Sterile Neutrinos: Experimental Hints and Status of Global Fits

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NuFact 2012, Williamsburg VA

OUTLINE

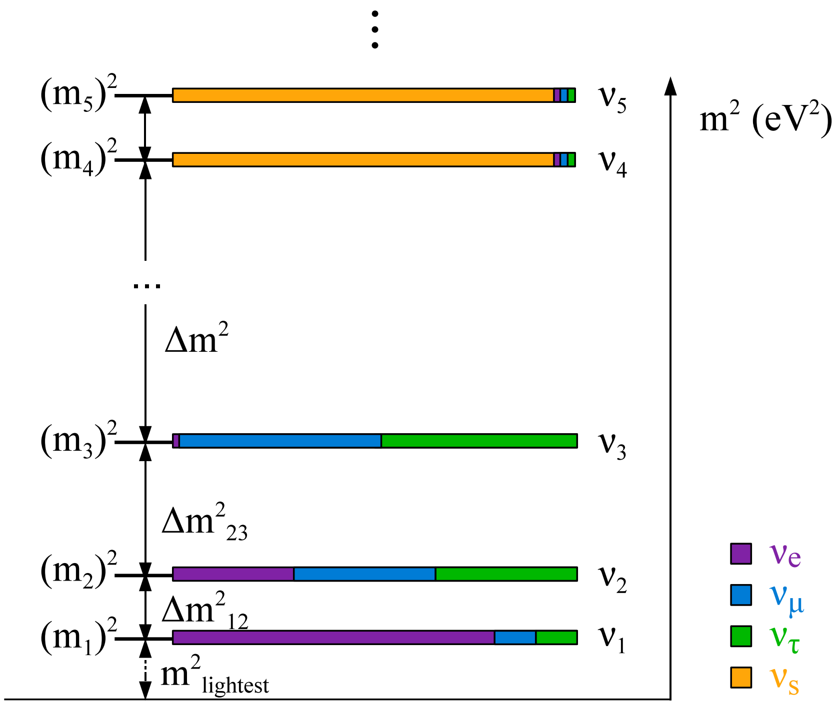
- Phenomenology of sterile neutrinos
- Experimental anomalies
- Experimental constraints
- Global fits (Conrad et al, hep-ph/1207.4765)
- What's next (more on this from B. Fleming)

PHENOMENOLOGY OF STERILE NEUTRINO OSCILLATIONS

- Additional neutrino "flavor" (and mass) states which have no weak interactions (through the standard W/Z bosons)

- Additional mass states are assumed to be produced through mixing with the standard model neutrinos

  → Can affect neutrino oscillations through mixing



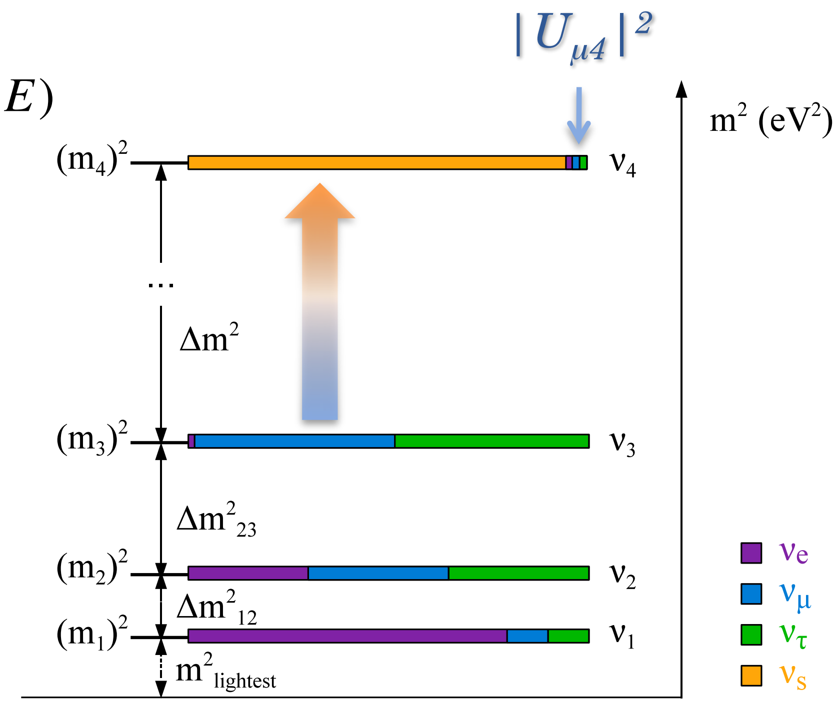
Phenomenology of Sterile Neutrino Oscillations: (3+1)

Oscillation effects:

ν_μ disappearance*:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

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



(3+1)

*$m_1 \approx m_2 \approx m_3 << m_4$

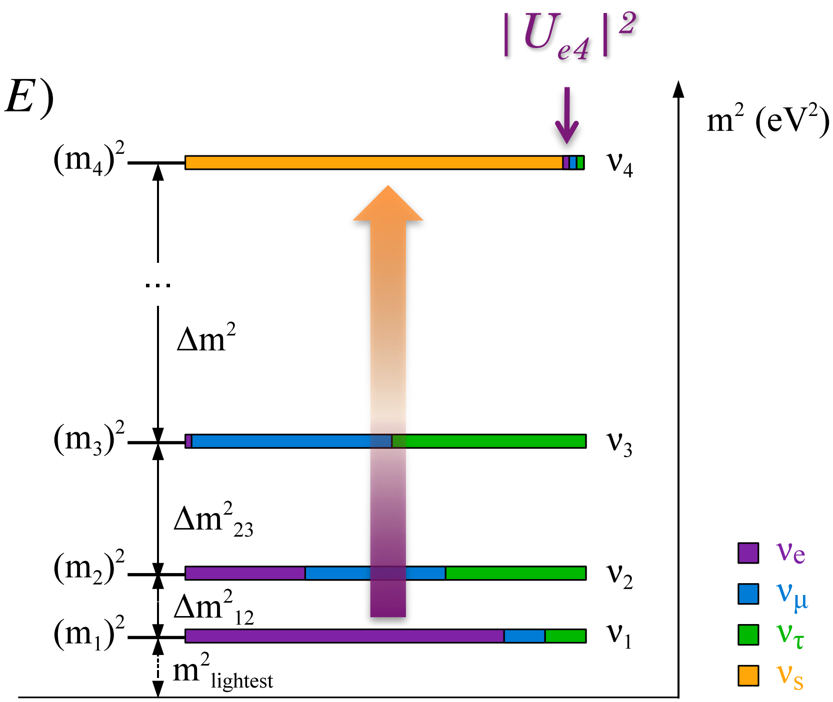
PHENOMENOLOGY OF STERILE NEUTRINO OSCILLATIONS: (3+1)

