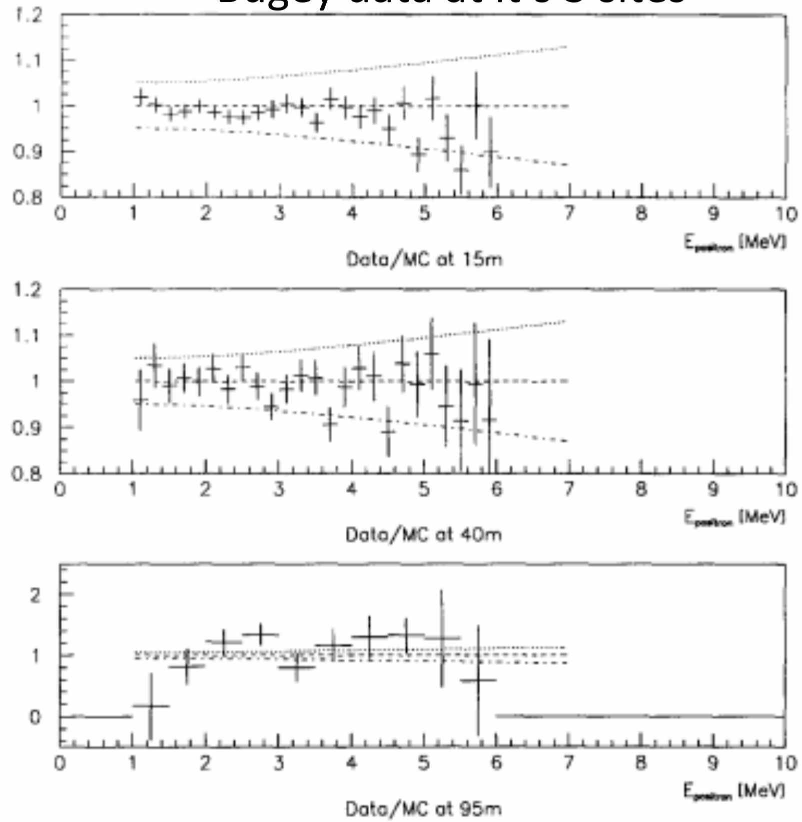




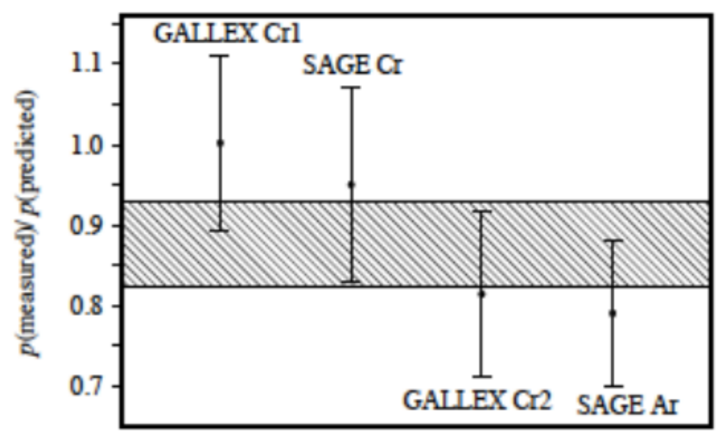
Problem with χ^2 in global fits

- Some experiments have 50 bins while others have 4…
- Treats all bins equally rather than all experiments equally
  - High bin experiments dominate χ^2

Bugey data at it's 3 sites



Gallex/Sage data



Parameter Goodness of Fit

Tests how well different sets of data agree with each other

$$PG = Prob(\chi^2_{PG}, ndf_{PG})$$

$$\chi^2_{PG} = \chi^2_{min,combined} - \sum_i \chi^2_{min,d}$$

i runs over datasets

$$ndf_{PG} = \sum_d N_{p_d} - N_{p_{combined}}$$

Independent parameters per dataset

Independent parameters in global fit

Reference: M. Maltoni and T. Schwetz 2003 arXiv:hep-ph/0304176

Parameter Goodness of Fit

Tests how well different sets of data agree with each other

Ex. $\nu \ vs \ \bar{\nu}$ for 3+1 fit

$$\chi^2_{PG}(\nu \ vs \ \bar{\nu}) = \boxed{\chi^2_{min}(all)} - \boxed{\chi^2_{min}(\nu)} - \boxed{\chi^2_{min}(\bar{\nu})}$$

χ^2 from global fit

χ^2 from fit to ν experiments only

χ^2 from fit to $\bar{\nu}$ experiments only

$$ndf_{PG}(\nu \ vs \ \bar{\nu}) = \boxed{3} + \boxed{3} - \boxed{3}$$

Parameters in ν 3+1 fit

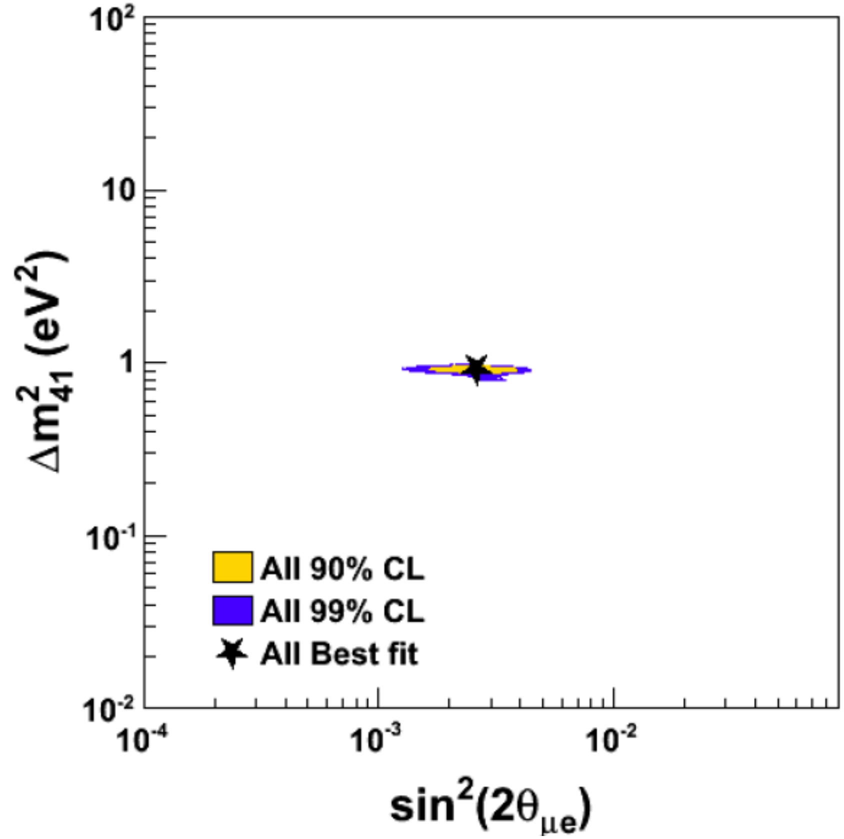
Parameters in $\bar{\nu}$ 3+1 fit

parameters in global 3+1 fit

3 parameters in each for this case: $\Delta m^2_{41}, U_{\mu 4},$ and U_{e4}

- Introduction
- Motivation for sterile neutrinos: LSND
- Sterile neutrino phenomenology
- MiniBooNE (arxiv:1207.4809)
- Other recent anomalies
- Constraints from other experiments
- Global Fits (arxiv:1207.4765)
- Future

