3+N Fits to World Data

Christina Ignarra
May 13, 2011

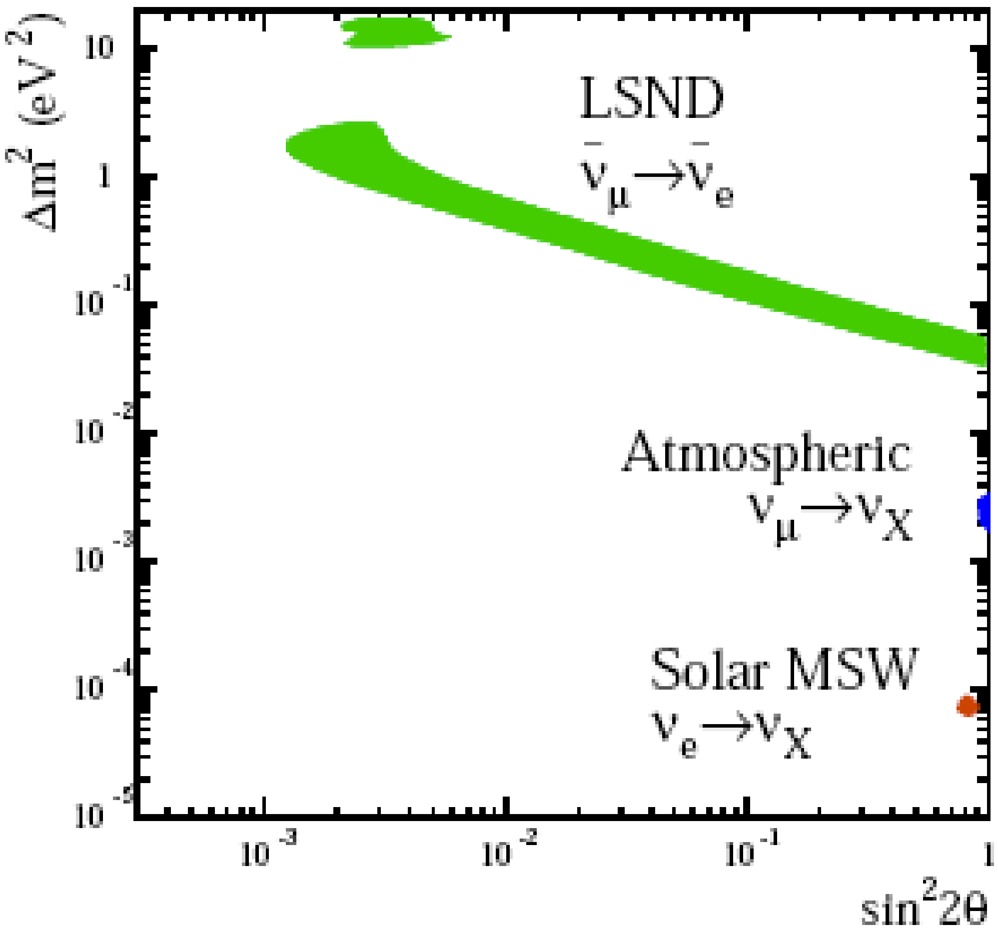
Fits by C. Ignarra And G. Karagiorgi,
With input from M. Shaevitz and J. Conrad

Outline

- Introduction to the data
- Old 3+1 fits
- New data and fits
- A little bit about 3+2 fits

- I've recently taken over these fits from Georgia Karagiorgi.
- Since this is a workshop, I'm going to show you work in progress!

Motivation



LSND result: Observed allowed region of Δm^2 not consistent with known mass splittings.

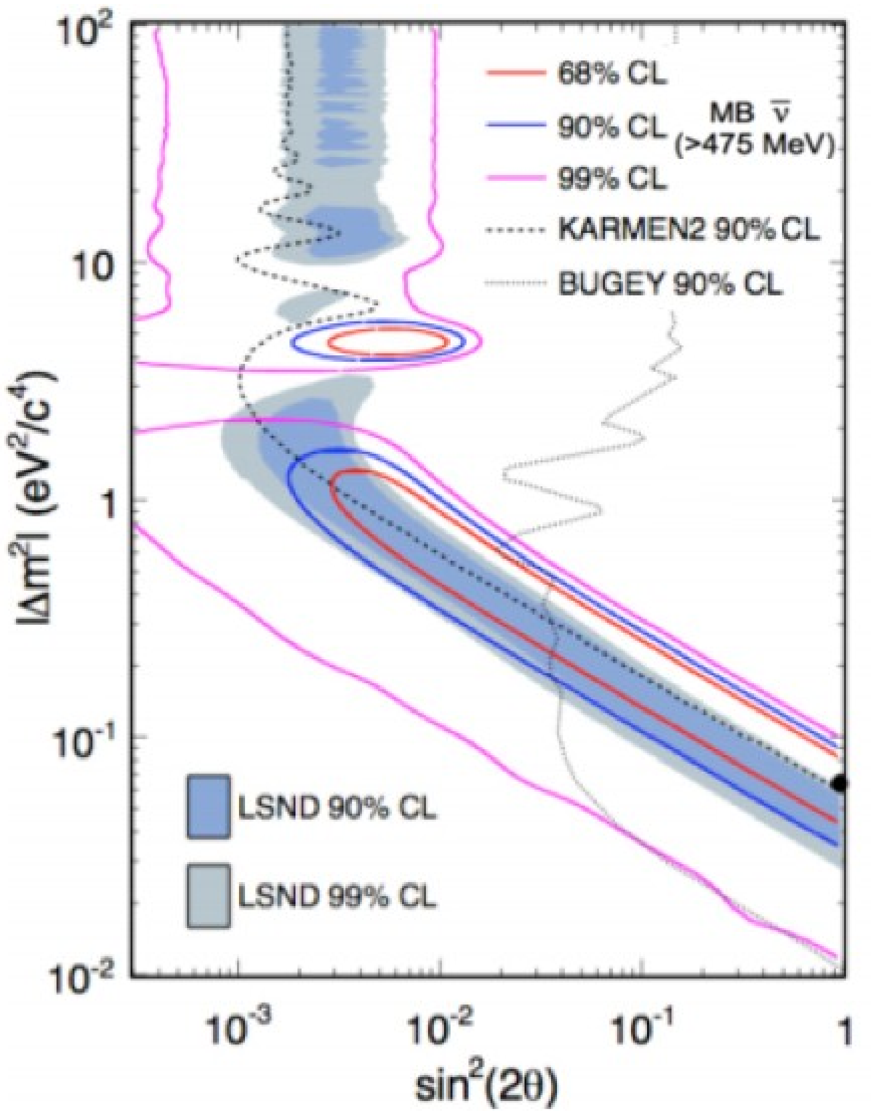
$\Delta m^2_{solar} \sim 10^{-5}$ eV^2

$\Delta m^2_{atm} \sim 10^{-3}$ eV^2

A 3rd mass splitting solves this problem

$\Delta m^2_{LSND} \sim 1$ eV^2

Motivation



Now MiniBooNE $\overline{\nu}$'s are showing a strong agreement with LSND

Though MiniBooNE ν's are not...

Other hints of a sterile neutrino in this region have also recently began popping up:

New reactor flux predictions

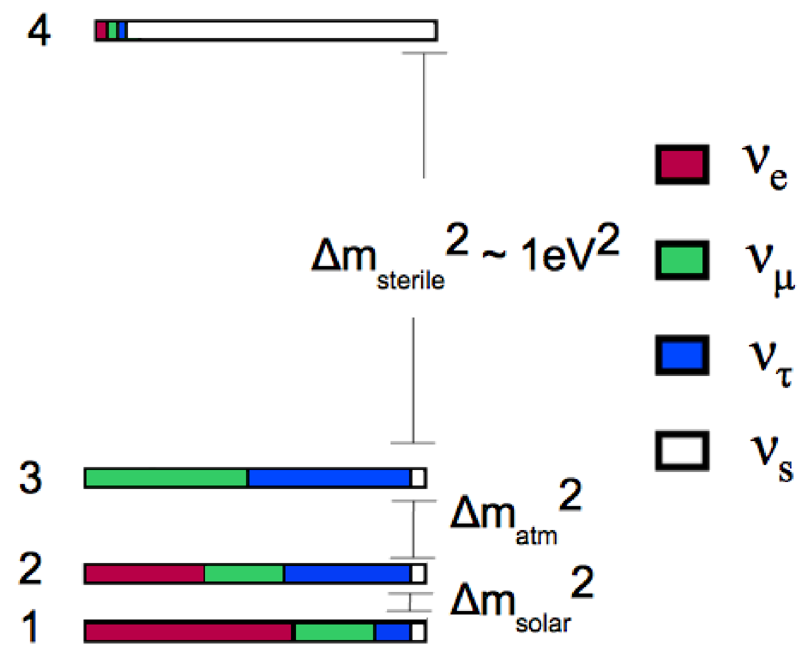
Gallium source experiments

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}

$\sin^2 2\theta_{\mu e} = 4\, U_{e4}^2\, U_{\mu 4}^2$ Already well constrained in both ν and $\bar{\nu}$ mode

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

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

Note: we constrain $U_{e4}^2 + U_{\mu 4}^2 < 0.5$ to prevent degeneracies in values of $U_{\mu 4}$ and U_{e4}

Included data sets – old fits

Neutrinos:

MiniBooNE $\nu_\mu \rightarrow \nu_e$

NOMAD $\nu_\mu \rightarrow \nu_e$

NuMI $\nu_\mu \rightarrow \nu_e$

CCFR84 $\nu_\mu \rightarrow \nu_\mu$

CDHS $\nu_\mu \rightarrow \nu_\mu$

Atmospheric $\nu_\mu \rightarrow \nu_\mu$

Antineutrinos:

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

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

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

Bugey $\bar{\nu}_e \rightarrow \bar{\nu}_e$

Chooz $\bar{\nu}_e \rightarrow \bar{\nu}_e$

Reference for 2009 fits: Georgia Karagiorgi et al arXiv:0906.1997v2

Included data sets – old fits

Neutrinos:

MiniBooNE $\nu_\mu \rightarrow \nu_e$

NOMAD $\nu_\mu \rightarrow \nu_e$

NuMI $\nu_\mu \rightarrow \nu_e$

CCFR84 $\nu_\mu \rightarrow \nu_\mu$

CDHS $\nu_\mu \rightarrow \nu_\mu$

Atmospheric $\nu_\mu \rightarrow \nu_\mu$

Antineutrinos:

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

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

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

Bugey $\bar{\nu}_e \rightarrow \bar{\nu}_e$

Chooz $\bar{\nu}_e \rightarrow \bar{\nu}_e$

There was already a lot of muon to electron flavor data

Included data sets – old fits

Neutrinos:

MiniBooNE $\nu_\mu \rightarrow \nu_e$

NOMAD $\nu_\mu \rightarrow \nu_e$

NuMI $\nu_\mu \rightarrow \nu_e$

CCFR84 $\nu_\mu \rightarrow \nu_\mu$

CDHS $\nu_\mu \rightarrow \nu_\mu$

Atmospheric $\nu_\mu \rightarrow \nu_\mu$

Antineutrinos:

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

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

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

Bugey $\bar{\nu}_e \rightarrow \bar{\nu}_e$

Chooz $\bar{\nu}_e \rightarrow \bar{\nu}_e$

Muon flavor disappearance is all in neutrino mode

An issue: We treat atmospheric as neutrino mode in fits, and while it is mostly neutrino data, there is some antineutrino component...