Oscillation effects:

ν_e disappearance*:

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)$$



(3+1)

*$m_1 \approx m_2 \approx m_3 << m_4$

Phenomenology of Sterile Neutrino Oscillations: (3+1)

Oscillation effects:

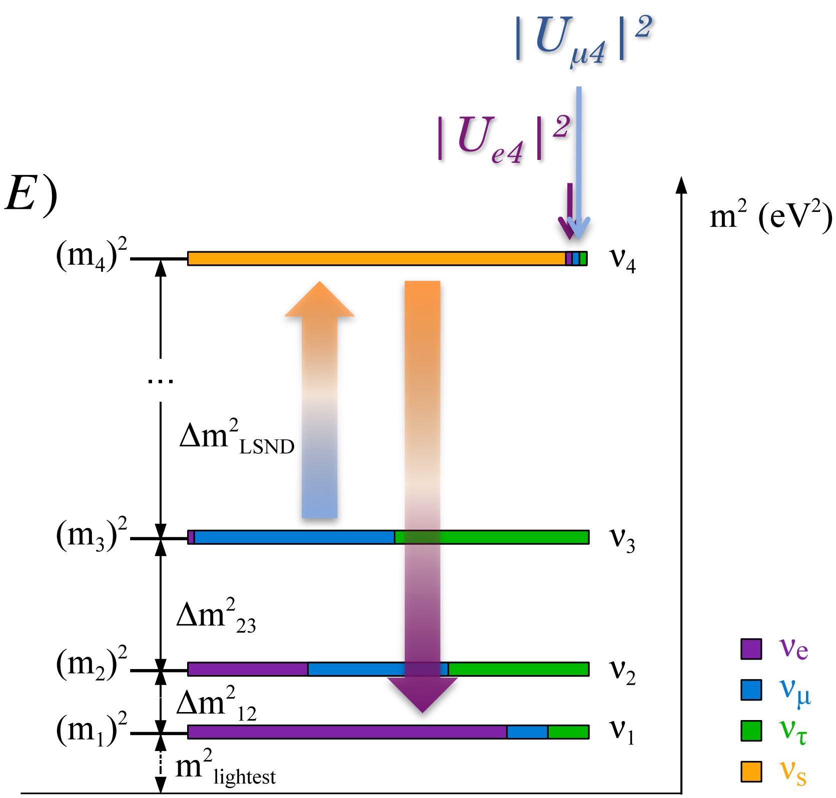
$\nu_\mu \rightarrow \nu_e$ appearance*:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow \quad 4|U_{e4}|^2|U_{\mu 4}|^2$$

In the same model, appearance comes from oscillation through ν_s:

$$\nu_\mu \to \nu_e = (\nu_\mu \to \nu_s) + (\nu_s \to \nu_e)$$

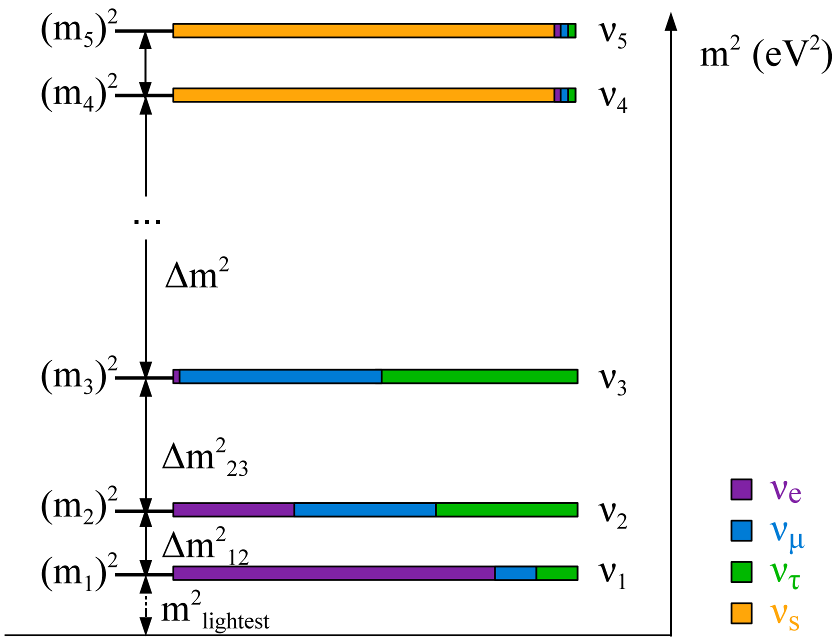


(3+1)

