Latest 3+N fit results and what they mean for MicroBooNE

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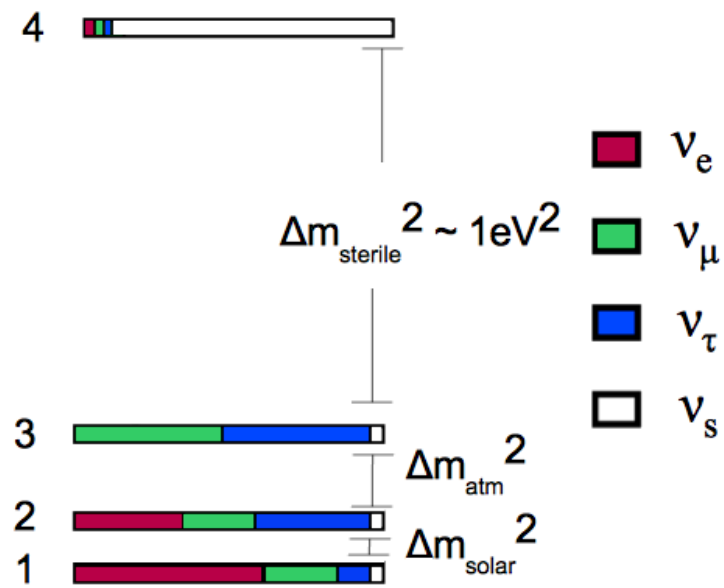
3+1 Model

- Assume one more neutrino that doesn't interact through the weak force but can still oscillate with other neutrinos

- Assume $\Delta m^2_{sterile} >> \Delta m^2_{atm}$ 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



3+1 model Fit parameters:

Oscillation Probabilities:

Appearance: $P(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}) = \sin^2 2\theta_{\alpha\beta} \sin^2[1.27\, \Delta m^2 (L/E)]$

Disappearance: $P(\nu_\alpha \rightarrow \nu_\alpha) = \sin^2 2\theta_{\alpha\alpha} \sin^2[1.27\, \Delta m^2 (L/E)]$

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

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

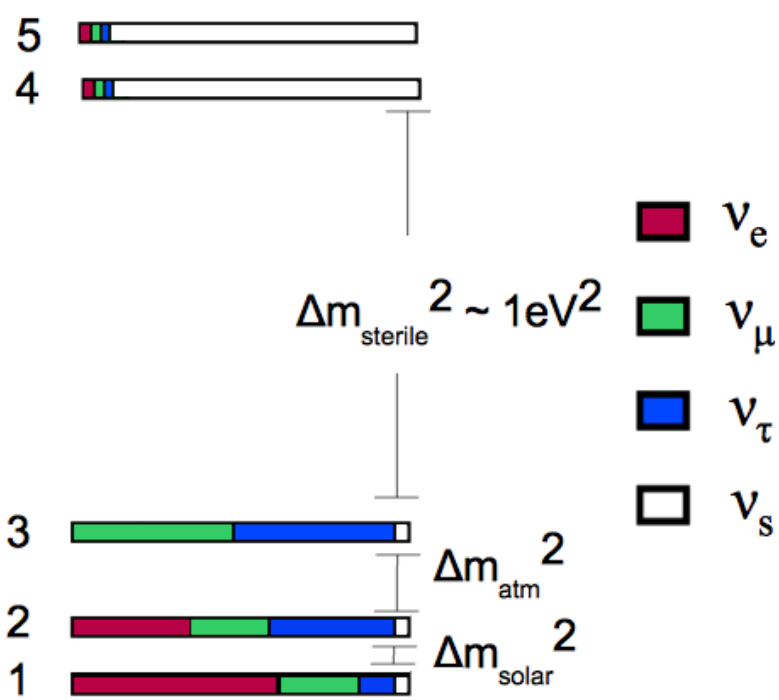
$\sin^2 2\theta_{\mu\mu} = 4\, U_{\mu 4}^2 (1 - U_{\mu 4}^2)$

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

3+2 model

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

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



Disappearance

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2) \cdot (|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 x_{54}]$$