Included data sets – old fits

Neutrinos:

MiniBooNE $\nu_\mu \to \nu_e$

NOMAD $\nu_\mu \to \nu_e$

NuMI $\nu_\mu \to \nu_e$

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

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

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

Antineutrinos:

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

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

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

Bugey $\bar{\nu}_e \to \bar{\nu}_e$

Chooz $\bar{\nu}_e \to \bar{\nu}_e$

All of the electron disappearance data is in antineutrino mode

Parameter Goodness of Fit

- Tests how well different data sets agree

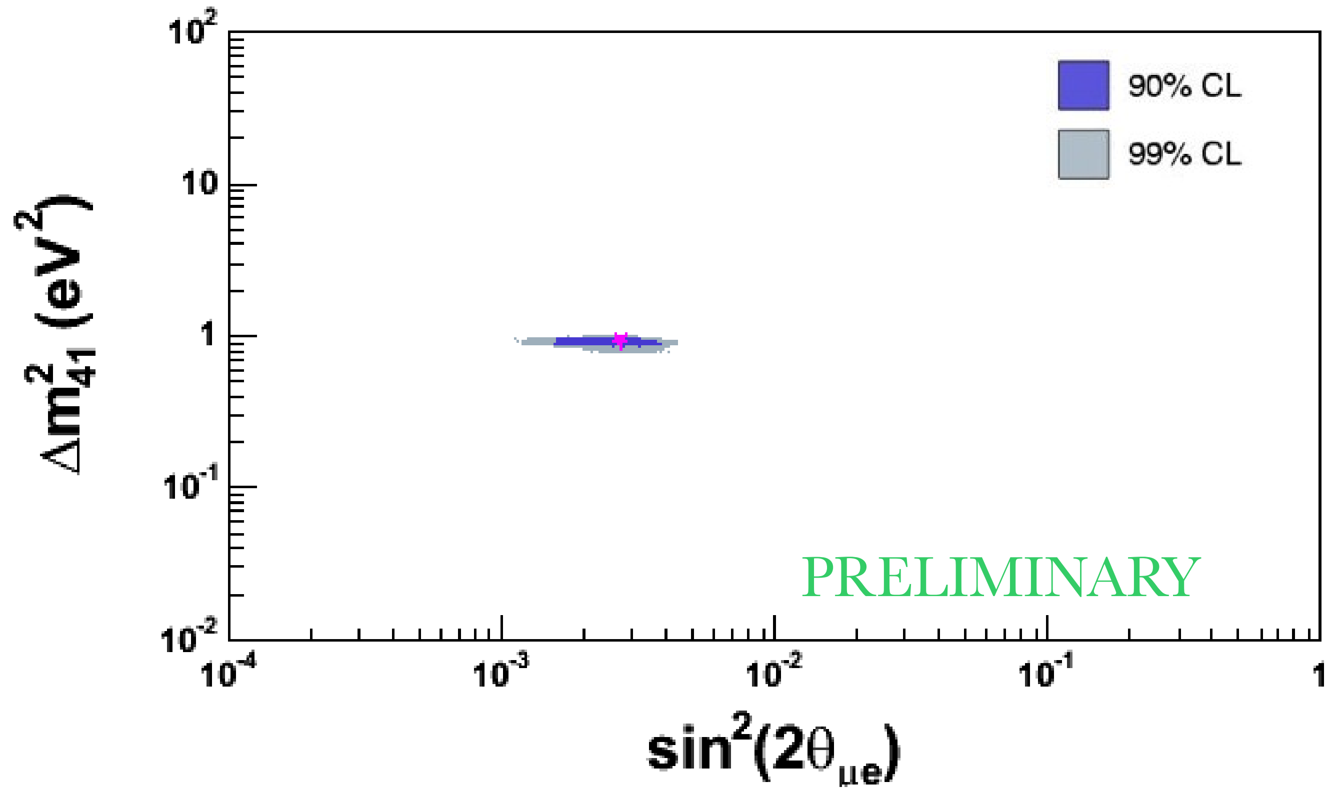
$$\chi^2_{PG} = \chi^2_{min,all} - \sum_i \chi^2_{min,i}$$

i runs over individual experiments

- Compatibility is then calculated from χ^2_{PG} and the common underlying fit parameters as the degrees of freedom

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

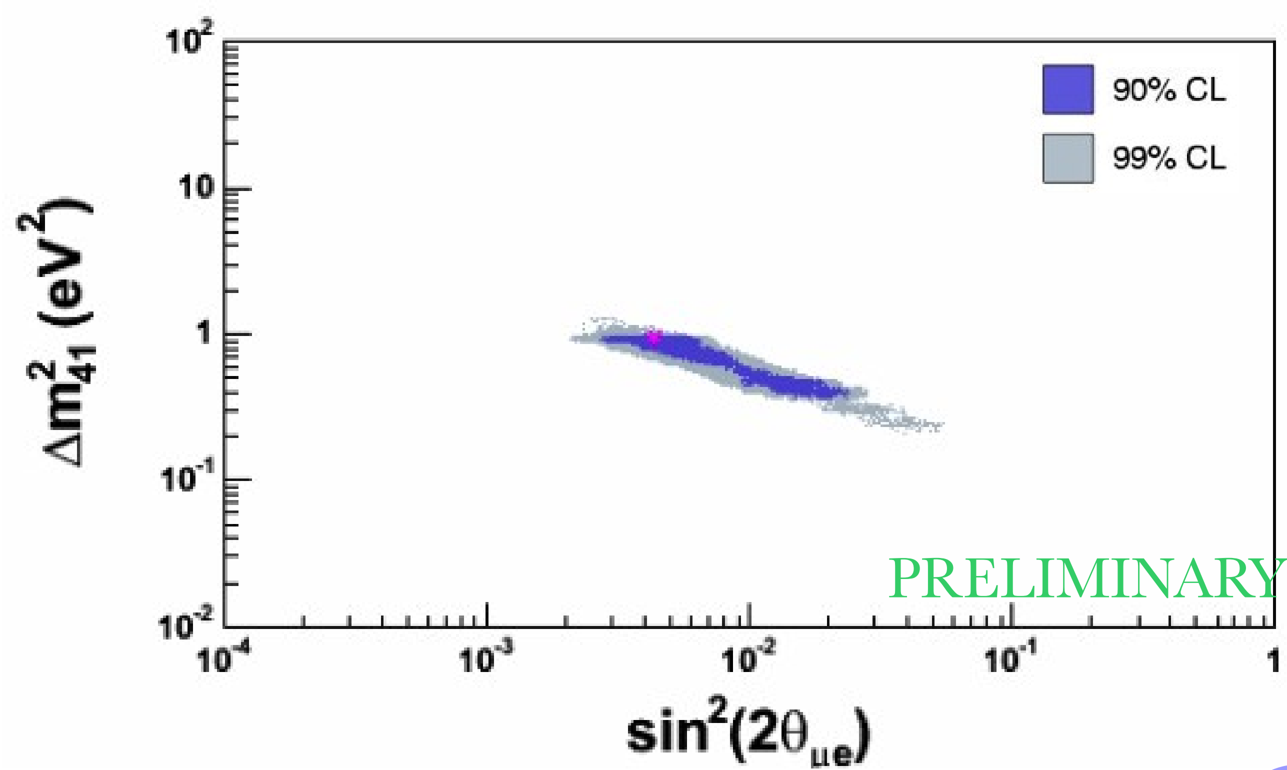
3+1 global fit –old data



ndf	χ^2_{null}	P(null)	χ^2_{3+1}	P(3+1)	PG %	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\sin^2 2\theta_{\mu\mu}$	$\sin^2 2\theta_{ee}$
196	247	0.81%	203	35%	0.043%	0.92	0.0027	0.14	0.076

There is a lot of tension here!

3+1 $\bar{\nu}$ fit –old data



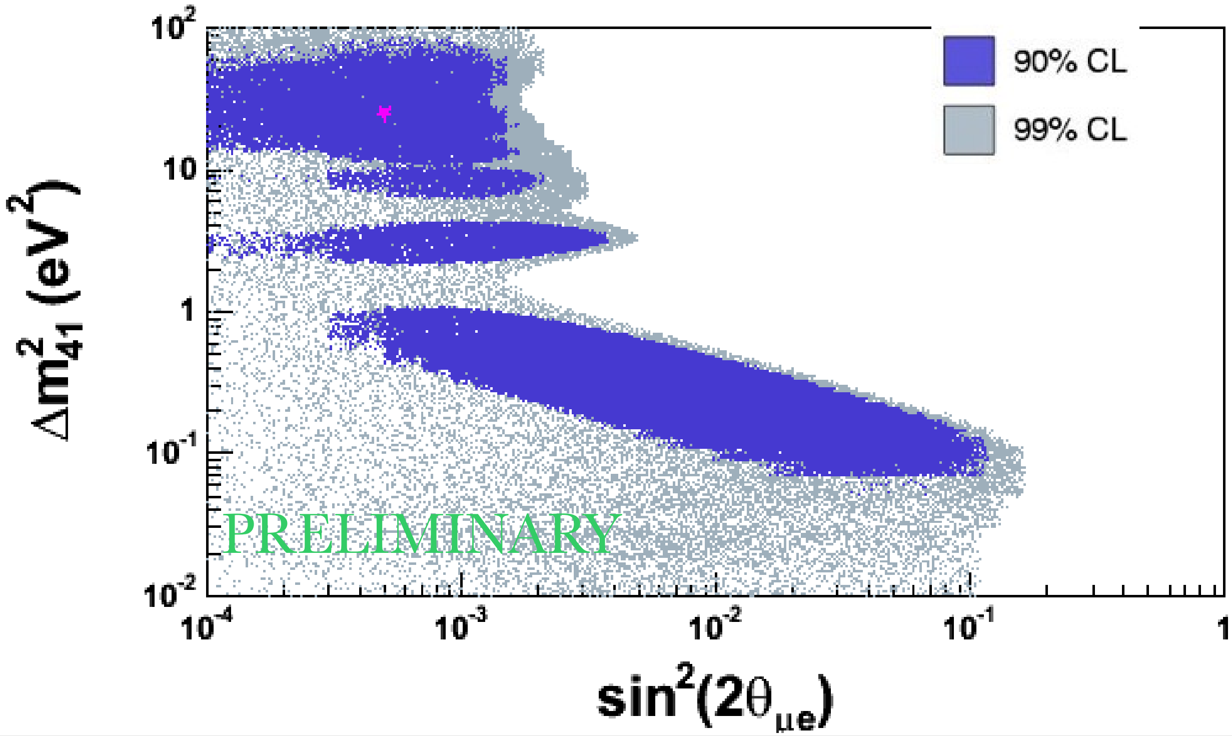
ndf	χ^2_{null}	P(null)	χ^2_{3+1}	P (3+1)	PG %	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\sin^2 2\theta_{\mu\mu}$	$\sin^2 2\theta_{ee}$
103	150	0.16%	92	78%	20%	0.91	0.0044	0.38	0.040

Much better!