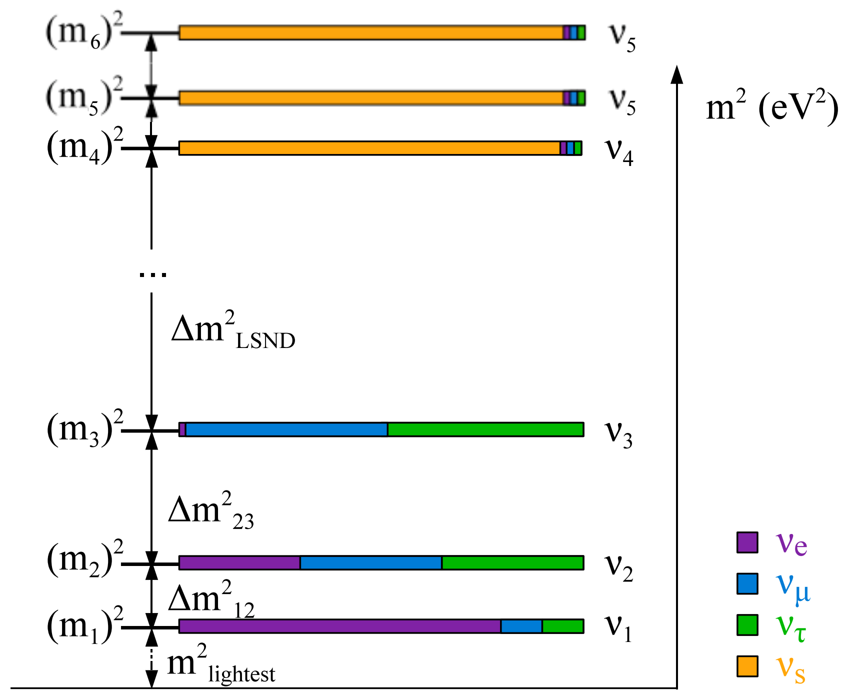
*$m_1 \approx m_2 \approx m_3 << m_4$

Phenomenology of Sterile Neutrino Oscillations: (3+1) and (3+2)

Can have more than one new state…



(3+2)

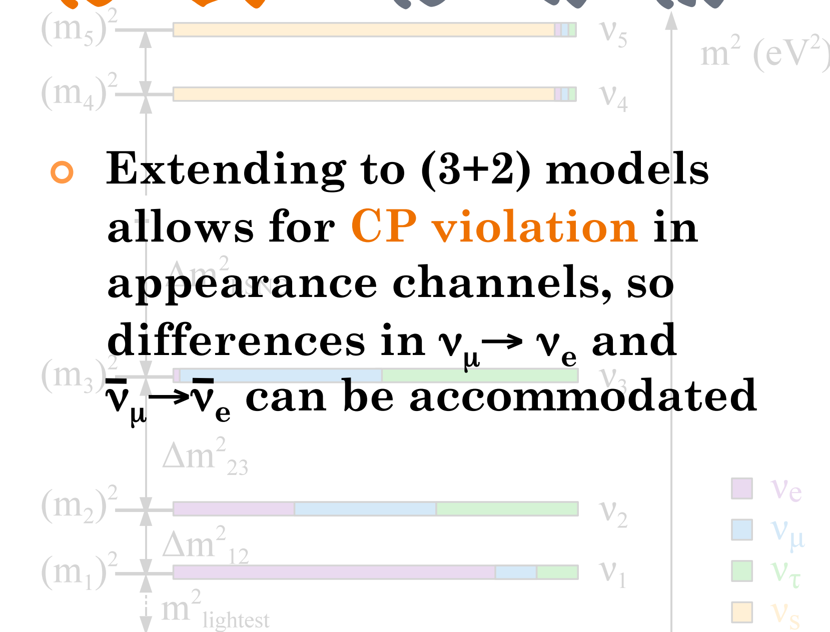


(3+3)

$*m_1 \approx m_2 \approx m_3 << m_4, m_5, m_6$

Phenomenology of Sterile Neutrino Oscillations: (3+1) and (3+2)

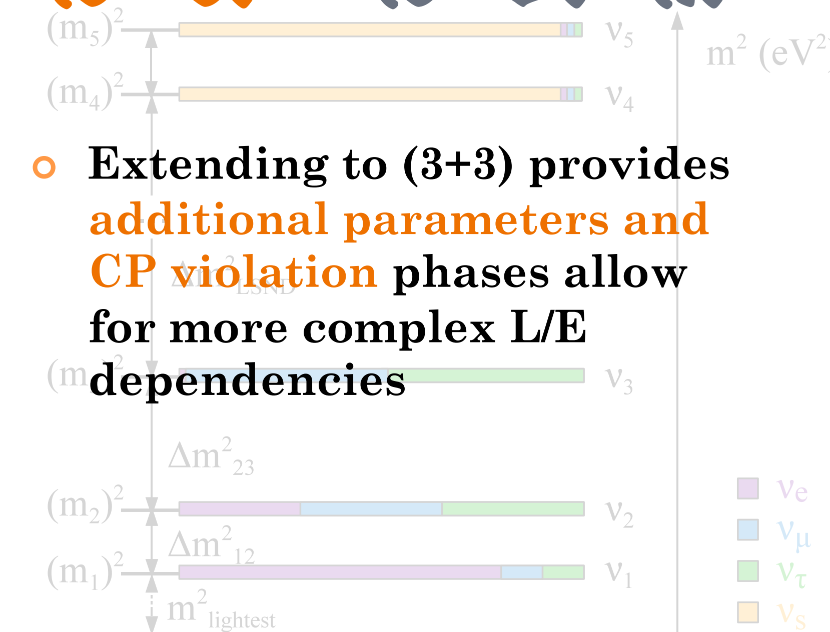
(3+2) » (3+1) (!)



- **Extending to (3+2) models allows for CP violation in appearance channels, so differences in $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ can be accommodated**

(3+2)

(3+3) » (3+2) (!)