3+1 Global Fit



χ^2_{bf} (dof)	χ^2_{null} (dof)	P_{bf}	P_{null}
233.9 (237)	286.5 (240)	55%	2.1%

Subsets of data

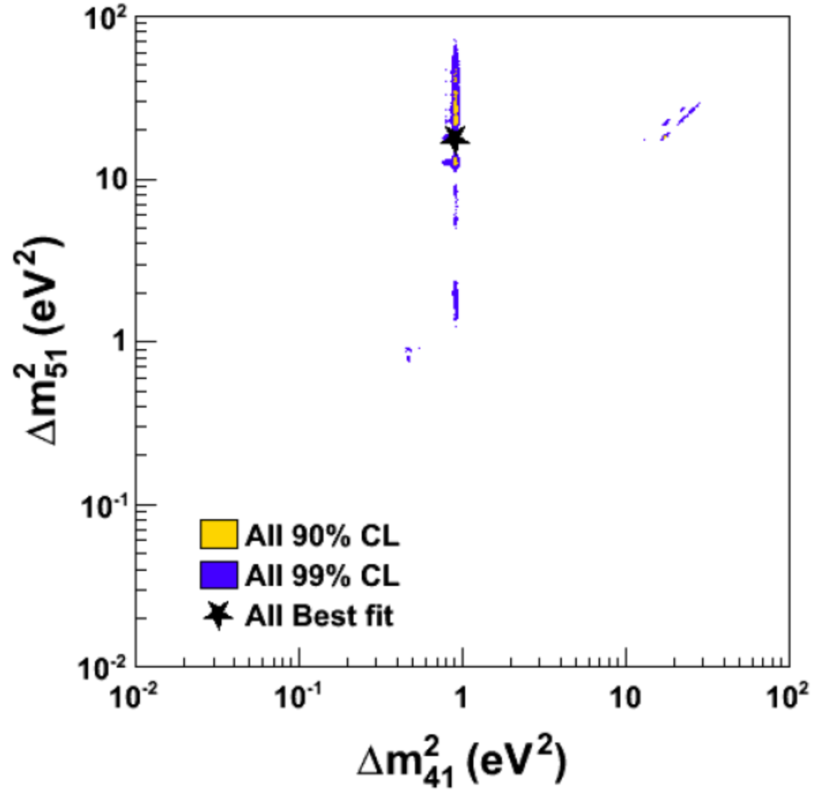
	χ^2_{min} (dof)	P_{best}	χ^2_{null} (dof)	P_{null}
3+1				
All	233.9 (237)	55%	286.5 (240)	2.1%
App	87.8 (87)	46%	147.3 (90)	0.013%
Dis	128.2 (147)	87%	139.3 (150)	72%
ν	123.5 (120)	39%	133.4 (123)	25%
$\overline{\nu}$	94.8 (114)	90%	153.1 (117)	1.4%

	χ^2_{PG} (dof)	PG (%)
App vs. Dis	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	15.6 (3)	0.14%

Best Fit Values

3+1	Δm^2_{41}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$
All	0.92	0.17	0.15

3+2 Global Fit



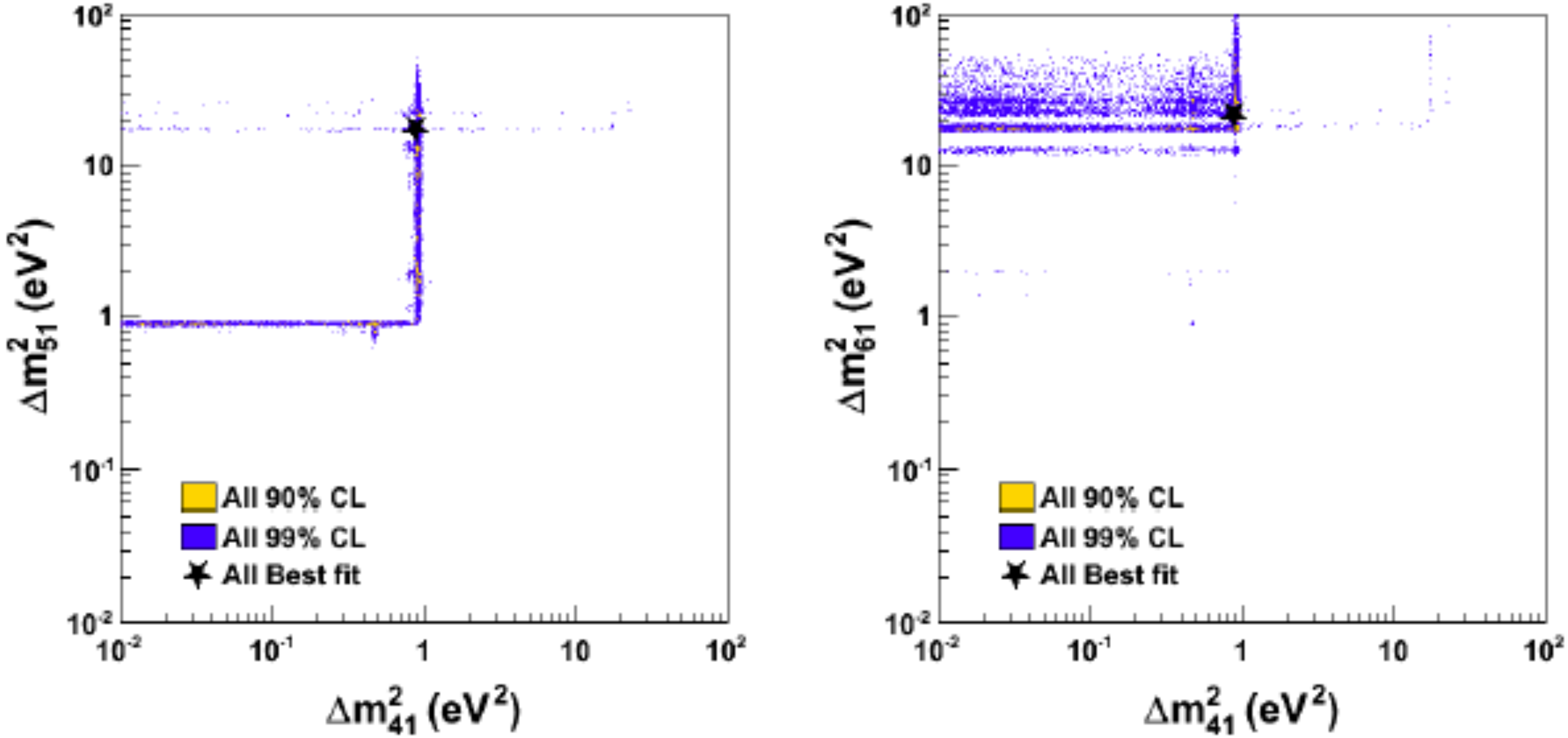
χ^2_{bf} (dof)	χ^2_{null} (dof)	P_{bf}	P_{null}
221.5 (233)	286.5 (240)	69%	2.1%

	χ^2_{min} (dof)	P_{best}
3+1		
All	233.9 (237)	55%
App	87.8 (87)	46%
Dis	128.2 (147)	87%
ν	123.5 (120)	39%
$\overline{\nu}$	94.8 (114)	90%
3+2		
All	221.5 (233)	69%
App	75.0 (85)	77%
Dis	122.6 (144)	90%
ν	116.8 (116)	77%
$\overline{\nu}$	90.8 (110)	90%