This is pretty big though since it is unconstrained! It is possible that this is why the fit gets better!

This is where we see a signal… it also is driving the global fit

3+1 ν —old data



ndf	χ^2_{null}	P(null)	χ^2_{3+1}	P (3+1)	PG %	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\sin^2 2\theta_{\mu\mu}$	$\sin^2 2\theta_{ee}$
90	103	16%	91	46%	6.4%	24	0.00050	0.099	0.020

Not bad ($\nu + \bar{\nu}$ was 0.04%)

This is nowhere near the global fit!

Included data sets (red=new!)

Neutrinos:

MiniBooNE $\nu_\mu \rightarrow \nu_e$

NOMAD $\nu_\mu \rightarrow \nu_e$

NuMI $\nu_\mu \rightarrow \nu_e$

CCFR84 $\nu_\mu \rightarrow \nu_\mu$

CDHS $\nu_\mu \rightarrow \nu_\mu$

~~**Atmospheric $\nu_\mu \rightarrow \nu_\mu$**~~

Gallium $\nu_e \rightarrow \nu_e$

MINOS NC $\nu_\mu \rightarrow \nu_\mu$

Antineutrinos:

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

MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **(updated)**

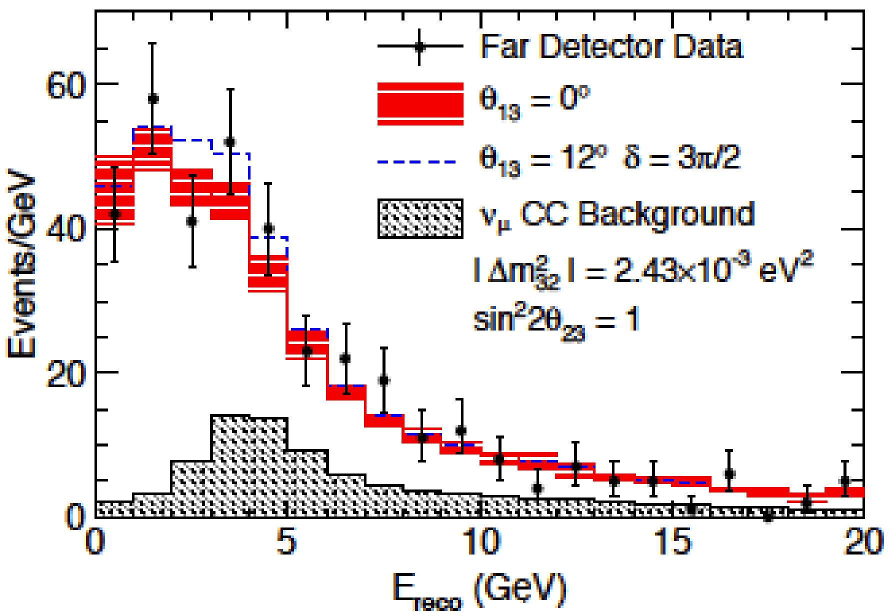
KARMEN $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Bugey $\bar{\nu}_e \rightarrow \bar{\nu}_e$ **(now using new reactor fluxes)**

Chooz $\bar{\nu}_e \rightarrow \bar{\nu}_e$ **(now using new reactor fluxes)**

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

Minos NC: arXiv:1001.0336v3



$$f_s \equiv \frac{P_{\nu_\mu\rightarrow\nu_s}}{1-P_{\nu_\mu\rightarrow\nu_\mu}}.$$

Assumptions:
θ_{14} =0, δ_2=0

$$\begin{aligned} P_{\nu_\mu\rightarrow\nu_\mu} &= 1-4\left\{|U_{\mu3}|^2\left(1-|U_{\mu3}|^2-|U_{\mu4}|^2\right)\sin^2\Delta_{31}\right. \\ &\left.+\frac{|U_{\mu4}|^2}{2}(1-|U_{\mu4}|^2)\right\}, \\ P_{\nu_\mu\rightarrow\nu_\alpha} &= 4\mathcal{R}\left\{\left(|U_{\mu3}|^2|U_{\alpha3}|^2+U^*_{\mu4}U_{\alpha4}U_{\mu3}U^*_{\alpha3}\right)\sin^2\Delta_{31}\right. \\ &\left.+\frac{|U_{\mu4}|^2|U_{\alpha4}|^2}{2}\right\}, \qquad (13)\end{aligned}$$

This component is coming from the Long-baseline oscillation

Any high Δm^2 sterile component would have $<\sin^2[1.27\ \Delta m^2\ (L/E)]> = 1/2$
So this is a search for an overall change in the normalization.

Minos NC: arXiv:1001.0336v3

$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}}.$$

Assumption: $\theta_{14} = 0$

Model	θ_{13}	χ^2/D.O.F.	θ_{23}	θ_{24}	θ_{34}	f_s
$m_4 = m_1$	0	47.5/39	$45.0^{+9.0}_{-8.9}$		$0.1^{+28.7}_{-0.1}$	0.51
	12	46.2/39	$47.1^{+8.8}_{-11.0}$		$23.0^{+22.6}_{-24.1}$	0.55
$m_4 \gg m_3$	0	47.5/38	$45.0^{+9.0}_{-8.9}$	$0.0^{+7.2}_{-0.0}$	$0.1^{+28.7}_{-0.1}$	0.52
	12	46.2/38	$47.1^{+8.8}_{-11.0}$	$0.0^{+7.2}_{-0.0}$	$23.0^{+22.6}_{-24.1}$	0.55

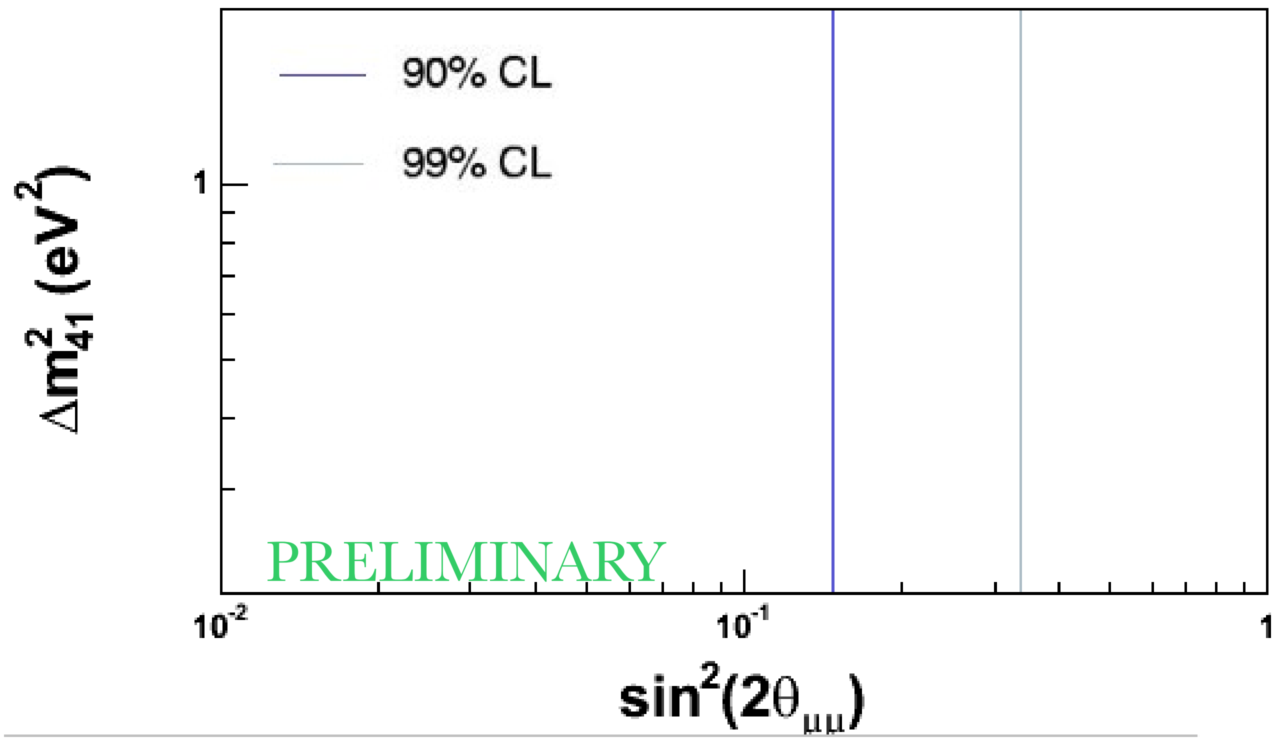
90% CL

$U_{\mu 4} = \cos\theta_{14} \sin\theta_{24} = \sin\theta_{24}$

$U_{\mu 4}$ is what we fit for, so we use their value for θ_{24} to constrain $U_{\mu 4}$.