- **Extending to (3+3) provides additional parameters and CP violation phases allow for more complex L/E dependencies**

(3+3)

$^*m_1 \approx m_2 \approx m_3 << m_4, m_5, m_6$

SUMMARY OF "ANOMALIES"

Google

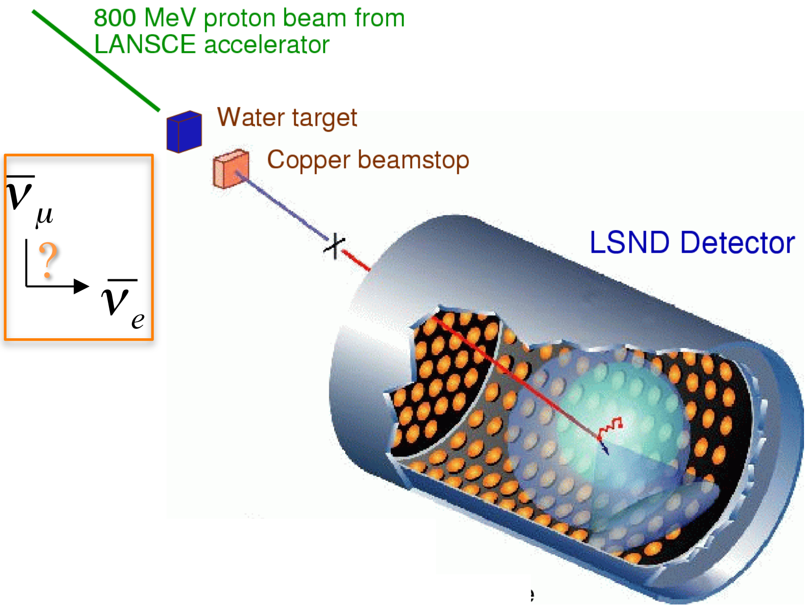
a·nom·a·ly /əˈnäməlē/

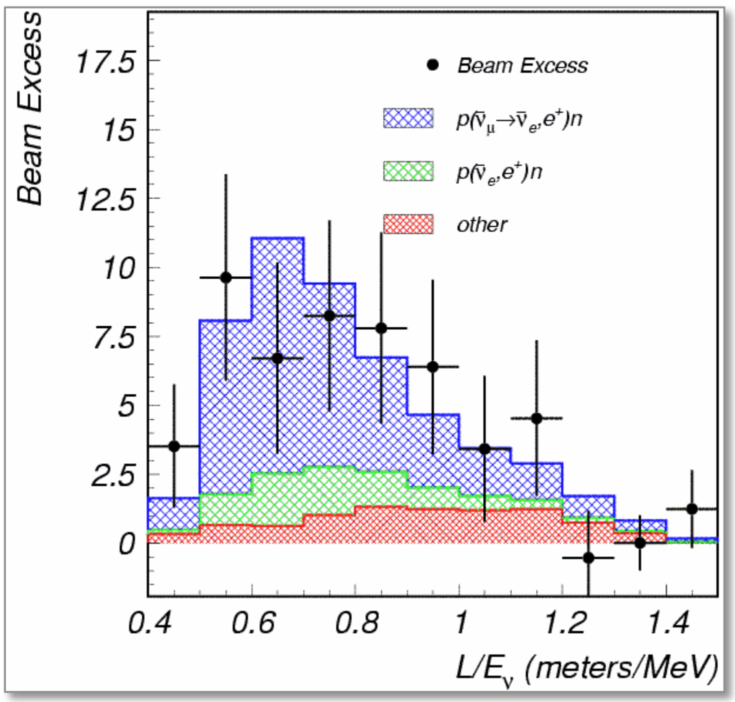
Noun: 1. Something that deviates from what is standard, normal, or expected.

Experiment	Neutrino source	Channel	Signature	L/E [m/MeV]	Significance
LSND	Decay-at-rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\bar{\nu}_e$ excess	0.4–1.5	3.8 σ
MiniBooNE ν	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	ν_e excess	0.2-2.5	3.4 σ
MiniBooNE $\bar{\nu}$	SBL accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\bar{\nu}_e$ excess	0.2-2.5	2.8 σ
Gallex/Sage	Calibration source (e capture)	$\nu_e \rightarrow \nu_e$	ν_e deficit	~0.1-10	2.7 σ
SBL Reactor	Reactor	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$\bar{\nu}_e$ deficit	~0.1-10	3.0 σ

Summary of "Anomalies": LSND

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu \xrightarrow{?} \bar{\nu}_e$$





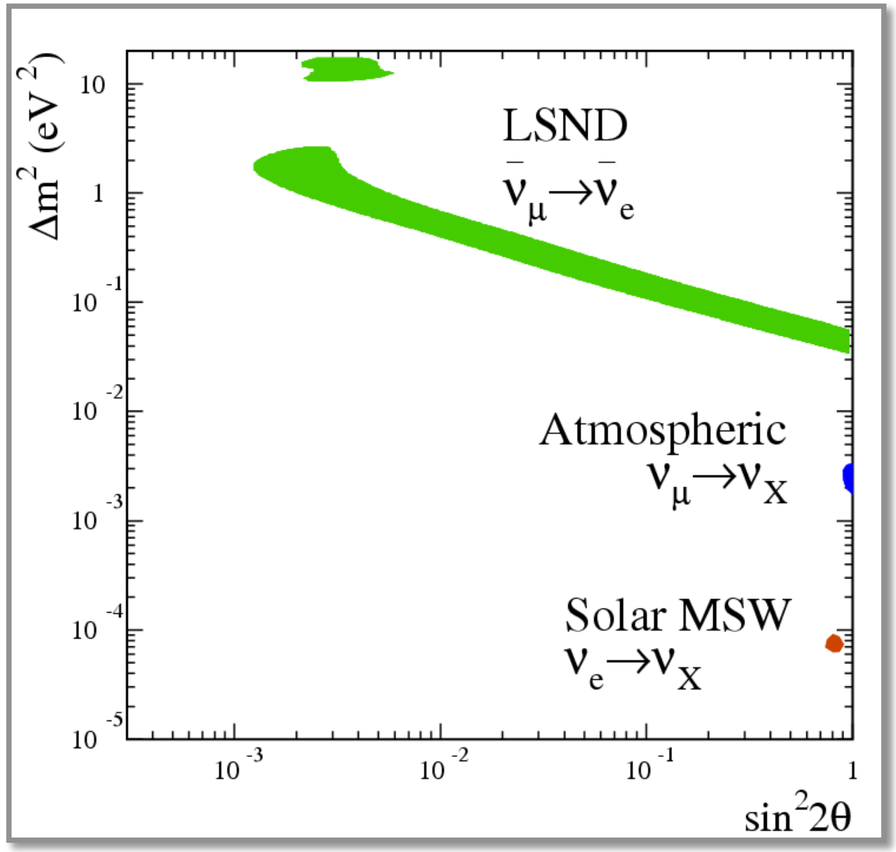
Observed excess of $\bar{\nu}_e$
described by **two-neutrino oscillations**:
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\ \%$