Appearance

$$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

$$x_{ji} \equiv 1.27 \Delta m^2_{ji} L/E$$

3+3 Model:

- 3rd mostly sterile mass eigenstate
- Introduce Δm^2_{61} $U_{\mu 6}$ U_{e6} Φ_{46} Φ_{56}
- 12 total parameters

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

Included data sets

Appearance

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

MiniBooNE $\nu_\mu \to \nu_e$

MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ (☆2012)

NOMAD $\nu_\mu \to \nu_e$

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

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

Disappearance:

Bugey $\bar{\nu}_e \to \bar{\nu}_e$ (☆new reactor fluxes)

☆Gallium $\nu_e \to \nu_e$

☆Karmen/LSND xsec $\nu_e \to \nu_e$

CCFR84 $\nu_\mu \to \nu_\mu$

CDHS $\nu_\mu \to \nu_\mu$

Atmospheric $\nu_\mu \to \nu_\mu$

☆MINOS CC $\bar{\nu}_\mu \to \bar{\nu}_\mu$ (2012)

MiniBooNE $\nu_\mu \to \nu_\mu$

☆ = New since arXiv:0906.1997 (Karagiorgi et. al. 2009)

Parameter Goodness of Fit

Tests how well different data sets agree with each other
(so a 50 bin experiment doesn't dominate the chi2)

PG=Prob(χ^2_{PG}, ndf_{PG})

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

i runs over individual experiments

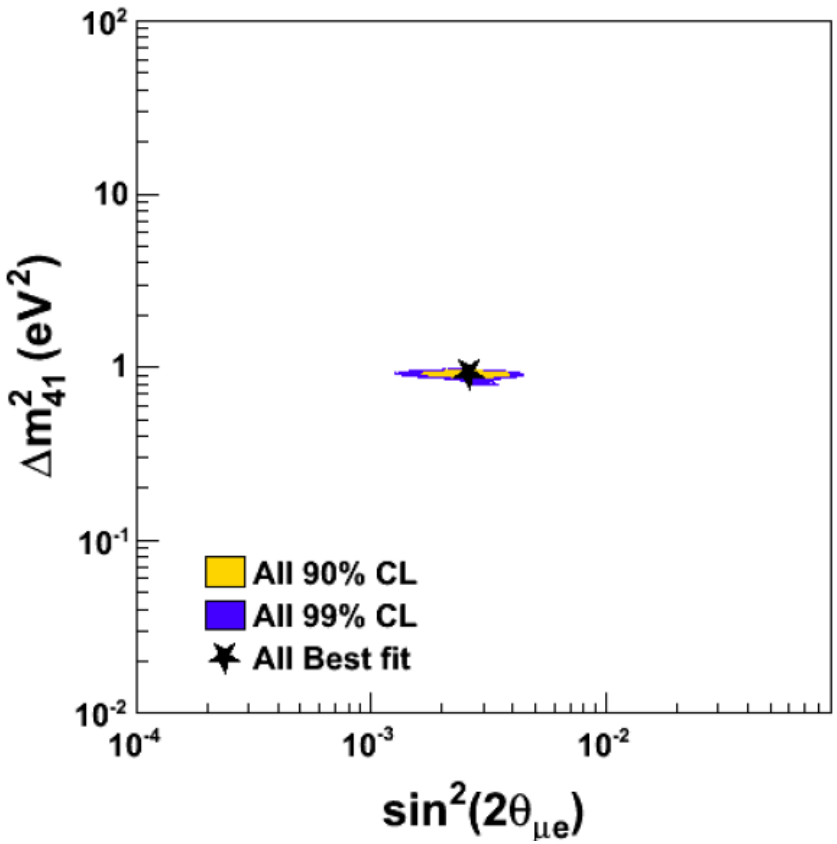
$$ndf_{PG} = \sum_d N_{p_d} - N_{p_{combined}}$$