Near/far comparison
Has no normalization
Offset, so consistent
With no oscillations

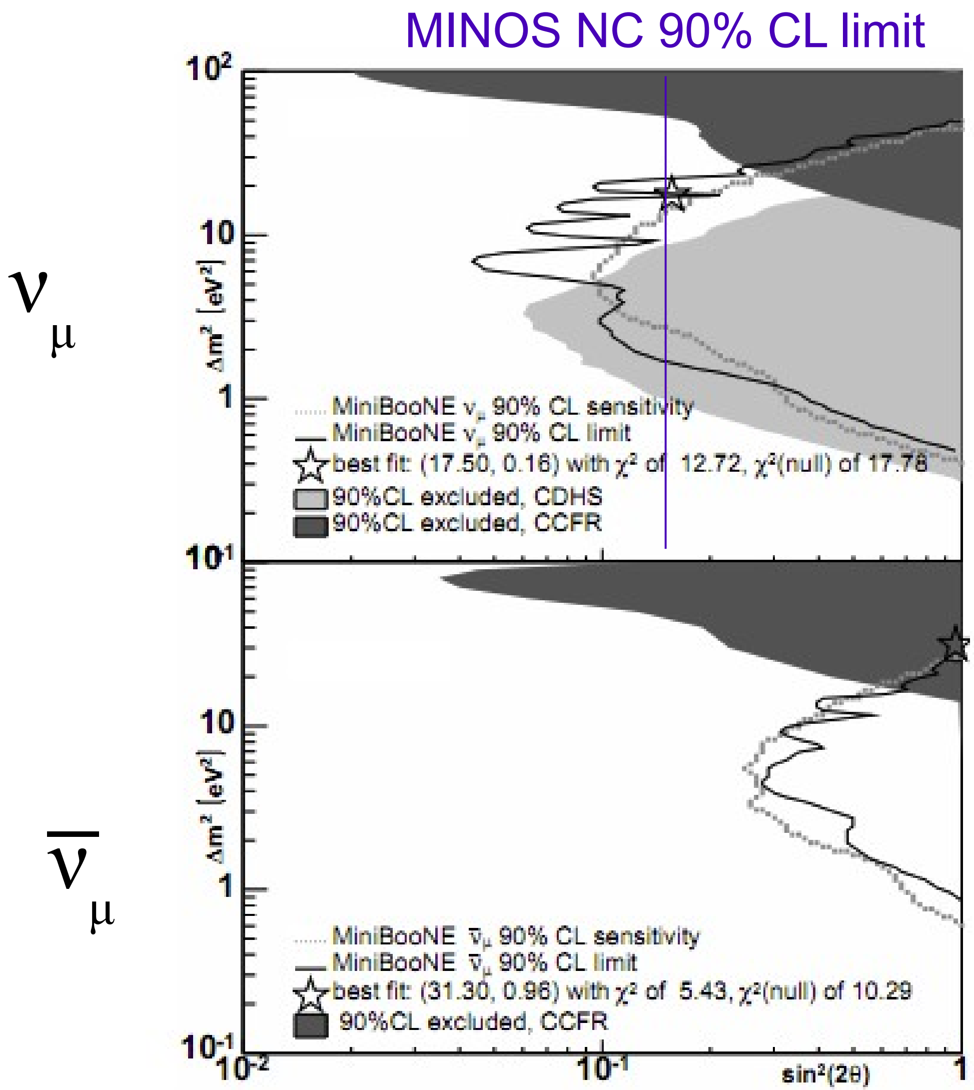
MINOS NC: 3+1 fit



Corresponds to a $U_{\mu 4}{}^2 < 3.5\%$ at 90% CL

Δm^2 constrained to be below 2 eV^2 to prevent oscillations in the near detector and above 0.2 eV^2 so that there will be an overall normalization in the far detector (which were assumptions of their fit)

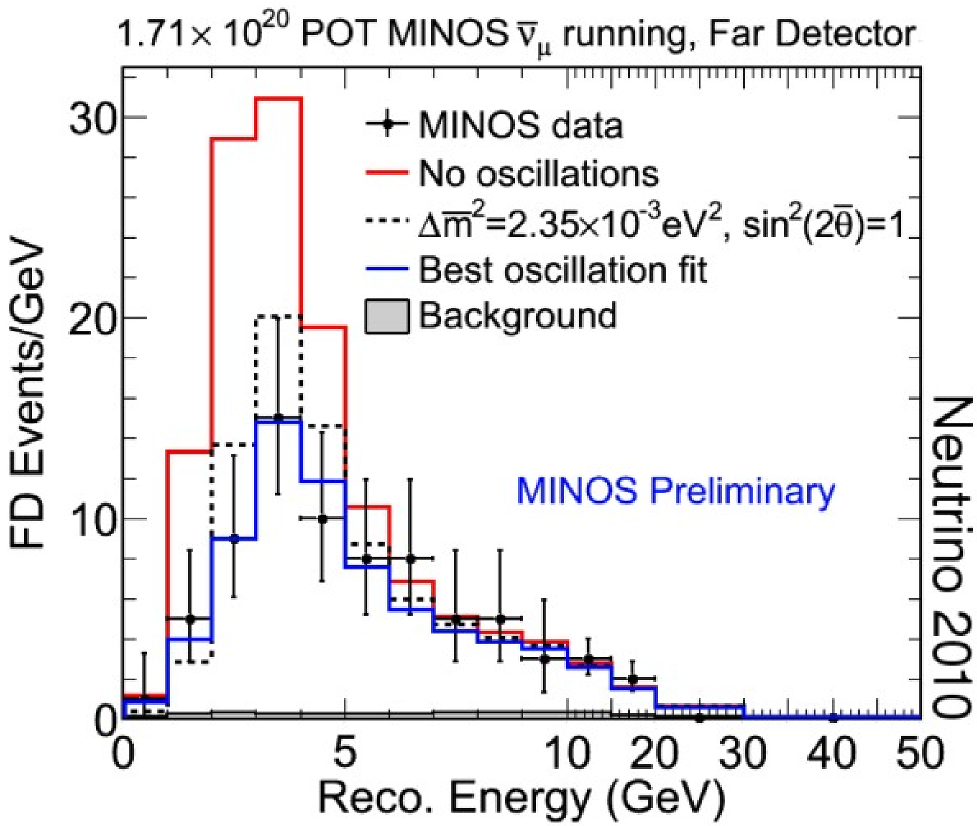
MiniBooNE ν_μ and $\bar{\nu}_\mu$ disappearance search

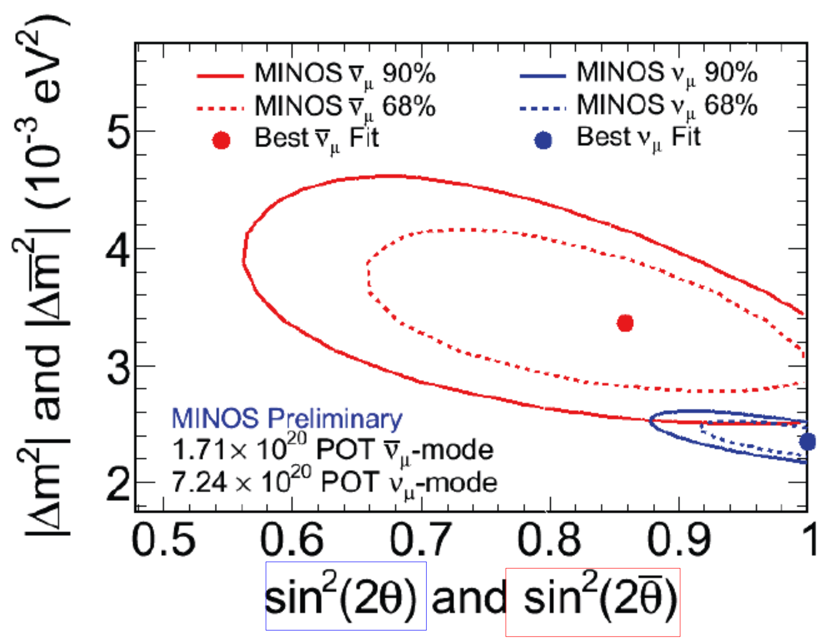


Not included in our fits since MINOS is a more stringent limit for the region we are interested in

We would really like MINOS to do a NC $\bar{\nu}$ fit too!