(**3.8σ** evidence)

Summary of "Anomalies": LSND

LSND excess in a (3+1) model →

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

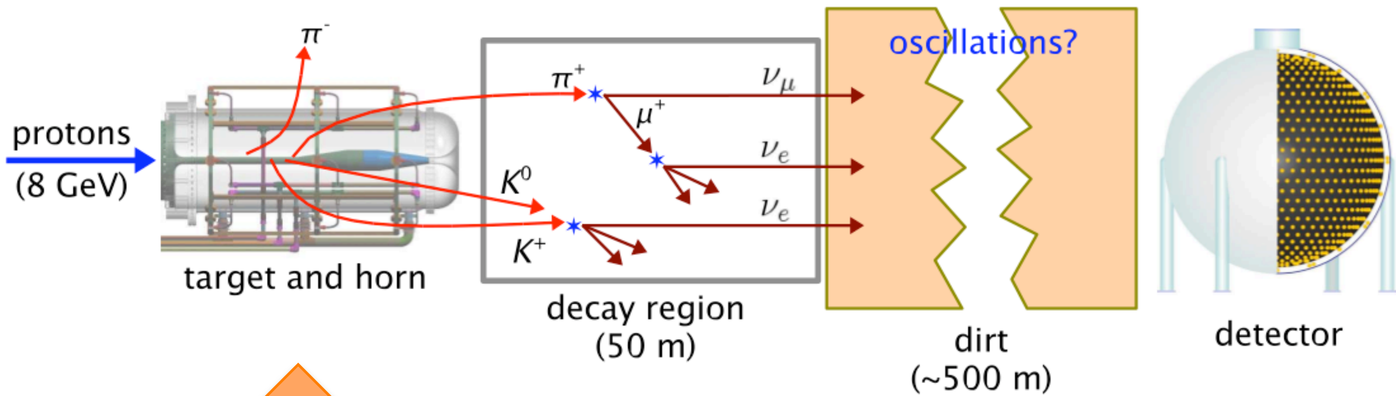


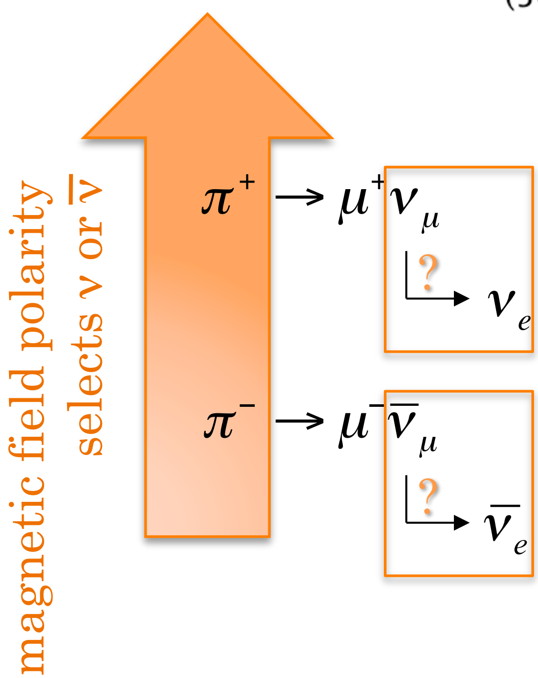
LSND in conjunction with the atmospheric and solar oscillation results needs more than 3 ν's