	χ^2_{PG} (dof)	PG (%)
3+1		
App vs. Dis	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	15.6 (3)	0.14%
3+2		
App vs. Dis	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	13.9 (7)	5.3%

3+2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	ϕ_{54}
All	0.92	17	0.13	0.15	0.16	0.069	1.8π

3+3 Global Fit



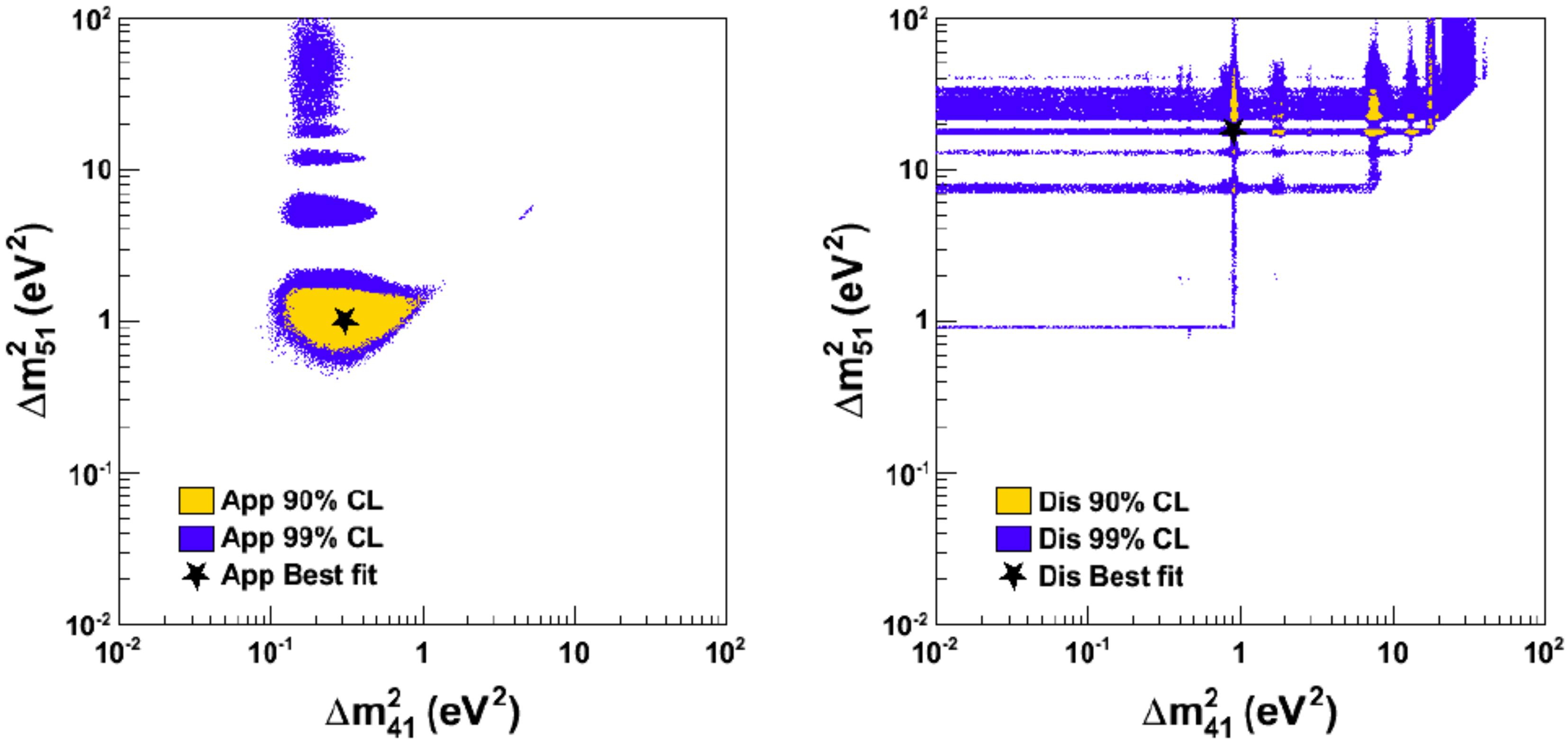
χ^2_{bf} (dof)	χ^2_{null} (dof)	P_{bf}	P_{null}
218.2 (228)	286.5 (240)	67%	2.1%

	χ^2_{min} (dof)	P_{best}
3+1		
All	233.9 (237)	55%
App	87.8 (87)	46%
Dis	128.2 (147)	87%
ν	123.5 (120)	39%
$\overline{\nu}$	94.8 (114)	90%
3+2		
All	221.5 (233)	69%
App	75.0 (85)	77%
Dis	122.6 (144)	90%
ν	116.8 (116)	77%
$\overline{\nu}$	90.8 (110)	90%
3+3		
All	218.2 (228)	67%
App	70.8 (81)	78%
Dis	120.3 (141)	90%
ν	116.7 (111)	34%
$\overline{\nu}$	90.6 (105)	84%

	χ^2_{PG} (dof)	PG (%)
App vs. Dis	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	15.6 (3)	0.14%
App vs. Dis	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	13.9 (7)	5.3%
App vs. Dis	27.1 (6)	0.014%
ν vs. $\overline{\nu}$	10.9 (12)	53%

Why Does App vs. Dis not get better?

3+2 fits (3+3 is similar)

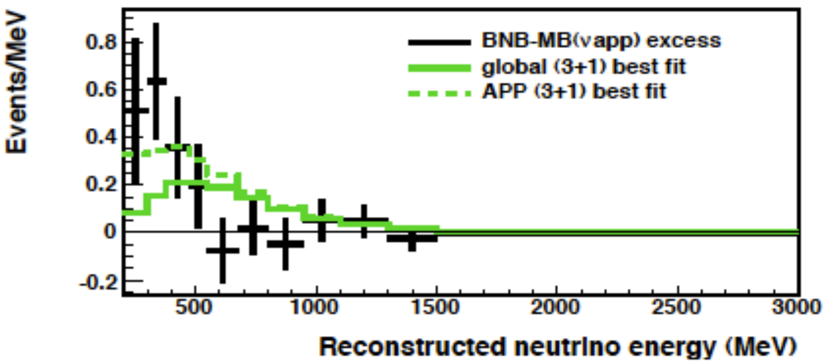


They are finding different best fit points…

It turns out the appearance fit is largely driven by MB

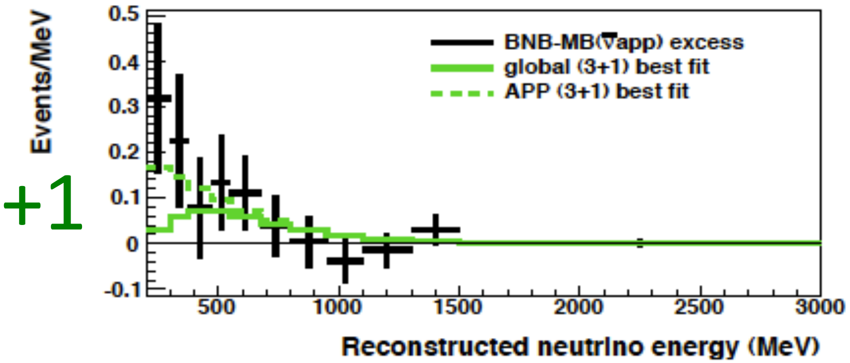
Does Not explain MiniBooNE low energy excess