MINOS CC: arXiv:1104.0344v1

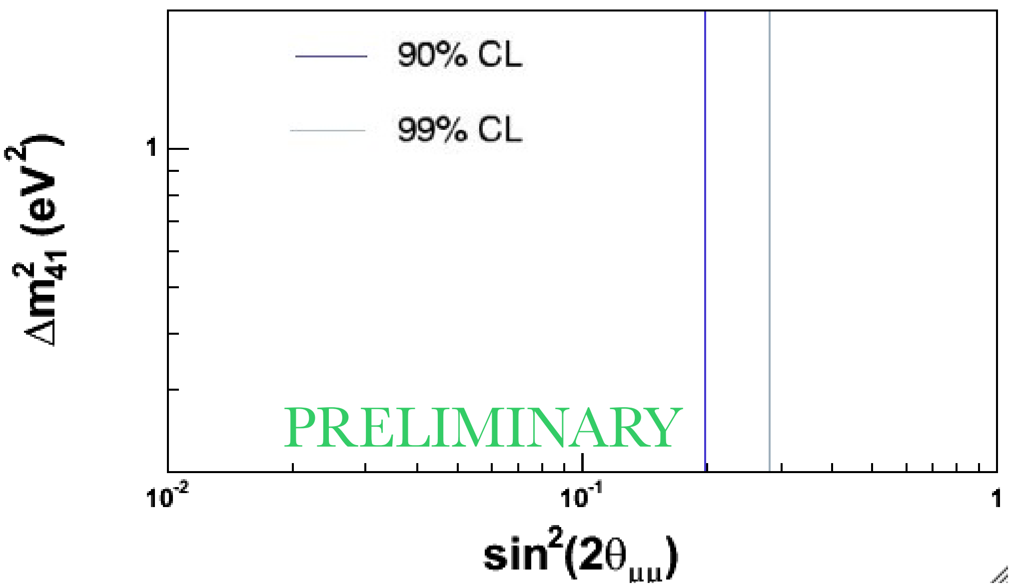




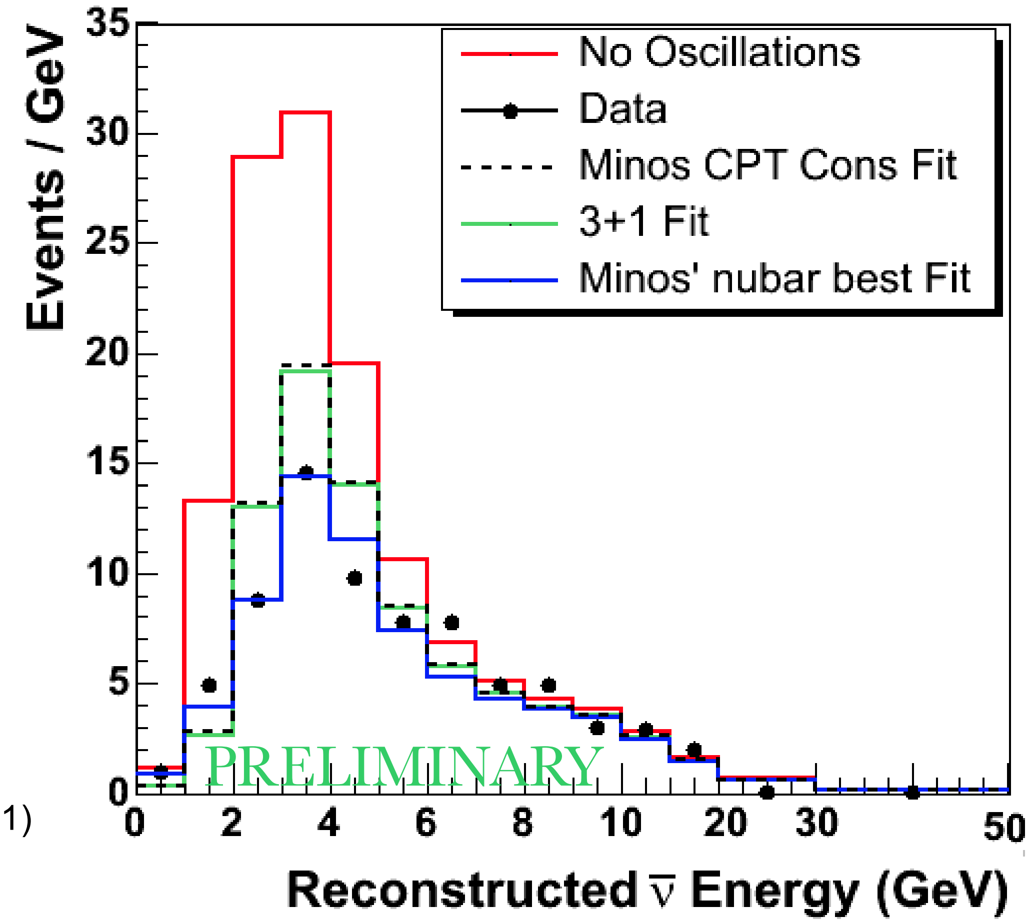
For the most conservative approximation, we assume that the neutrinos have not oscillated into sterile and that the deficit seen in the antineutrino running is due to a sterile neutrino.

Assumes difference between ν and $\bar{\nu}$, so will be left out of Global $\nu + \bar{\nu}$ fits

MINOS CC 3+1 fit



dof	χ^2_{null}	χ^2_{3+1}	Prob(null)	Prob (3+1)
12	14.2	14.0	28.6%	30.3%



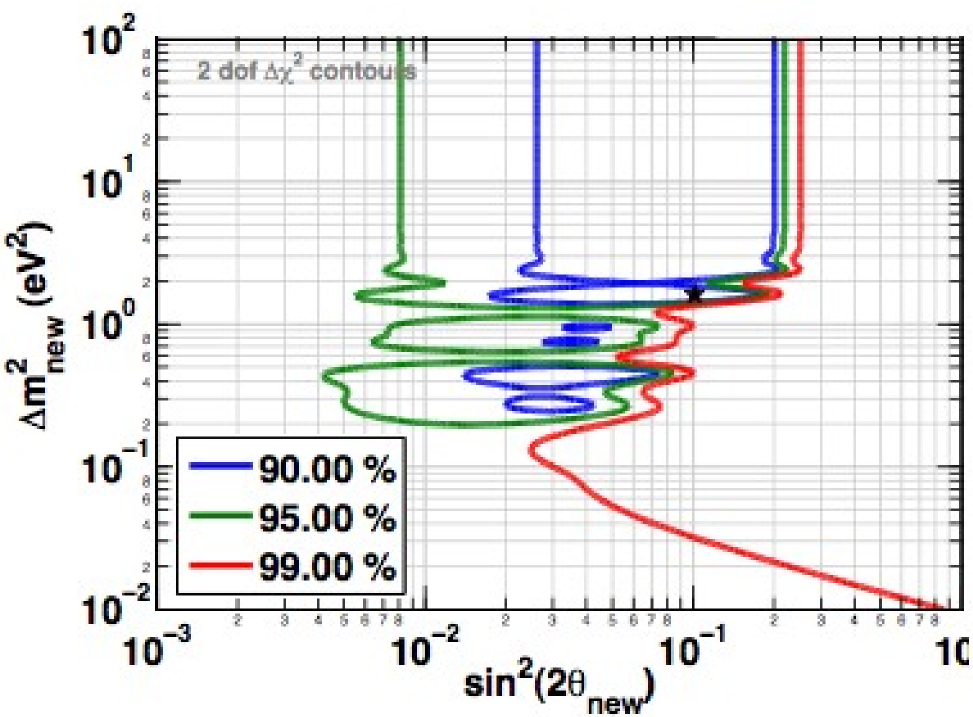
Note: the error on the data is left out of this plot, but was used in the fit as it is on the previous slide

A sterile neutrino in this range does not explain the MINOS $\bar{\nu}$ data

This makes sense, since when we assume fast oscillations, we are concerned with the shape of the histogram, and some of the neutrino fit bins are below the data

Reactor Anomaly: arXiv:1101.2755

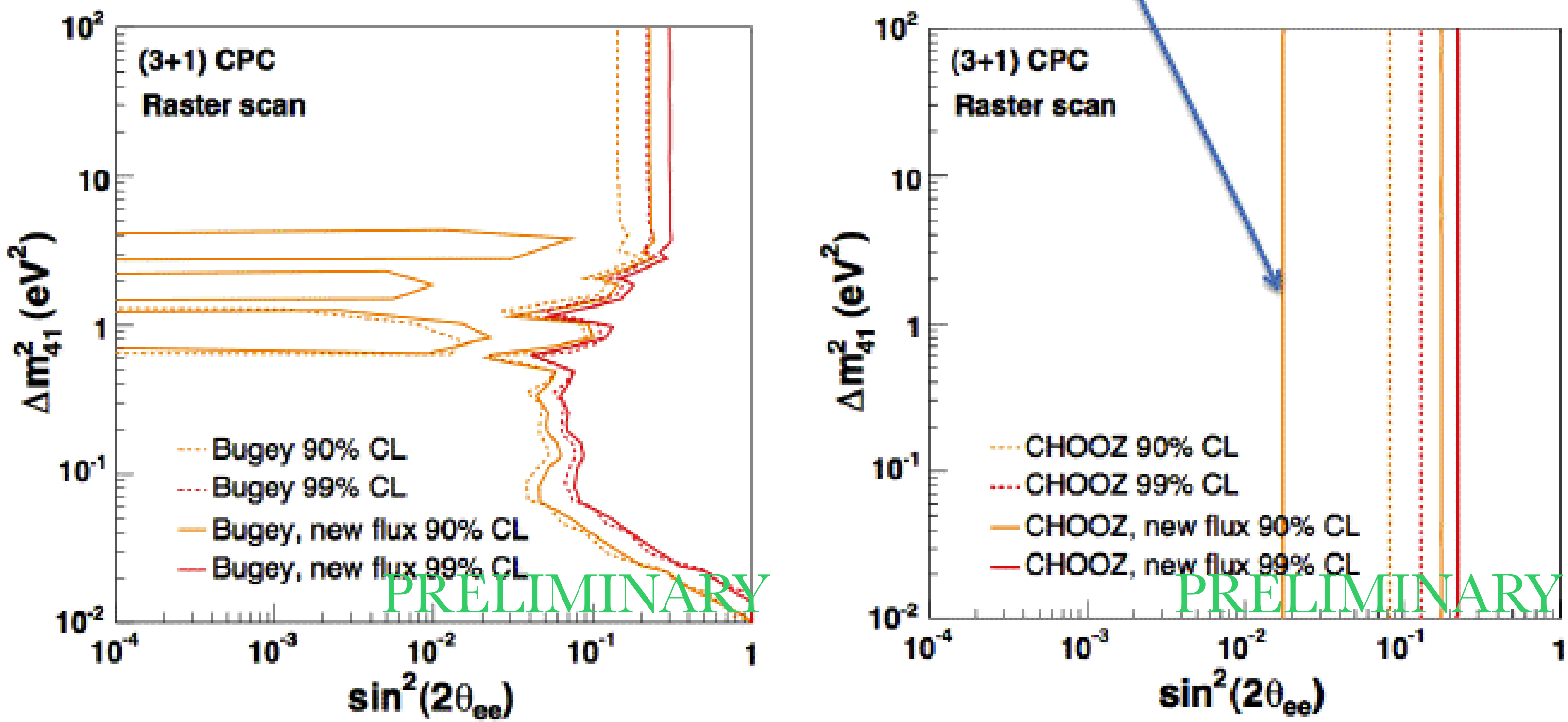
- New reactor flux predictions correspond to a total deficit of ~7%



- Fit from paper to reactor experiments: Bugey, Krasnoyarsk, Rovno, SRP
- Bestfit Δm^2 around 2 eV^2

Bugey and Chooz 3+1 fits

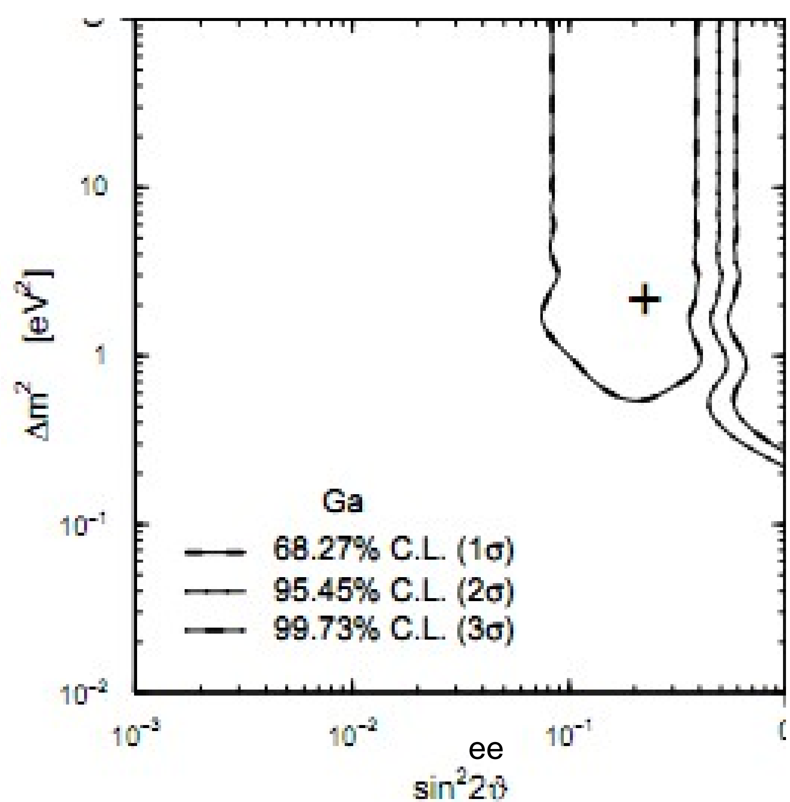
No closed contours when doing global scan, but lower limit for raster scan