Independent parameters per dataset

Independent parameters in global fit

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

3+1 Global Fit

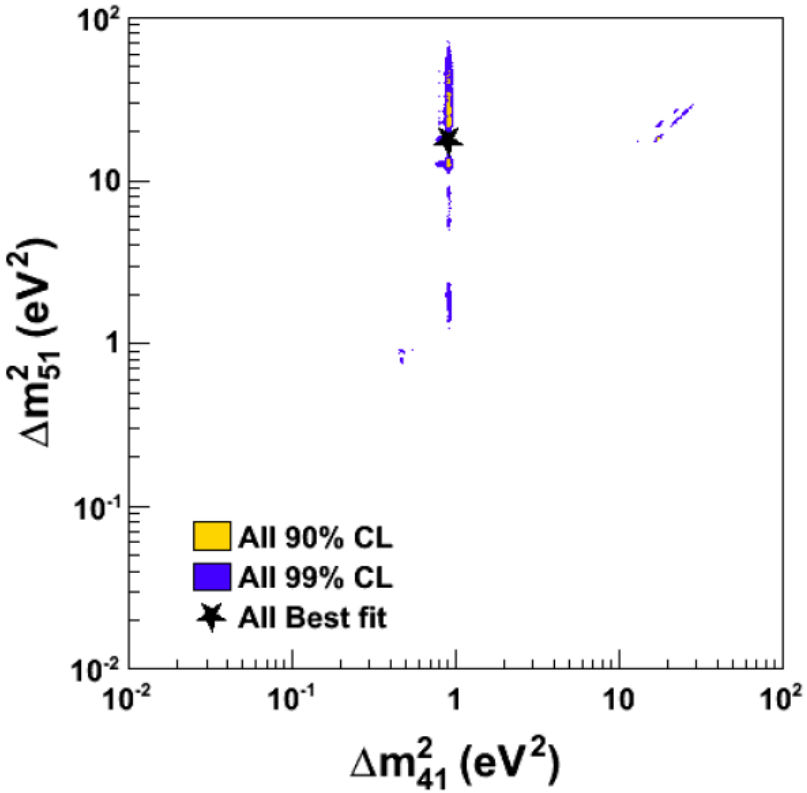


χ^2(dof)	χ^2_{null} (dof)	gof	null gof	χ^2_{PG} (dof)	PG
233.9 (237)	286.5 (240)	55%	2.1%	54 (24)	0.043%