→ Models developed with 1 or 2 sterile ν's

→ Now also 3 sterile ν's

Summary of "Anomalies": MiniBooNE

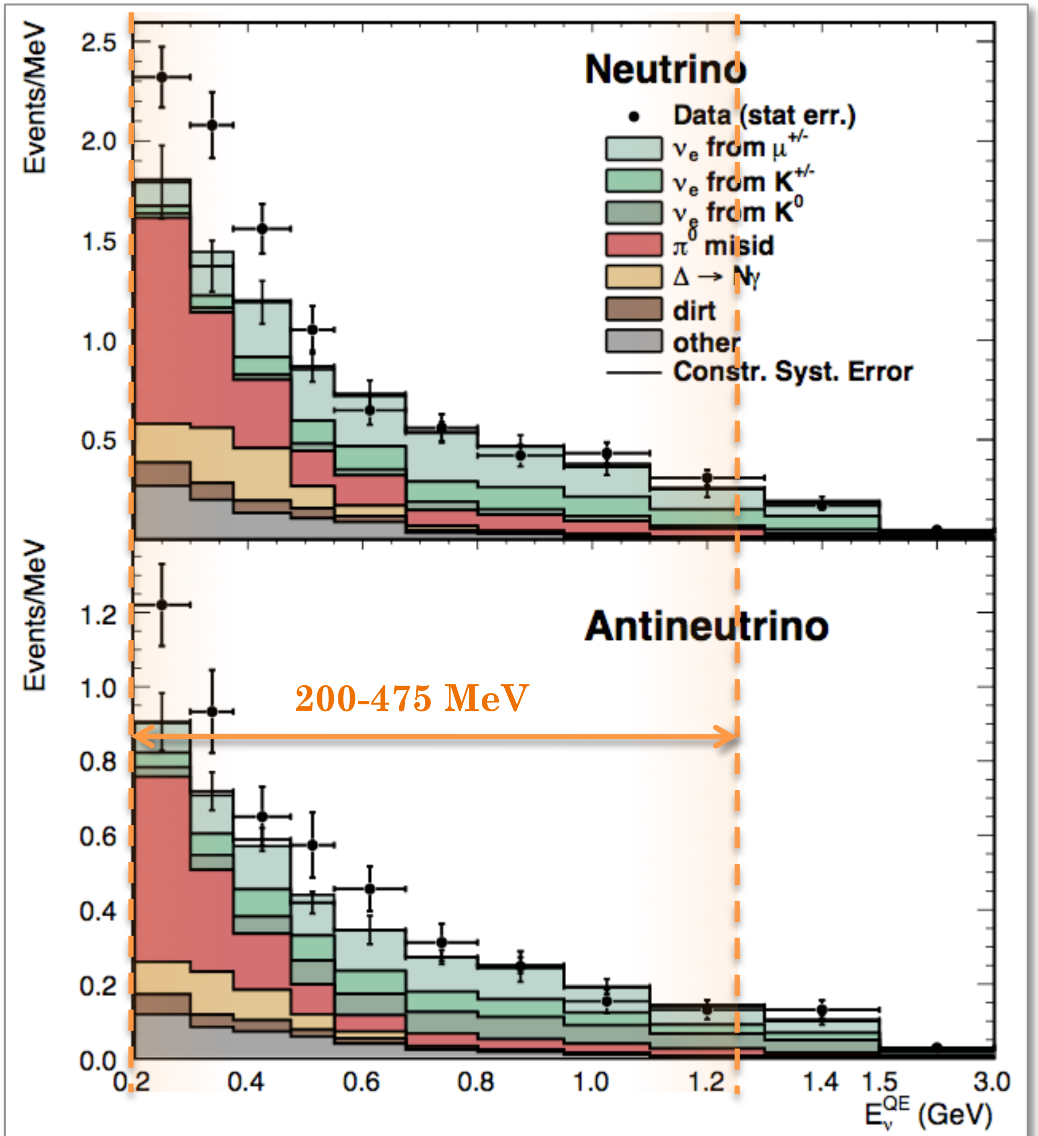




Similar L/E as LSND
but
• Different energy, beam and detector systematics

• Different event signatures and backgrounds

SUMMARY OF "ANOMALIES": MINIBOONE



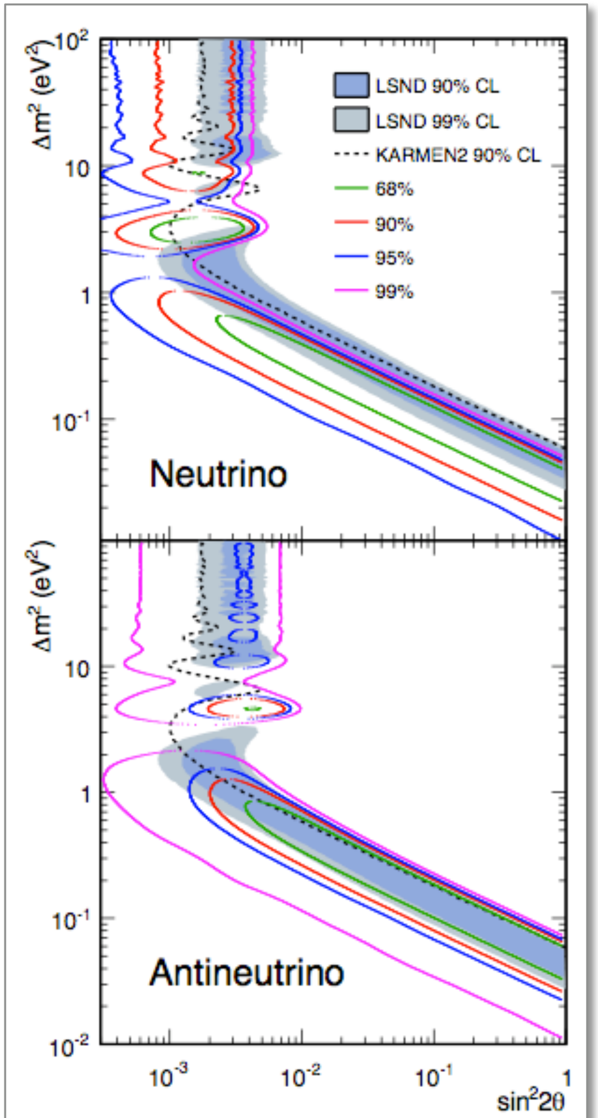
MiniBooNE combined neutrino and antineutrino appearance analysis:

Excess = 240.3 ± 62.9 (3.8 σ)

3.4 σ in neutrino mode +
2.8 σ in antineutrino mode

MiniBooNE June 2012 results → hep-ex/1207.4809

Summary of "Anomalies": MiniBooNE



Neutrino (3+1) best fit:
χ^2-probability = 6.1%
(Δm^2, $\sin^2 2\theta$) = (3.14 eV^2, 0.002)