Bugey Chooz

Gallium (Gallex and Sage): arXiv:0711.4222v3

- Cr-51 and Ar-37 sources were used to calibrate the GALLEX and SAGE solar neutrino experiments
- Very short baseline (meter scale) so would be sensitive to ~$1\mathrm{eV}^2$ neutrino oscillation
- Bestfit Δm^2 also is in our region of interest!
- Will also constrain U_e in neutrino mode

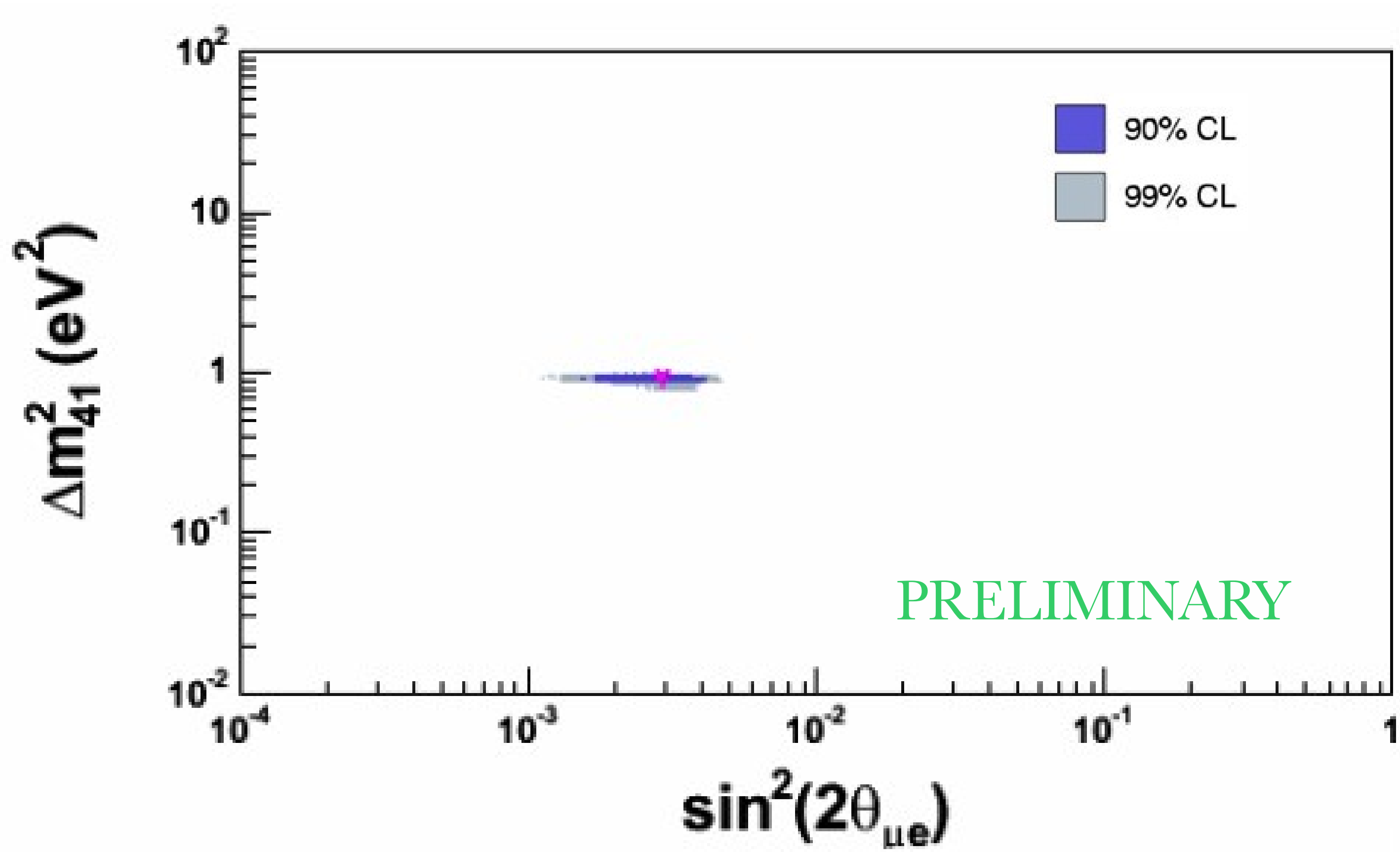


Probability of interaction

$$R = \frac{\int \mathrm{d}V\, L^{-2} \sum_i (\mathrm{B.R.})_i\, \sigma_i\, P_{\nu_e \to \nu_e}(L, E_{\nu,i})}{\sum_i (\mathrm{B.R.})_i\, \sigma_i \int \mathrm{d}V\, L^{-2}}$$

Weighted according to flux

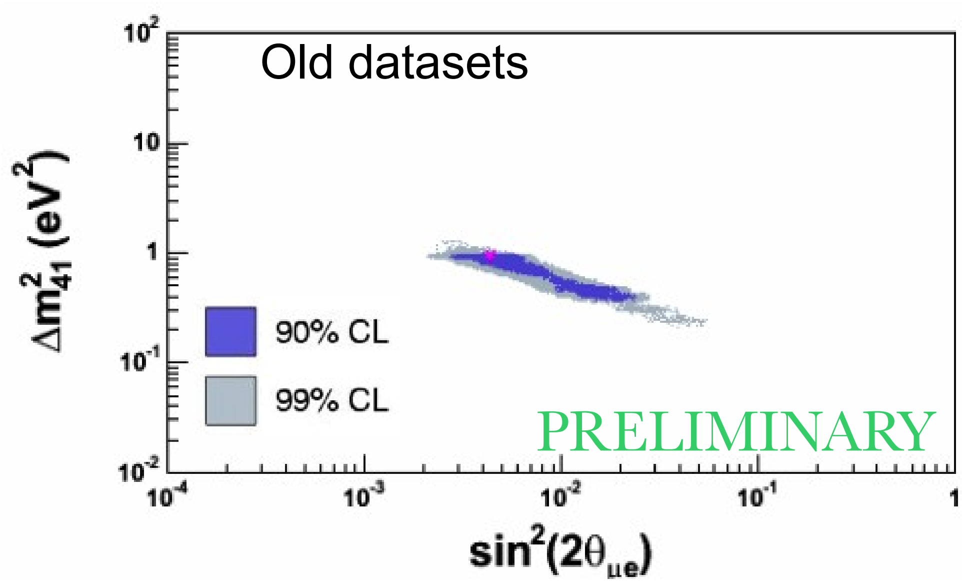
3+1 Global fit

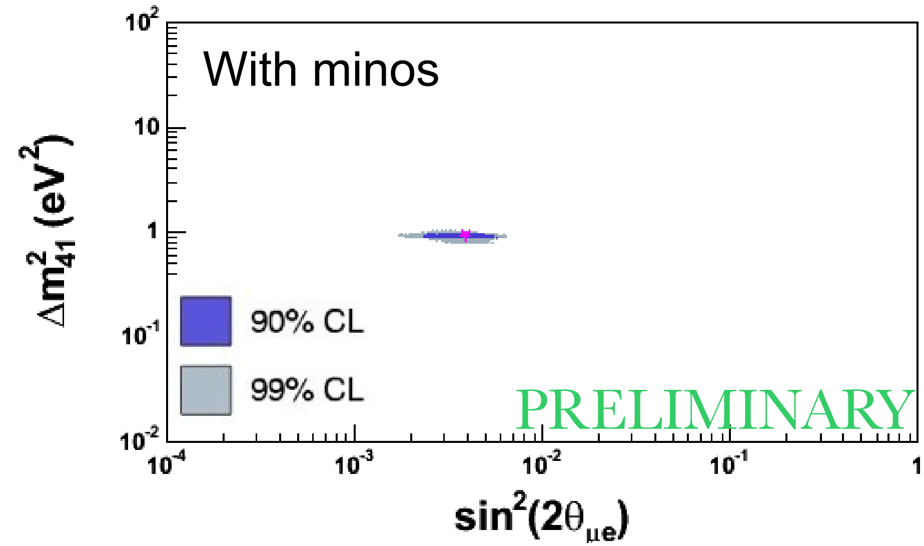


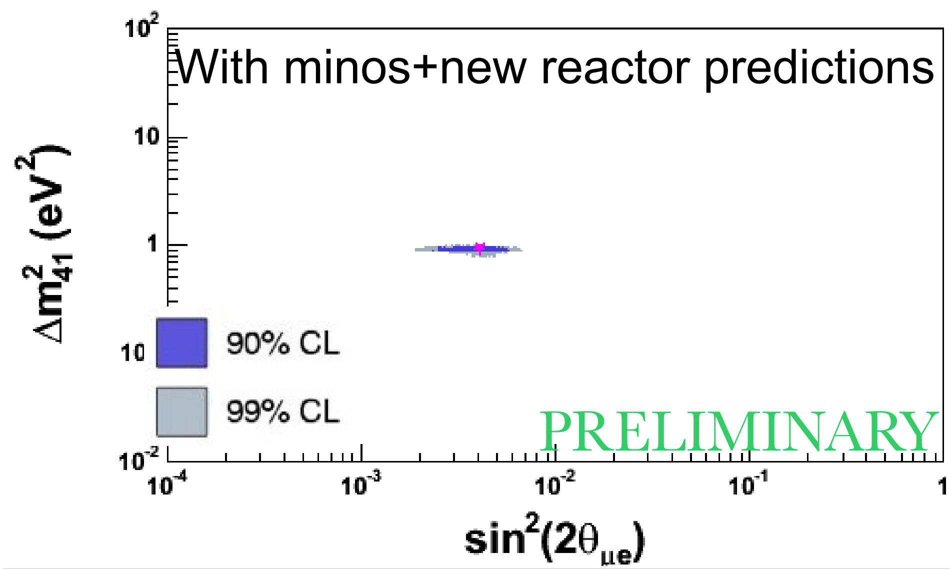
This plot includes all experiments (except for MINOS CC) plus the new fluxes, but the regions are the same for the other fits..

	ndf	χ^2_{null}	P(null)	χ^2_{3+1}	P(3+1)	PG %	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\sin^2 2\theta_{\mu\mu}$	$\sin^2 2\theta_{ee}$
old datasets	196	247	0.81%	203	35%	0.043%	0.92	0.0027	0.14	0.076
including new	200	255	0.48%	209	32%	0.044%	0.91	0.0027	0.14	0.073
new reactor flux	200	259	0.27%	205	40%	0.12%	0.91	0.0029	0.12	0.091