ν

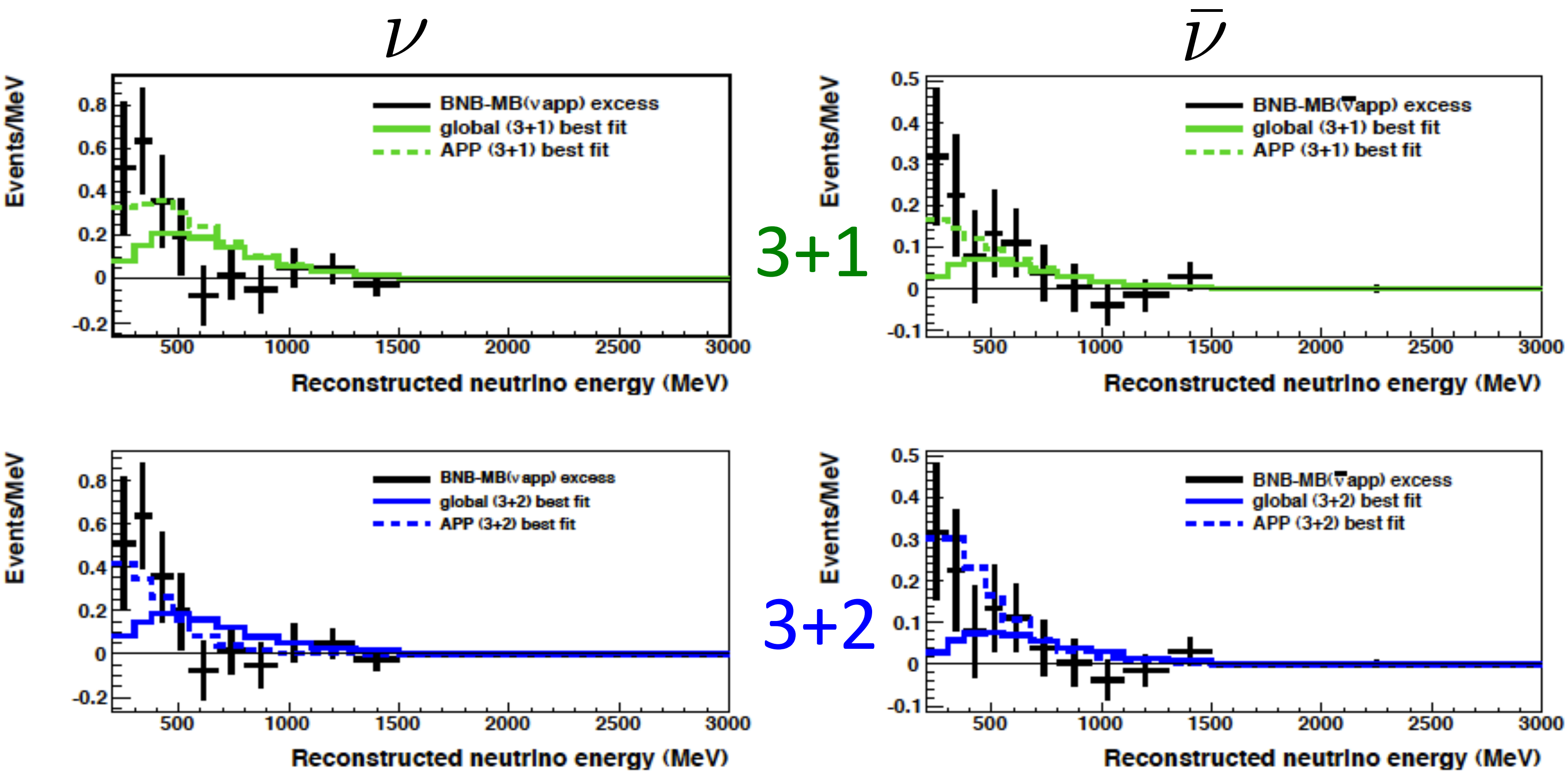


3+1

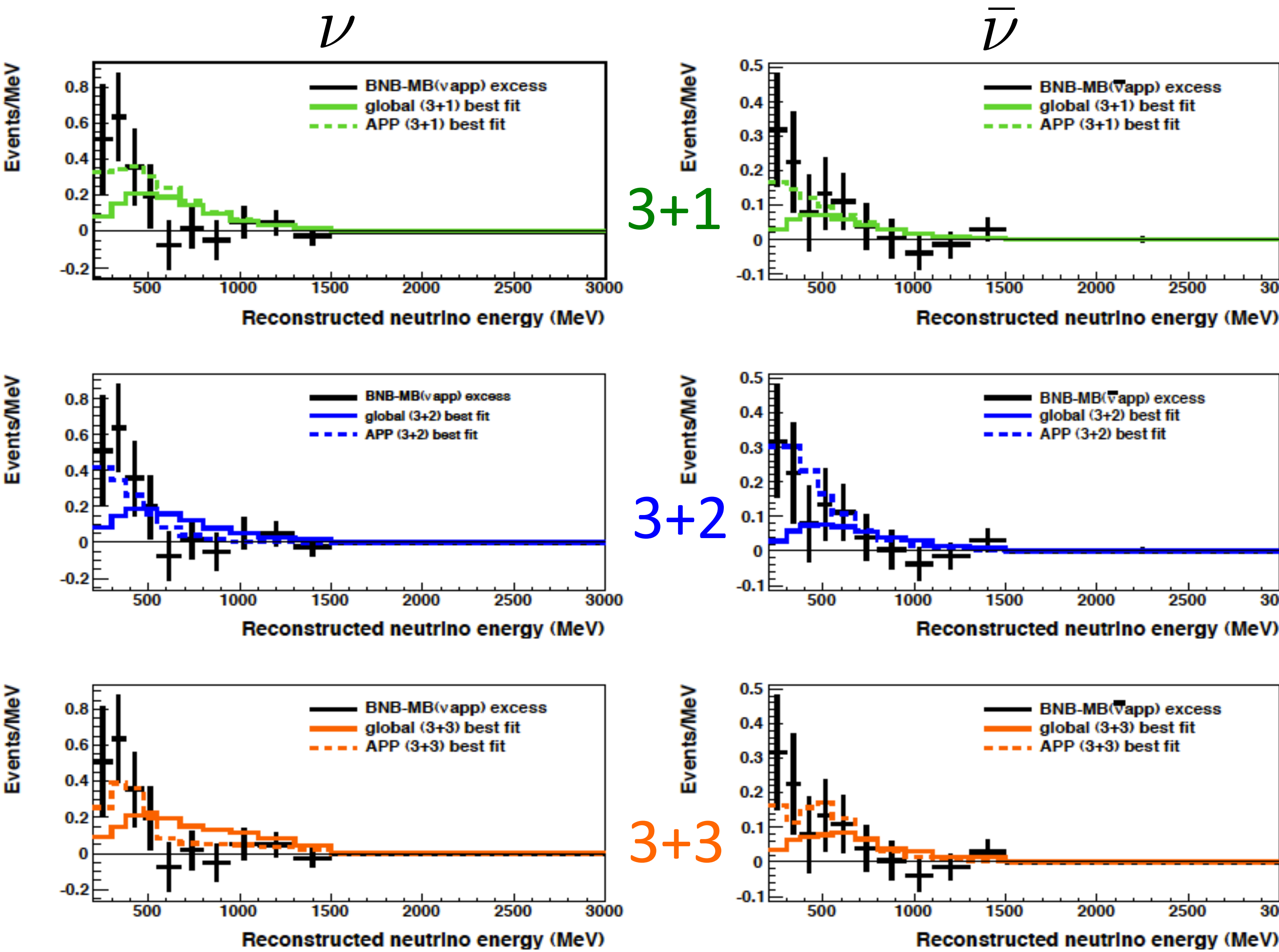
$\bar{\nu}$



Does Not explain MiniBooNE low energy excess



Does Not explain MiniBooNE low energy excess

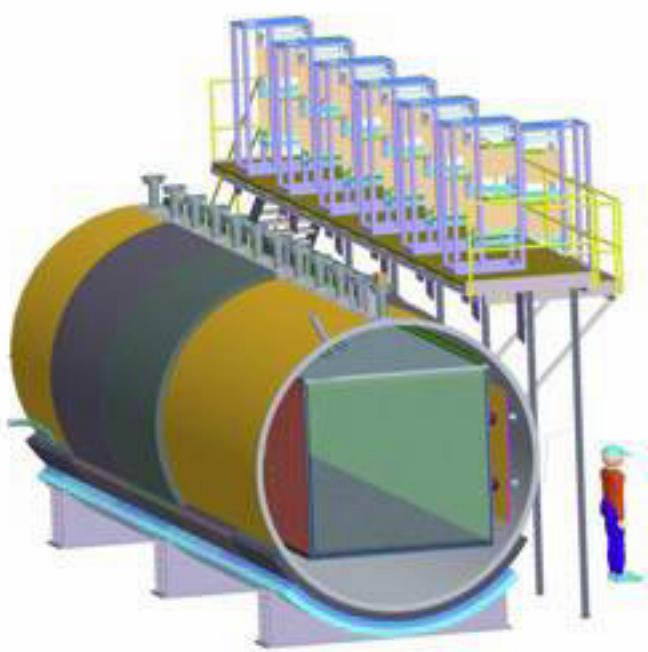


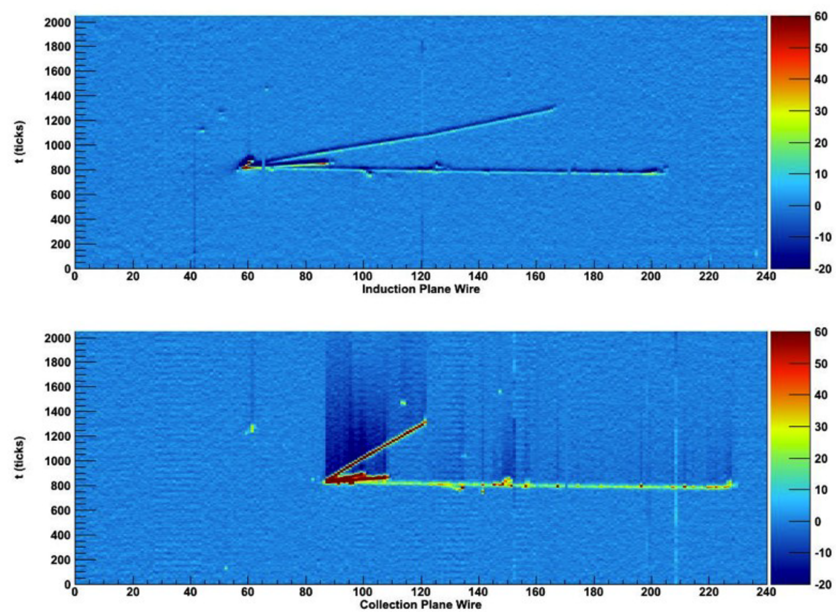
My predictions