Background-only relative to best fit: 1.6%

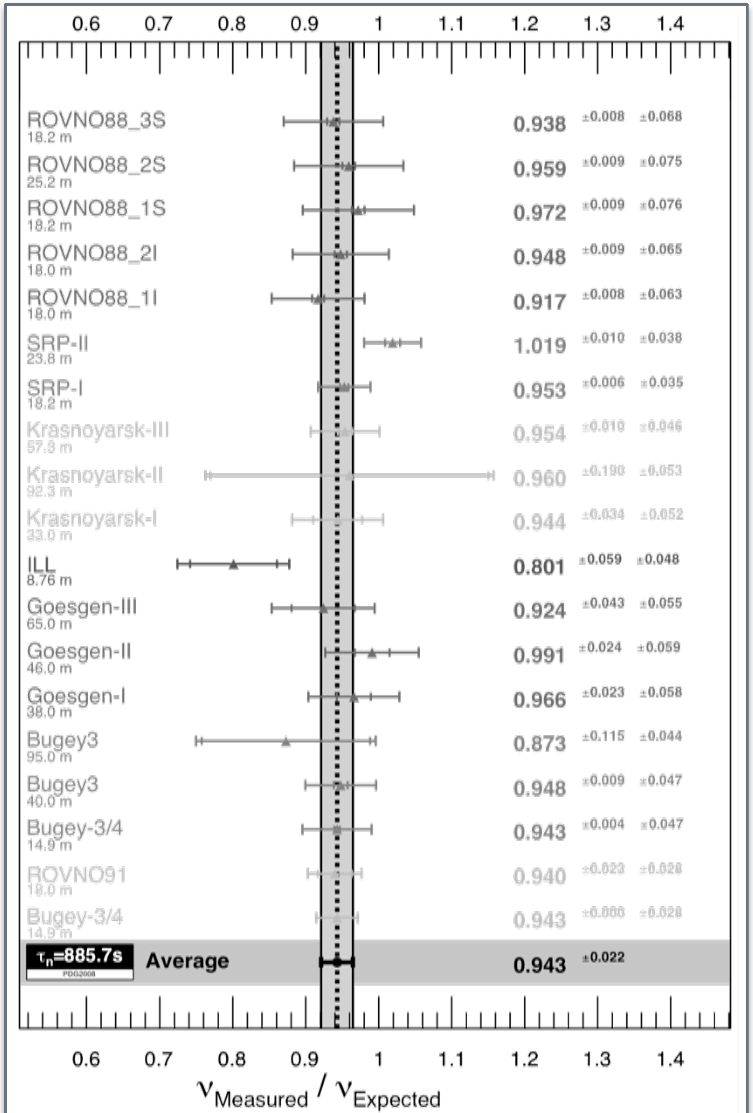
Antineutrino (3+1) best fit:
χ^2-probability = 67.5%
(Δm^2, $\sin^2 2\theta$) = (0.05 eV^2, 0.842)

Background-only relative to best fit: 0.5%

Both are consistent with (3+1) oscillations, but MiniBooNE antineutrino results seem more consistent with LSND than neutrino results.

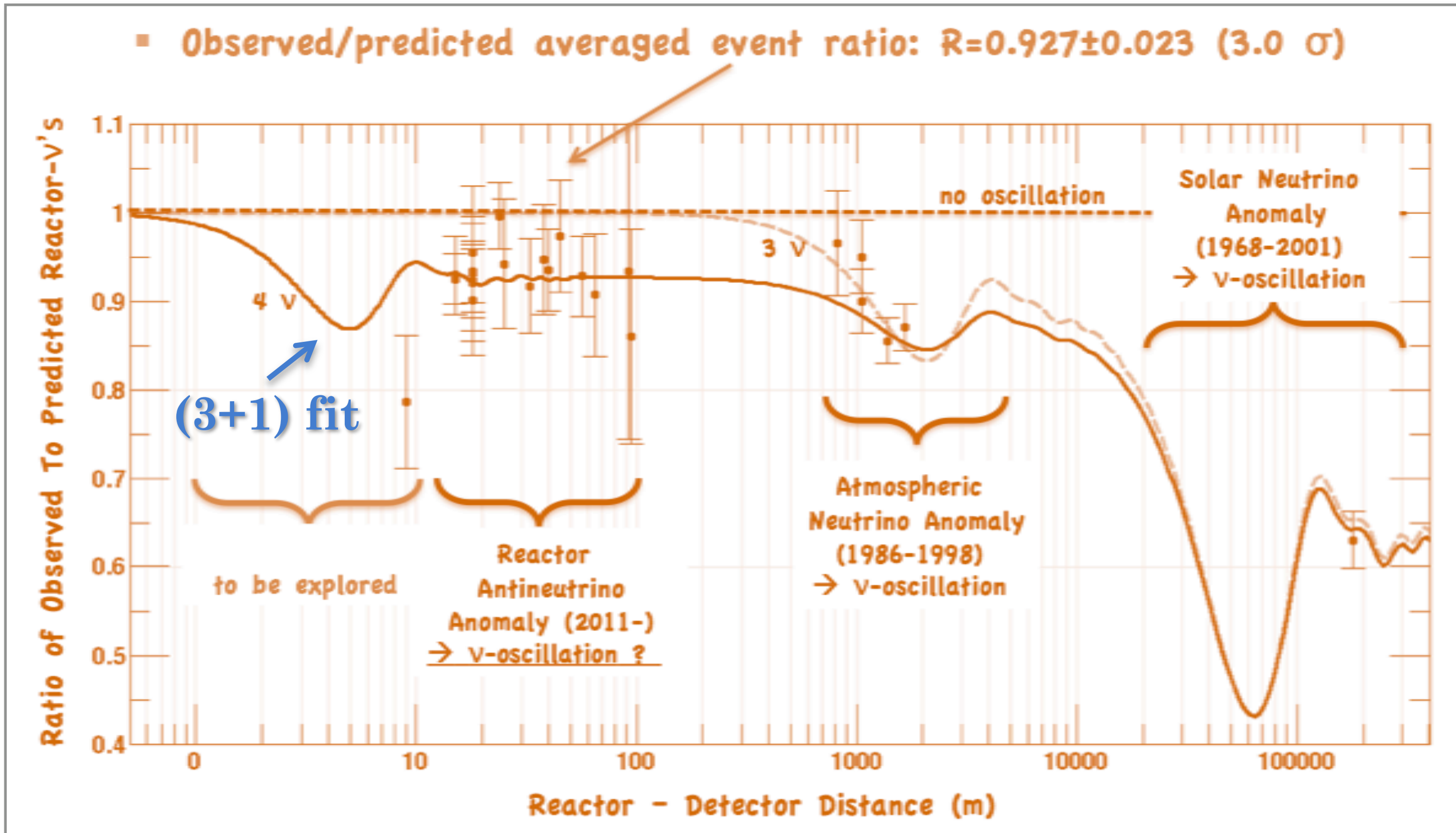
MiniBooNE June 2012 results → hep-ex/1207.4809