$\bar{\nu}$ Fits

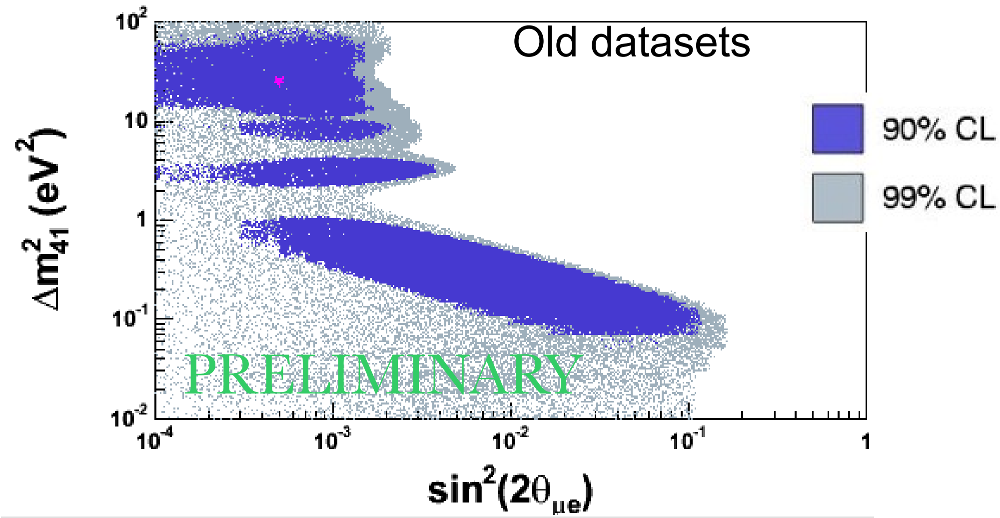


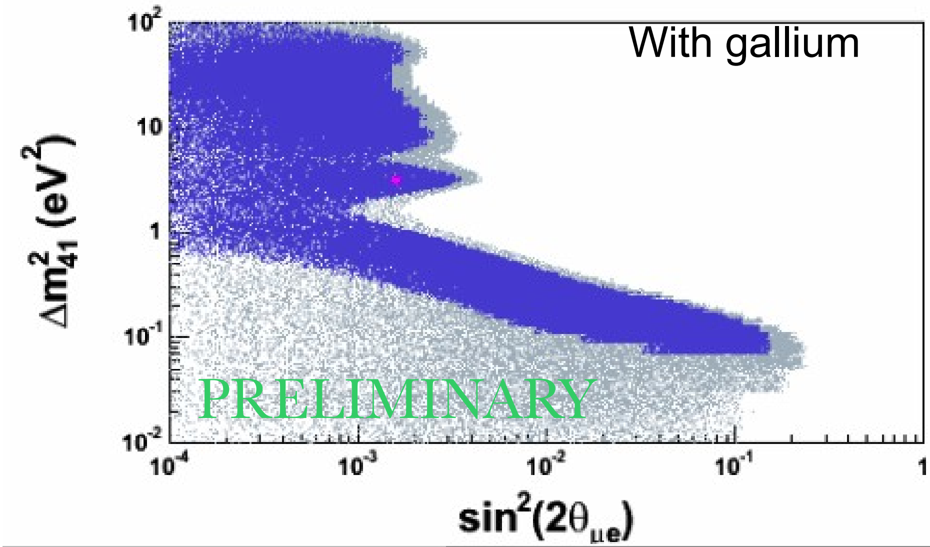


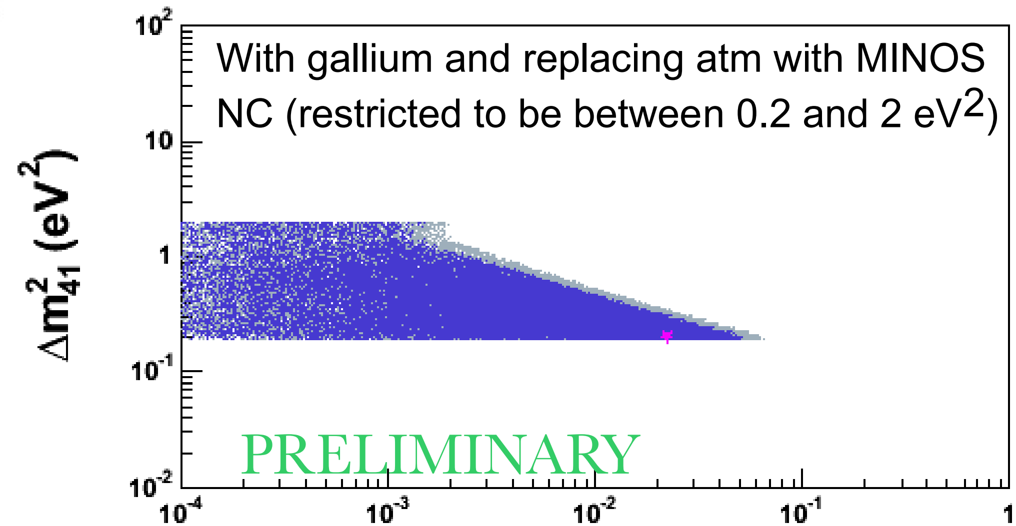


	ndf	χ^2_{null}	P(null)	χ^2_{3+1}	P (3+1)	PG %	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\sin^2 2\theta_{\mu\mu}$	$\sin^2 2\theta_{ee}$
old datasets	103	150	0.16%	92	77.90%	20%	0.91	0.0044	0.38	0.040
including minos	117	165	0.24%	111	63%	7.9%	0.91	0.0039	0.21	0.068
reactor anom	117	165	0.24%	108	71%	16%	0.91	0.0041	0.19	0.079

ν Fit







	ndf	χ^2_{null}	P(null)	χ^2_{3+1}	P (3+1)	PG %	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\sin^2 2\theta_{\mu\mu}$	$\sin^2 2\theta_{ee}$
old datasets	90	103	16%	91	46%	6.4%	24.43	0.00050	0.099	0.020
adding gallium	94	104	23%	96	42%	6.7%	3.13	0.0016	0.020	0.29
add nc (rm atm)	94	111	11%	98	36%	3.3%	0.2	0.022	0.099	0.69

Gallium fits in well with old data

Drop mostly due to restricting the region (PG before adding NC is 3.9% in this region)

How each experiment is affected

Final bestfit values

	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\sin^2 2\theta_{\mu\mu}$	$\sin^2 2\theta_{ee}$	U_μ	U_e	PG(%)
global	0.91	0.0029	0.12	0.091	0.15	0.18	0.12%
$\bar{\nu}$ only	0.91	0.0041	0.19	0.079	0.22	0.14	16%
ν only (no nc)	3.1	0.0016	0.020	0.29	0.07	0.28	6.7%

χ^2 for each experiment

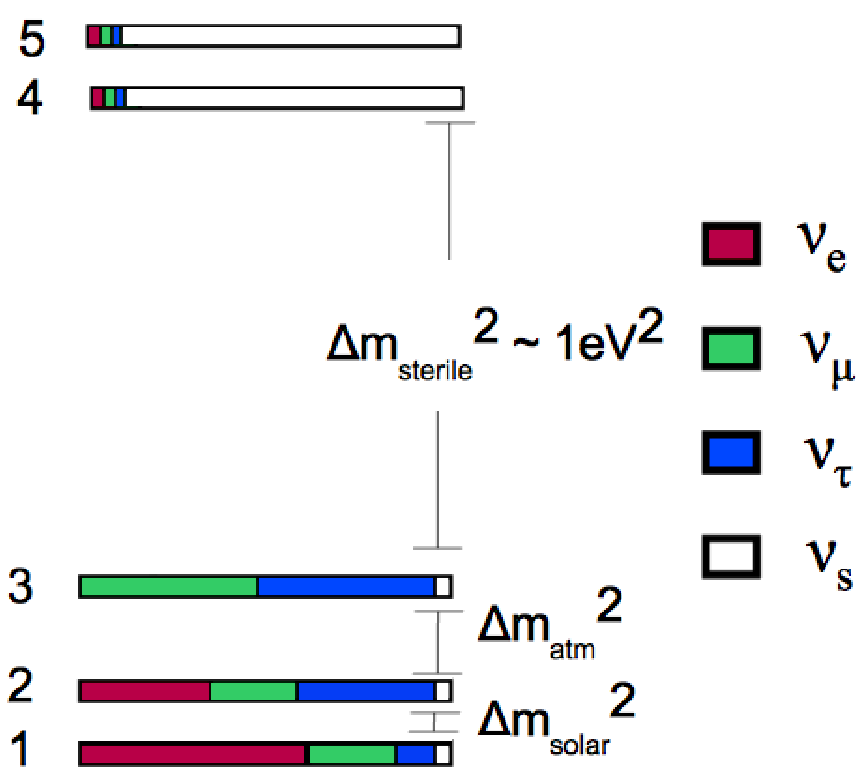
		dof	χ^2_{null}	χ^2_{3+1} Global	χ^2_{3+1} $\nu/\bar{\nu}$	P(null)	P (Global)	P($\nu/\bar{\nu}$)		
ν	MiniBooNE ν	16	22	25	18	14%	6.9%	35%	MiniBooNE ν	$\nu_\mu \to \nu_e$
	NOMAD	28	35	35	35	16%	16%	16%	NOMAD	$\nu_\mu \to \nu_e$
	NUMI	8	6.7	5.3	6.0	57%	72%	64%	NUMI	$\nu_\mu \to \nu_e$
	CCFR84	16	18	18	18	34%	34%	34%	CCFR84	$\nu_\mu \to \nu_\mu$
	CDHS	13	14	18	16	35%	18%	25%	CDHS	$\nu_\mu \to \nu_\mu$
	Gallium	2	8.0	5.4	3.5	1.8%	6.6%	18%	Gallium	$\nu_e \to \nu_e$
$\bar{\nu}$	LSND	3	53	8.8	5.0	0.00%	3.3%	17%	LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$
	MiniBooNE $\bar{\nu}$	16	33	25	24	0.70%	6.2%	9.2%	MiniBooNE $\bar{\nu}$	$\bar{\nu}_\mu \to \bar{\nu}_e$
	Karmen	7	7.1	8.4	9.7	42%	30%	21%	Karmen	$\bar{\nu}_\mu \to \bar{\nu}_e$
	Bugey	58	52	47	46.4	69%	84%	86%	Bugey	$\bar{\nu}_e \to \bar{\nu}_e$
	Chooz	12	10	6.2	6.3	60%	91%	90%	Chooz	$\bar{\nu}_e \to \bar{\nu}_e$
	MINOSCC	14	14	-	17	43%	-	27%	MINOSCC	$\bar{\nu}_\mu \to \bar{\nu}_\mu$