- Not all of the MiniBooNE excess is from oscillations, some is from background, multinucleon effects, or some other unknown process
- There are at least 2 new Δm^2 parameters to differentiate

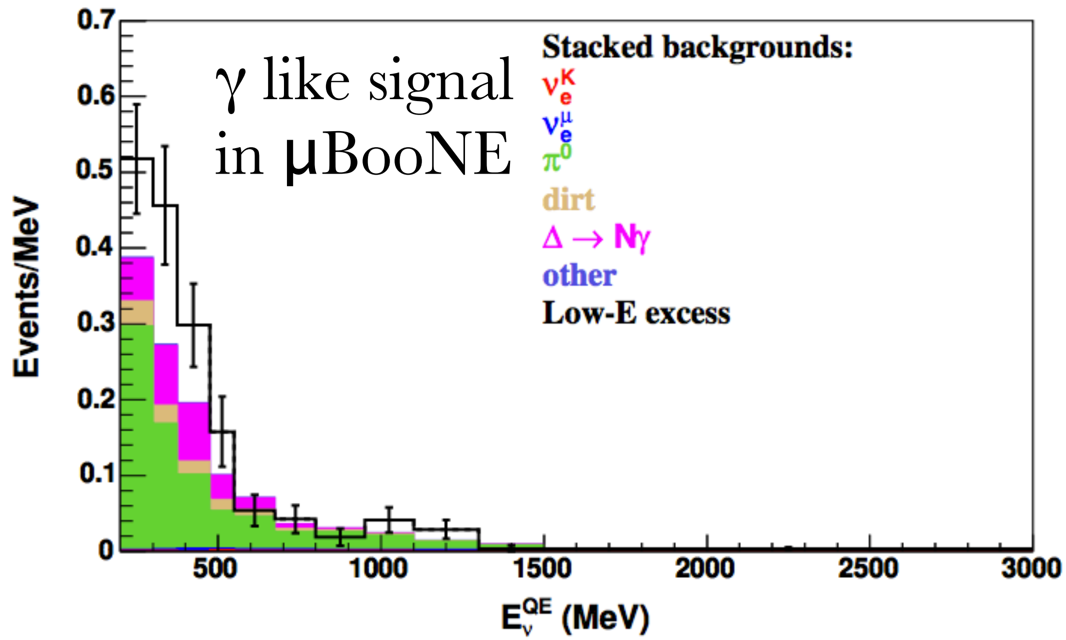
Can MicroBooNE explain MiniBooNE low energy excess?