Δm^2_{41}	$U_{\mu 4}$	U_{e4}
0.92	0.17	0.15

"Parameter Goodness of fit"
Tests compatibility between datasets

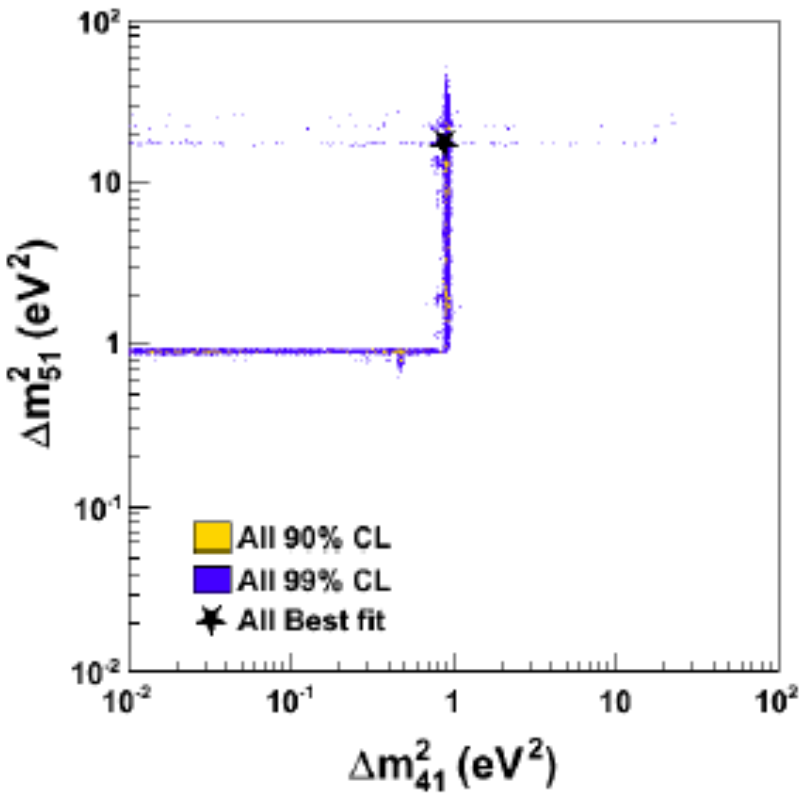
3+2 Global Fit

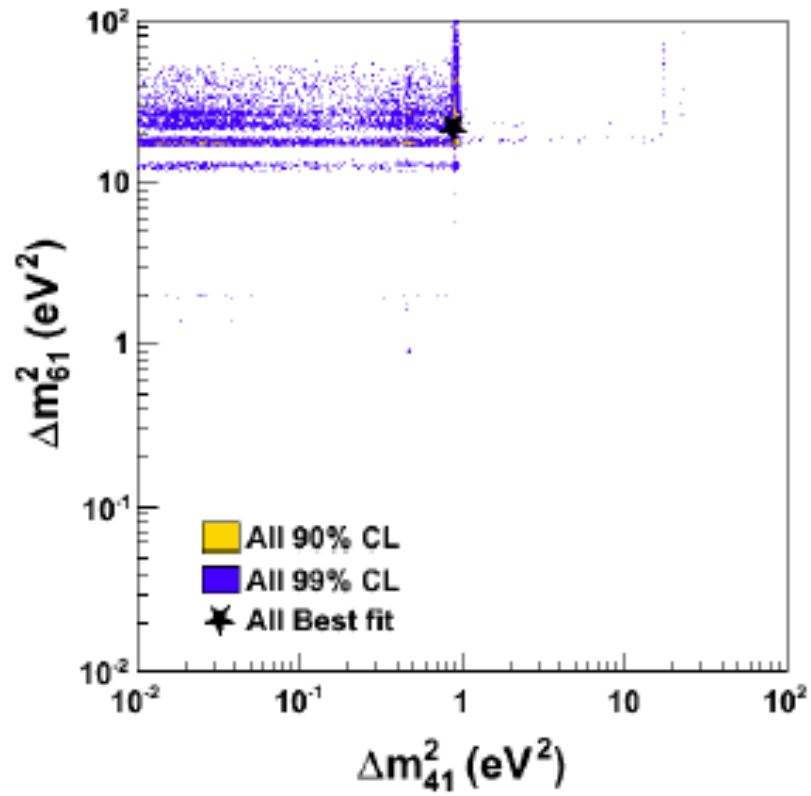


χ^2(dof)	χ^2_{null} (dof)	gof	null gof	χ^2_{PG} (dof)	PG
221.5 (233)	286.5 (240)	69%	2.1%	63.8 (52)	13%

Δm^2_{41}	Δm^2_{51}	$U_{\mu 4}$	U_{e4}	$U_{\mu 5}$	U_{e5}	φ_{45}
0.92	17	0.13	0.15	0.16	0.069	1.8π

3+3 Global Fit





χ^2(dof)	χ^2_{null} (dof)	gof	null gof	χ^2_{PG} (dof)	PG
218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%