PRELIMINARY

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



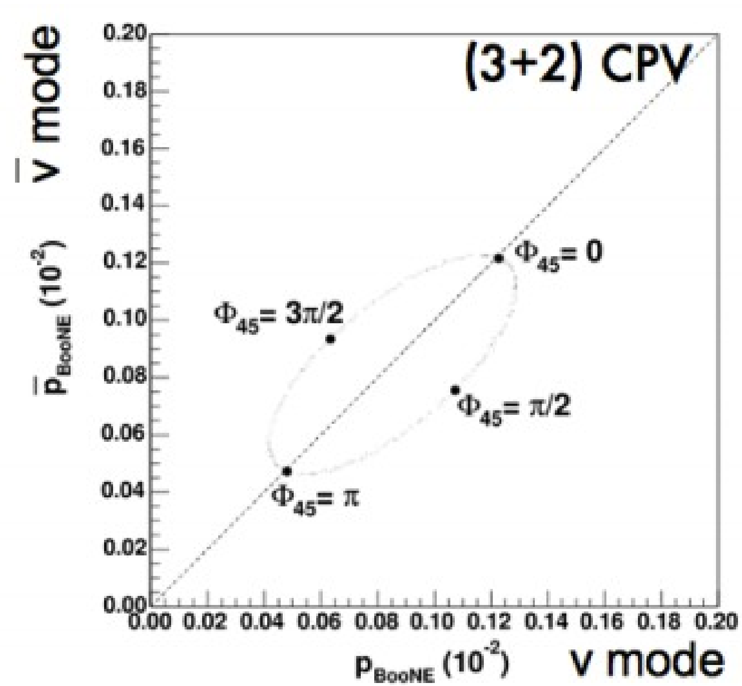
Disappearance

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

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+2 fits

Dataset	CP	χ^2 (ndf)	gof	Δm^2_{41}	Δm^2_{51}	U_{e4}	$U_{\mu4}$	U_{e5}	$U_{\mu5}$	φ_{45}
All: old	**CPC**	191.5 (193)	52%	0.92	24.0	0.12	0.14	0.070	0.14	0
	CPV	189.3 (192)	54%	0.92	26.5	0.13	0.13	0.078	0.15	1.7π
All: including new reactor fluxes	**CPC**	186.1 (193)	62%	0.92	23.8	0.13	0.13	0.083	0.14	0
	CPV	182.6 (192)	67%	0.92	26.6	0.14	0.14	0.077	0.15	1.7π

PRELIMINARY

New reactor fluxes decrease tension among data

Gallium and minos not yet included here

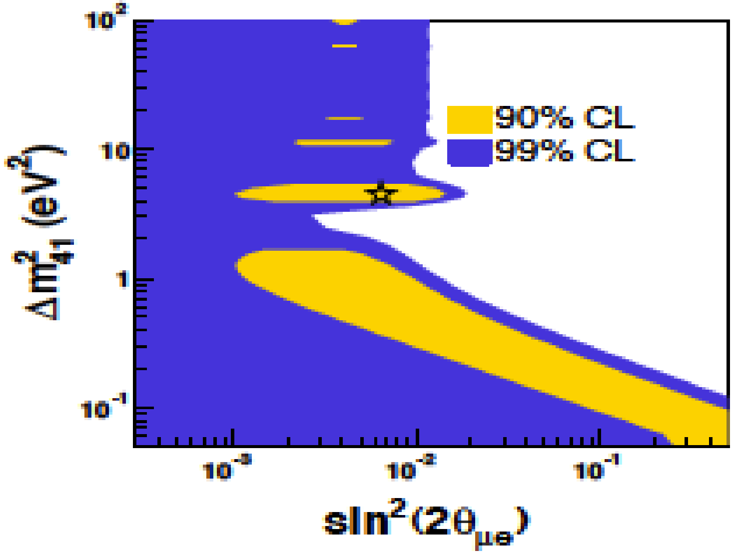
Conclusions

- MINOS is able to constrain Umu4, and the final $\bar{\nu}$ fit still has a PG of 16%
- Gallium fits in nicely with the ν fit: PG=6.7%, but constraining the Δm^2 to 2 eV^2 to include MINOS NC lowers this to 3.3%
- Reactor anomaly reduces the tension in all of the fits, but an overall global 3+1 fit still doesn't do very well: PG = 0.12%
- Reactor anomaly reduces the tension in the 3+2 cpv fits: PG=6%
- An overall 3+1 fit is not a good fit to the data! We must either introduce a second sterile neutrino to allow for cp violation or separate neutrinos from antineutrinos in a 3+1 fit.
    - We have no physical explanation for why neutrinos would behave differently than antineutrinos in 3+1 fits!

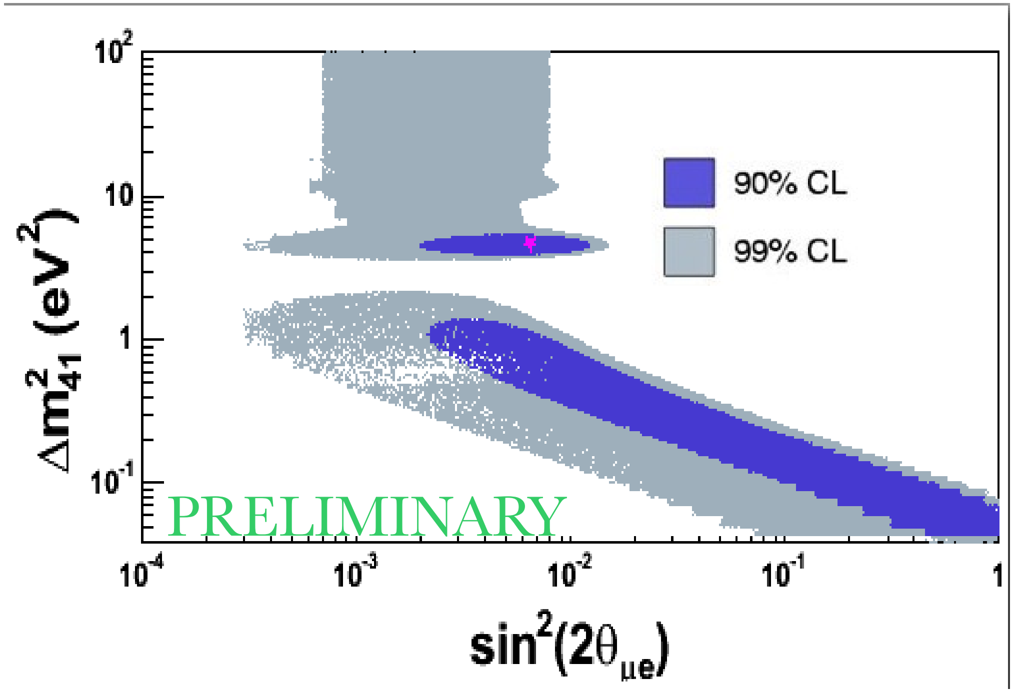
Backup slides

MiniBooNE $\bar{\nu}$ update

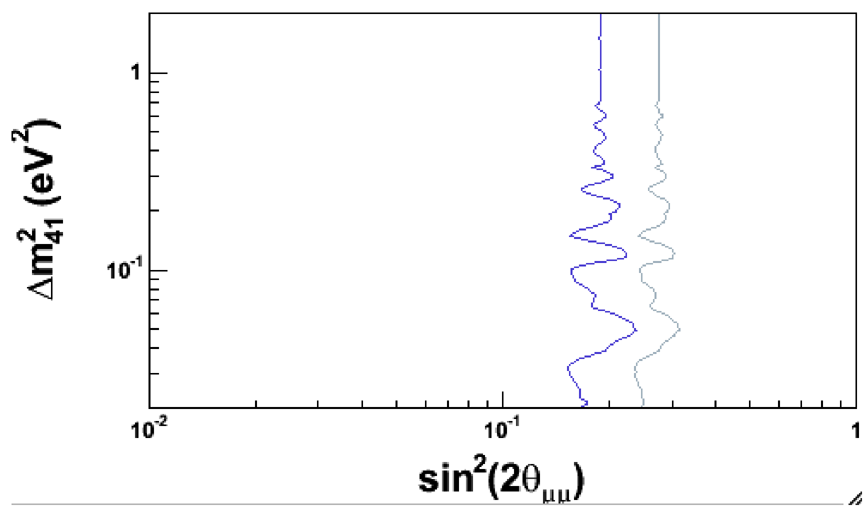
arXiv:0906.1997v2

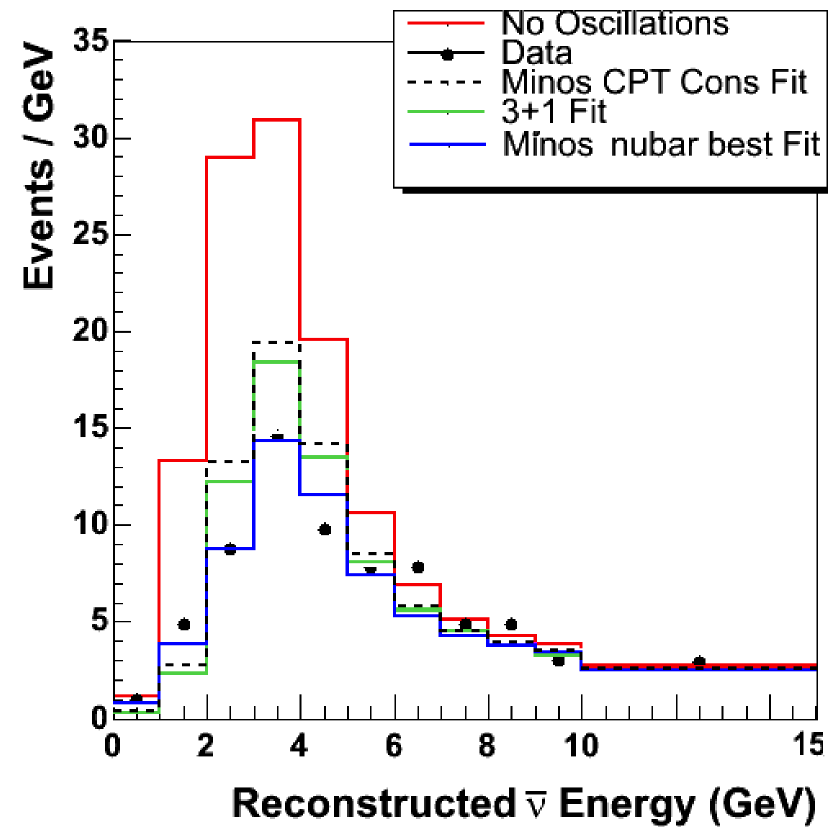


2010 data release update



MINOS CC without fast oscillations only





dof	χ^2_{null}	χ^2_{3+1}	Prob(null)	Prob (3+1)	Δm^2_{41}	$\sin^2 2\theta_{\mu\mu}$
12	14.2	14.0	28.6%	30.3%	0.050	0.071

Fast oscillations condition rather than only so that fit can go lower.

It looks like the wiggles are still an effect of energy resolution issues, and since our bestfit regions are higher than this anyway, it was less complicated to restrict the region to where fast oscillations is definitely a good approximation for our global fits.