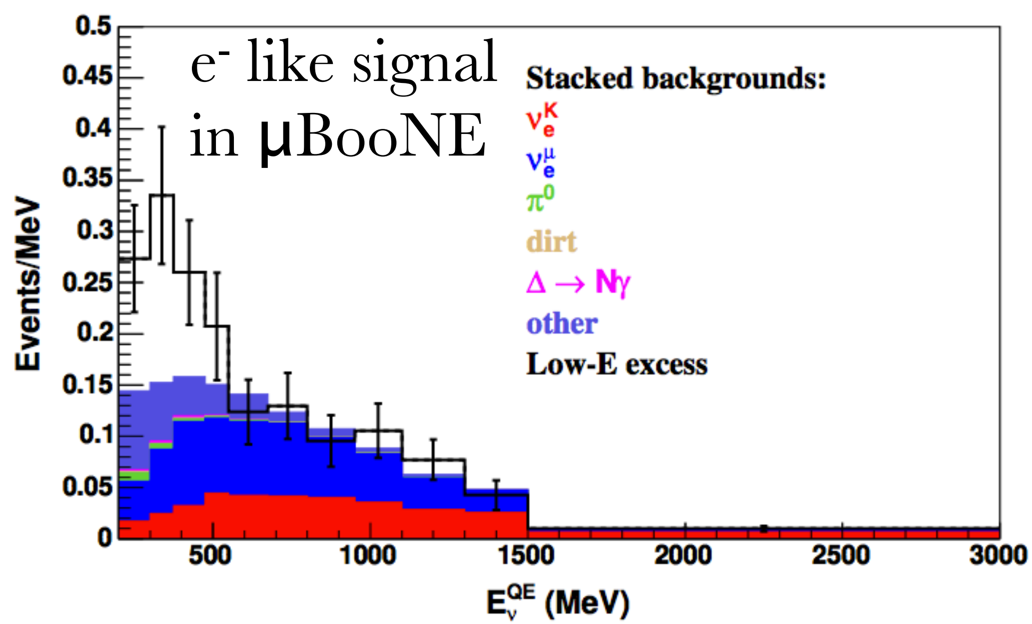
- MiniBooNE excess is not consistent with the global picture even within sterile neutrino models
- MicroBooNE will explore this (2014): New detector technology which can tell the difference between ν_es and γs
- MicroBooNE would also be sensitive to multinucleon effects.



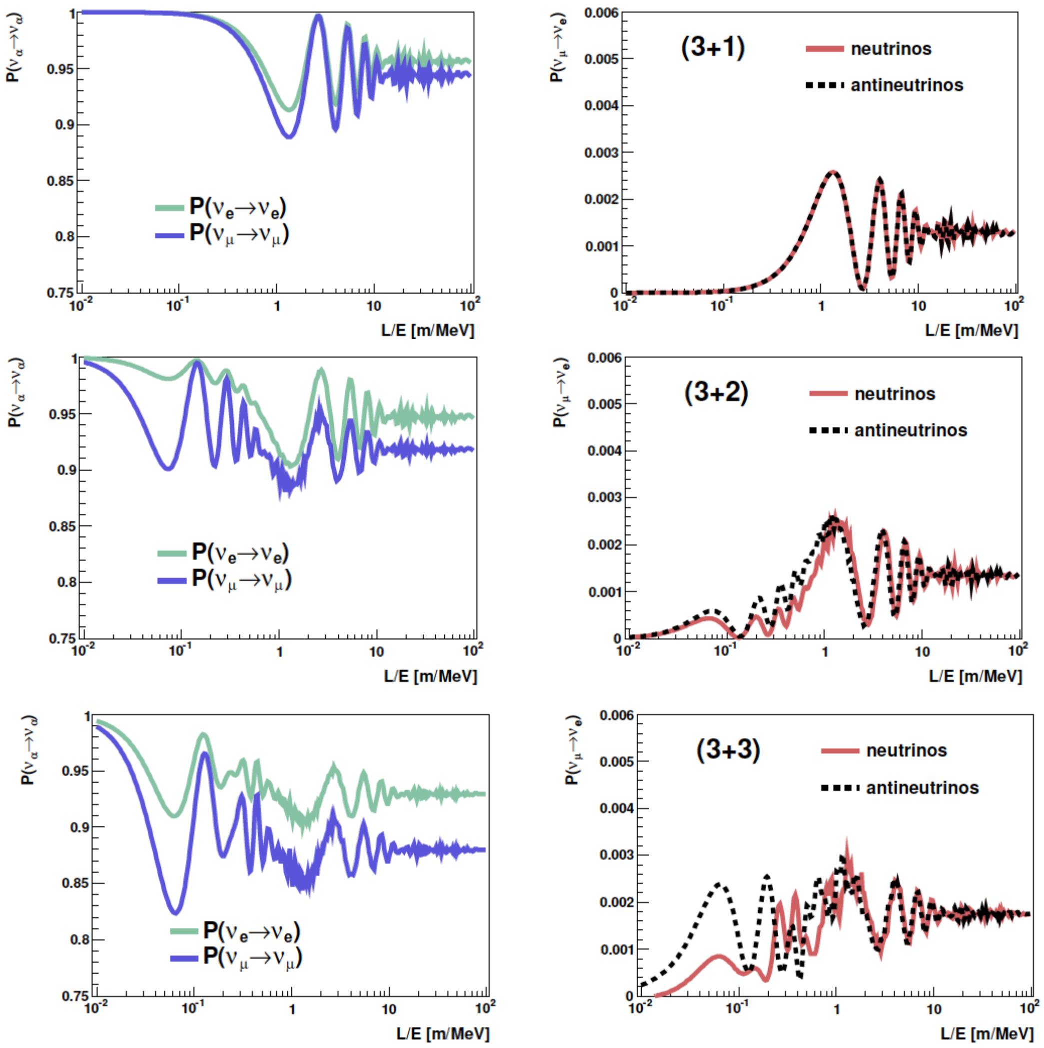


My prediction is that at least some of the MiniBooNE low energy excess is not due to oscillations (even within the framework of sterile neutrino oscillations)





Oscillation Probabilities for Global Best Fit Parameters



Future experiments should aim to have sensitivities in these regions

- Introduction
- Motivation for sterile neutrinos: LSND
- Sterile neutrino phenomenology
- MiniBooNE (arxiv:1207.4809)
- Other recent anomalies
- Constraints from other experiments
- Global Fits (arxiv:1207.4765)
- Future