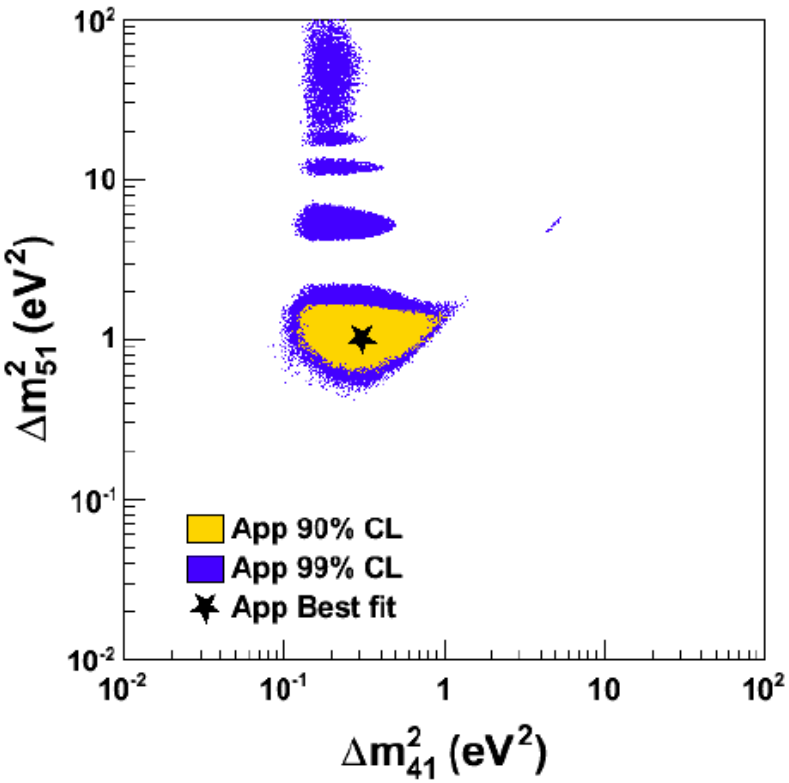
Δm^2_{41}	Δm^2_{51}	Δm^2_{61}	$U_{\mu 4}$	U_{e4}	$U_{\mu 5}$	U_{e5}	$U_{\mu 6}$	U_{e6}	φ_{45}	φ_{46}	φ_{56}
0.90	17	22	0.118	0.11	0.17	0.11	0.14	0.11	1.6π	0.28π	1.4π

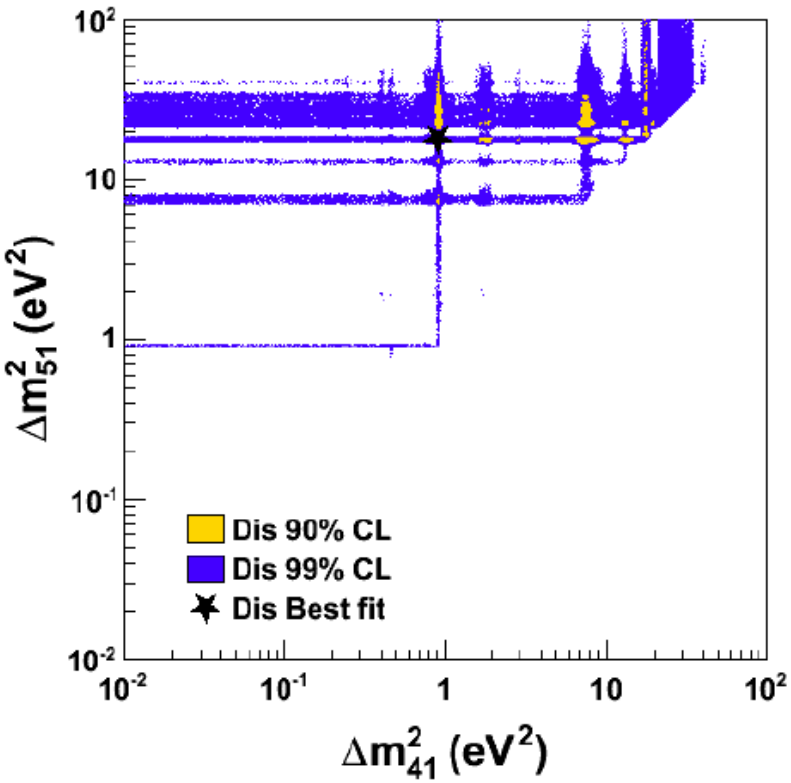
Subsets of data

	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	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

Why Does App vs. Dis not get better?