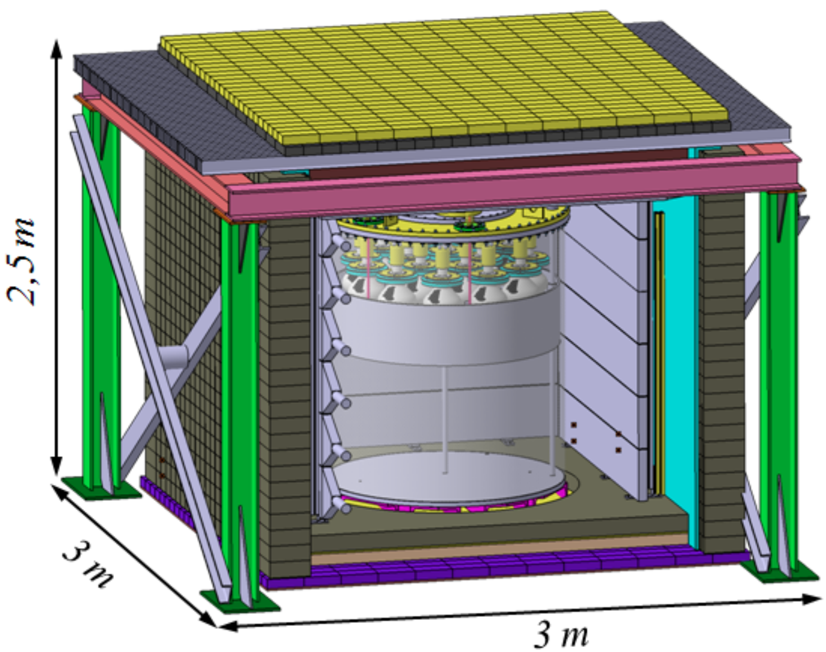
Future Experiments

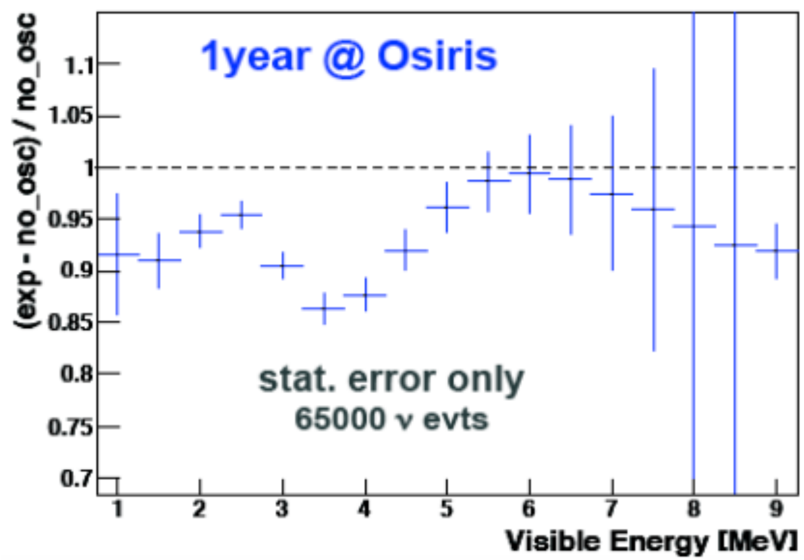
Future and proposed experiments for sterile neutrino searches

Source	App/Dis	Channel	Experiment
Reactor	Dis	$\bar{\nu}_e \to \bar{\nu}_e$	Nucifer, Stereo, SCRAMM, NIST, Neutrino4, DANSS
Radioactive	Dis	$\nu_e \to \nu_e$ $\bar{\nu}_e \to \bar{\nu}_e$	Baksan, LENS, Borexino, SNO+, Ricochet, CeLAND, Daya Bay
Accelerator-based isotope	Dis	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon DAR	App & Dis	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$ $\nu_\mu \to \nu_e$	OscSNS, DAEδALUS, KDAR
Accelerator (Pion DIF)	App & Dis	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-energy ν-Factory	App & Dis	$\nu_e \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$	νSTORM

Nucifer

- Located 7m from Saclay Osiris research reactor
- R&D for nonproliferation technology
- Sensitivity to sterile neutrino oscillations (L/E ~ 1 eV^2)
(E-dependent probe of reactor anomaly)
- Currently operational!