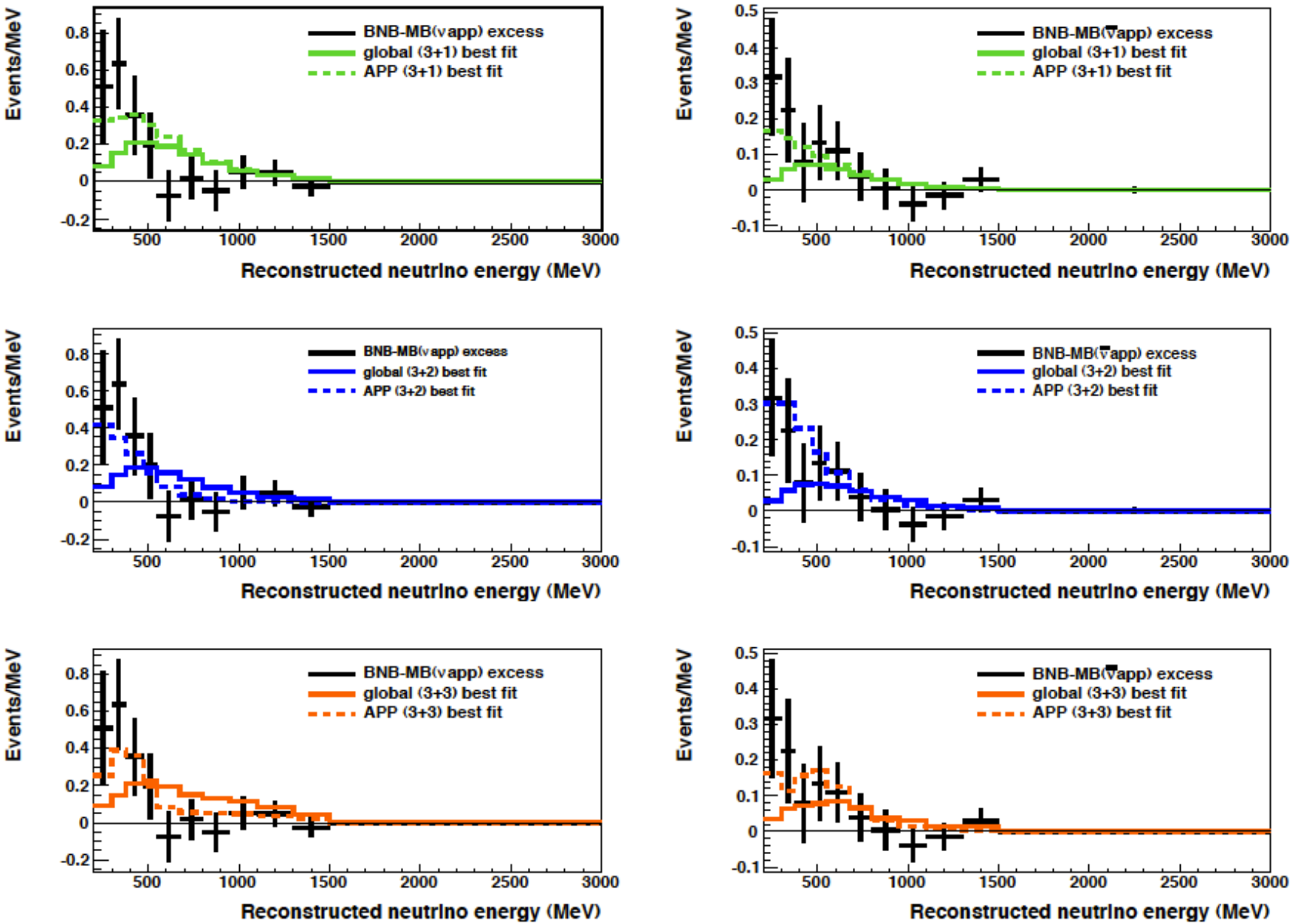
3+2 fits (3+3 is similar)





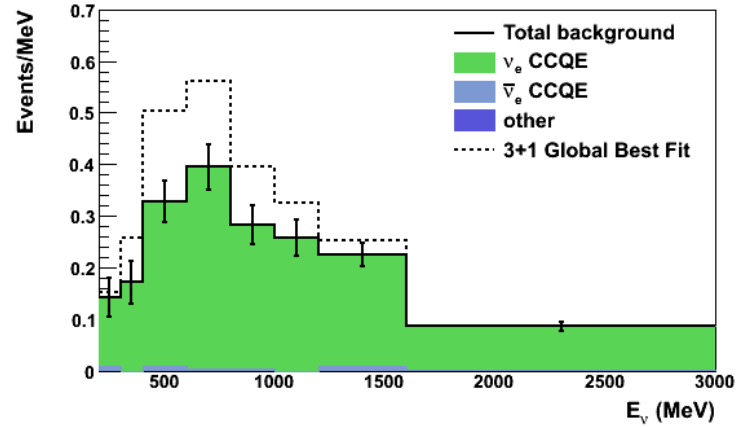
They are finding different best fit points… It turns out the appearance fit is largely driven by MB

Does Not explain MB low energy excess!

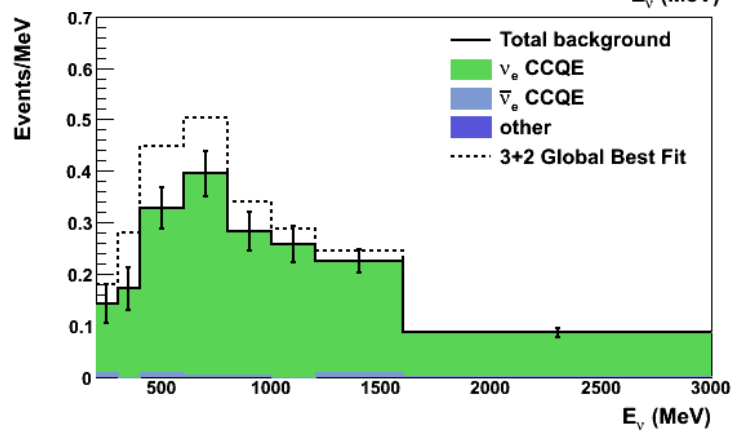


Predictions for MicroBooNE

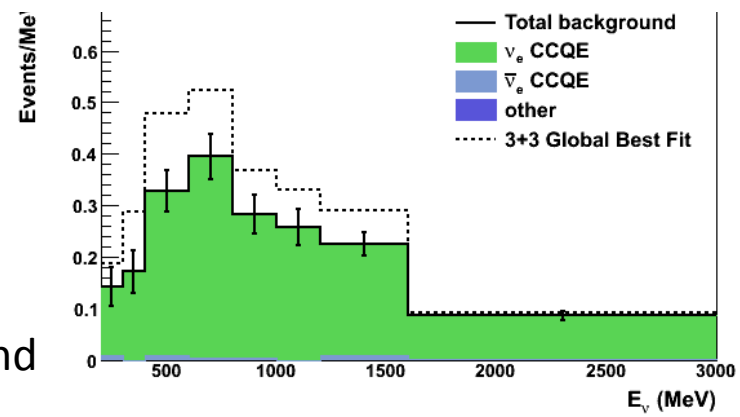
3+1 Global Best Fit (2 parameters):
Stat err only: chi2= 35
Stat + 5% sys: chi2= 29
Total signal: 115 events
Total background 296 events



3+2 Global Best Fit (5 parameters):
Stat err only: chi2= 20
Stat + 5% sys: chi2= 17
Total signal: 80 events



3+3 Global Best Fit (9 parameters):
Stat err only: chi2= 35
Stat + 5% sys: chi2= 29
Total signal: 110 events



-Chi2 calculation uses stat error on signal+background
-Error bars shown are stat errors on the background
-MC by Georgia and Roxanne: Assumes 80% neutrino reconstruction efficiency, 61.4 metric tons of fiducial volume, and 6E20 POT

Conclusions

- Was already known that 3+1 fits were not a good description of world data (PG=0.043% in this case)
- And that adding a second sterile neutrino helps a lot (PG=13%)
- Adding a 3rd neutrino helps the compatibility even more (PG=90%)
- Does not resolve tension between appearance and disappearance experiments
- Does not explain MB low energy excess
- Any of these signals will show up nicely in MicroBooNE!