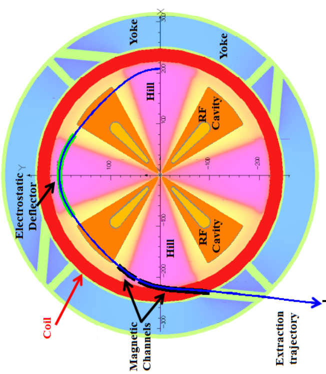


$$\Delta m^2 = 2.4\ eV^2, \ \ \sin^2 2\theta = 0.15$$

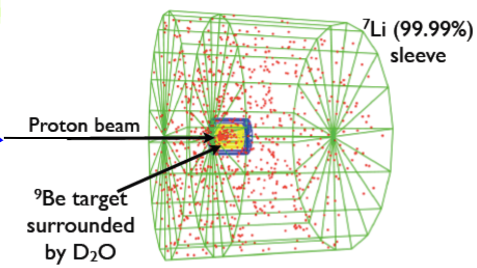
Doesn't include backgrounds

Ref: Slides from PANIC11, Andi S. Cucoanes

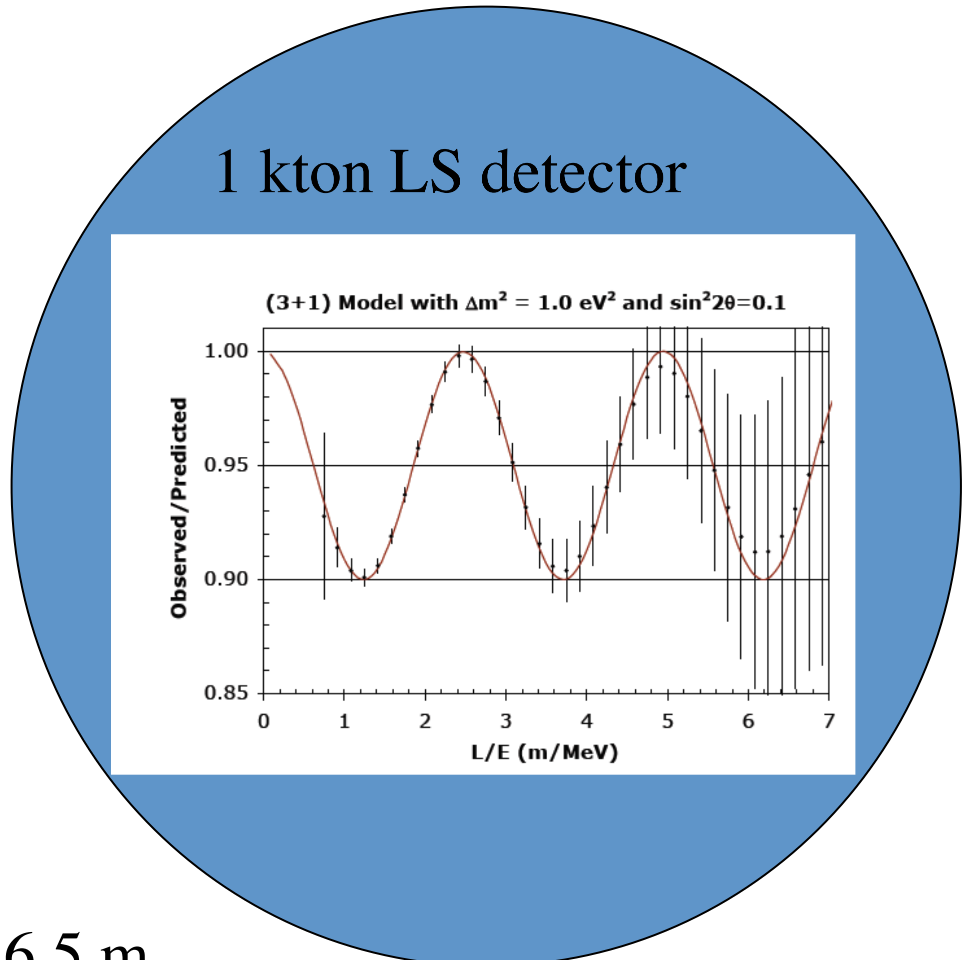
IsoDAR



$^{8}Li \rightarrow {}^{8}Be + e^{-} + \overline{\nu}_e$



Low energy, high-powered cyclotron



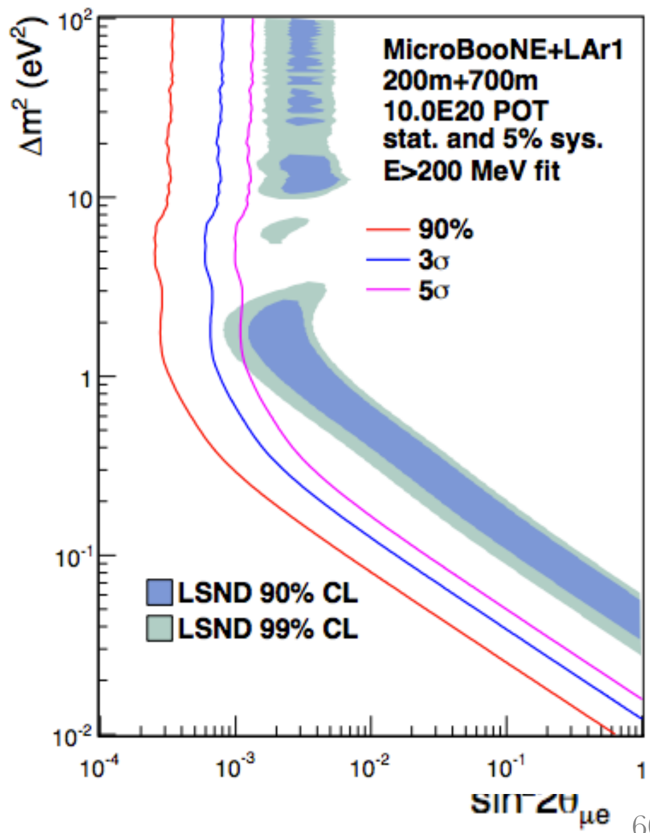
Not to scale

16.5 m

arXiv:1205.4419

LAr1

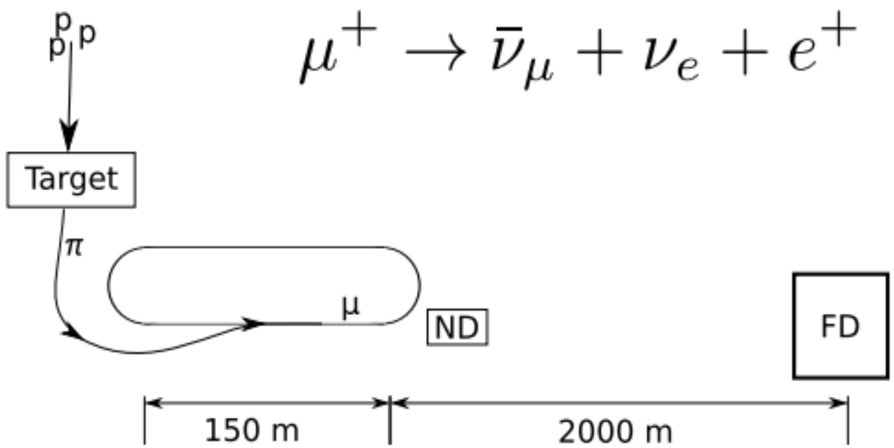
- Far detector to MicroBooNE
- Step in the U.S. Liquid Argon TPC program (leading up to LBNE)



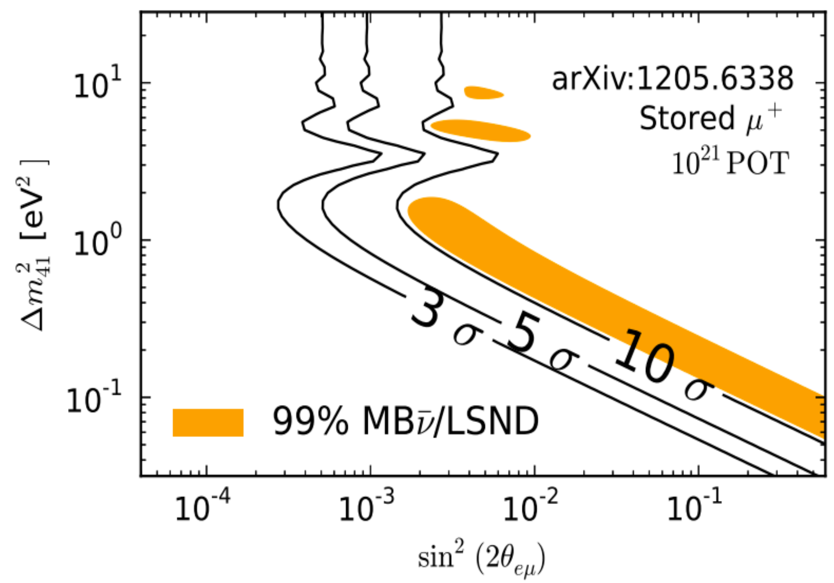
ν Storm

Look for $\nu_e \to \nu_\mu$ oscillations at neutrino factory

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



statistics-only χ^2 using spectral information



arXiv:1206.0294

Conclusions

- There are anomalies in short baseline experiments that need to be addressed
- 3+1 fits are not a good description of world data, but they are better than fits with no sterile neutrinos
- 3+2 helps -- cp violation helps resolve tension between neutrino and antineutrino data
- 3+3 is not a significant improvement over 3+2
- Still tension between appearance and disappearance experiments
- Does not explain MiniBooNE low energy excess
- Need future experiments to shed light on this issue!

Thank You!

Backup

3+1	Δm^2_{41}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$
All	0.92	0.17	0.15
App	0.15	0.39	0.39
Dis	18	0.18	0.18
ν	7.8	0.059	0.26
$\bar{\nu}$	0.92	0.23	0.13

3+2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	ϕ_{54}
All	0.92	17	0.13	0.15	0.16	0.069	1.8π
App	0.31	1.0	0.31	0.31	0.17	0.17	1.1π
Dis	0.92	18	0.015	0.12	0.17	0.12	N/A
ν	7.6	17.6	0.05	0.27	0.18	0.052	1.8π
$\bar{\nu}$	0.92	3.8	0.25	0.13	0.12	0.079	0.35π

3+3	Δm^2_{41}	Δm^2_{51}	Δm^2_{61}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 6}\rvert$	$\lvert U_{e6}\rvert$	ϕ_{54}	ϕ_{64}	ϕ_{65}
All	0.90	17	22	0.12	0.11	0.17	0.11	0.14	0.11	1.6π	0.28π	1.4π
App	0.15	1.8	2.7	0.37	0.37	0.12	0.12	0.12	0.12	1.4π	0.32π	0.94π
Dis	0.92	7.2	18	0.013	0.12	0.019	0.16	0.15	0.069	N/A	N/A	N/A
ν	13	17	26	0.076	0.24	0.16	0.067	0.10	0.017	1.1π	1.8π	0.037π
$\bar{\nu}$	7.5	9.1	18	0.024	0.28	0.098	0.11	0.18	0.029	1.8π	2.0π	0.61π

	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+1						
All	233.9 (237)	286.5 (240)	55%	2.1%	54.0 (24)	0.043%
App	87.8 (87)	147.3 (90)	46%	0.013%	14.1 (9)	12%
Dis	128.2 (147)	139.3 (150)	87%	72%	22.1 (19)	28%
ν	123.5 (120)	133.4 (123)	39%	25%	26.6 (14)	2.2%
$\overline{\nu}$	94.8 (114)	153.1 (117)	90%	1.4%	11.8 (7)	11%
App vs. Dis	-	-	-	-	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	-	-	-	-	15.6 (3)	0.14%
3+2						
All	221.5 (233)	286.5 (240)	69%	2.1%	63.8 (52)	13%
App	75.0 (85)	147.3 (90)	77%	0.013%	16.3 (25)	90%
Dis	122.6 (144)	139.3 (150)	90%	72%	23.6 (23)	43%
ν	116.8 (116)	133.4 (123)	77%	25%	35.0 (29)	21%
$\overline{\nu}$	90.8 (110)	153.1 (117)	90%	1.4%	15.0 (16)	53%
App vs. Dis	-	-	-	-	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	-	-	-	-	13.9 (7)	5.3%
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\overline{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	27.1 (6)	0.014%
ν vs. $\overline{\nu}$	-	-	-	-	10.9 (12)	53%