Summary of "Anomalies": SBL Reactor



- New reactor antineutrino spectra
  - Net 3% upward shift in energy-averaged fluxes
  - Phys. Rev. C83, 054615, 2011
- Recent re-analysis of 19 reactor neutrino results
  - Neutron lifetime correction & off-equilibrium effects
  - Phys. Rev. D83, 073006, 2011
  - **Obs/Pred = 0.927±0.023 (3 σ)**
- At least three alternatives
  - Wrong prediction of $\bar{\nu}$ spectra?
  - Bias in all experiments?
  - **New physics at short baselines: mixing with a 4th neutrino state**

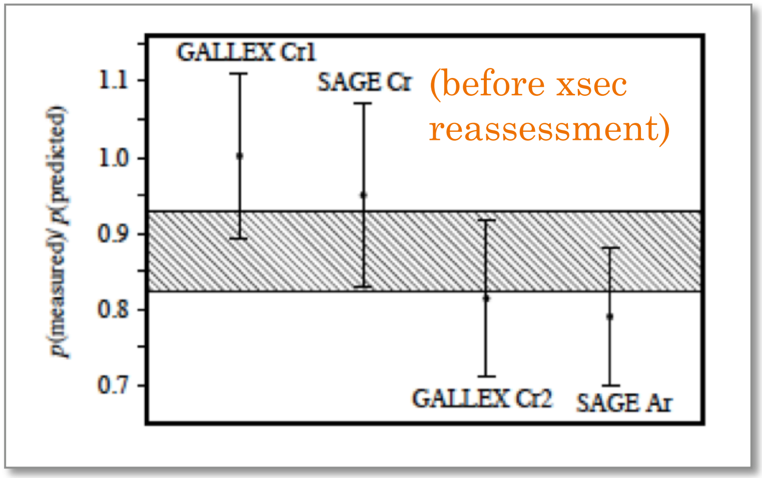
SUMMARY OF "ANOMALIES": SBL REACTOR



- Kamland at much larger L → in "solar" Δm^2 region
- θ_{13} experiments at atmospheric L → near/far comparisons remove anomaly
- **To see the anomaly effect, need very short baseline detectors: L < 10m**

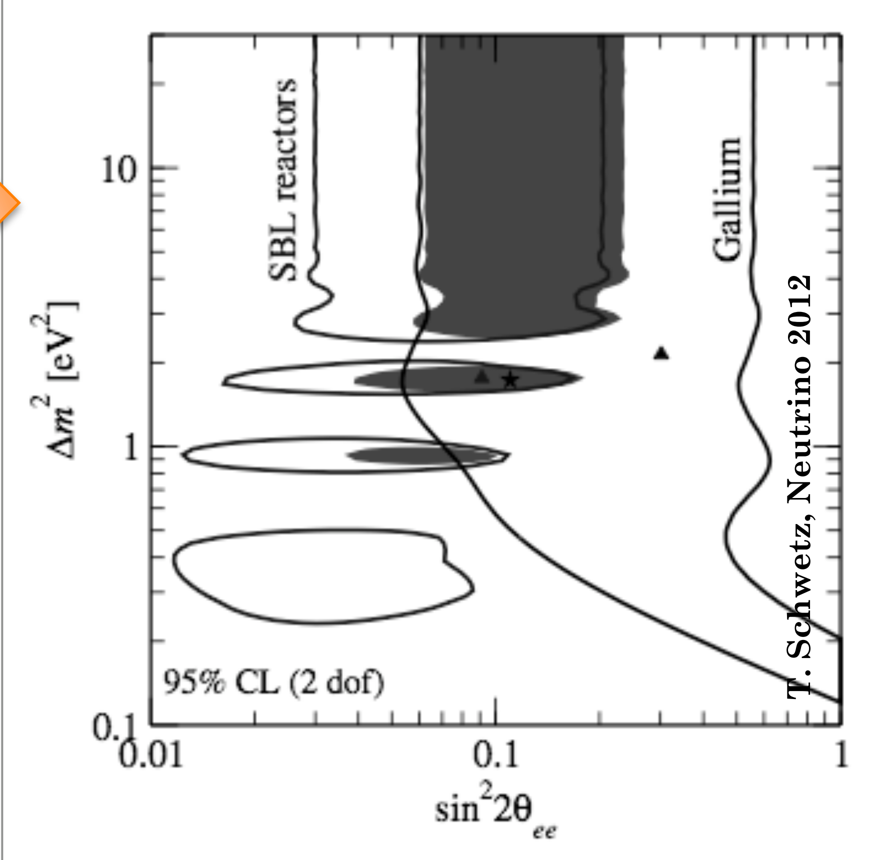
SUMMARY OF "ANOMALIES": GALLEX/SAGE

- **Gallium-based** solar neutrino experiments SAGE and GALLEX used ^{37}Ar and ^{51}Cr ν_e sources to calibrate their detectors
  - **Ratio (observation/prediction) = 0.76 ± 0.09 (3 σ deficit)**
  - **(3+1) oscillation interpretation gives:**
    $\Delta m^2 > 0.35$ eV^2
    $\sin^2 2\theta > 0.07$



(before xsec reassessment)

(Giunti and Laveder, 1006.3244v3 [hep-ph])



T. Schwetz, Neutrino 2012

Conrad et al, hep-ph/1207.4765

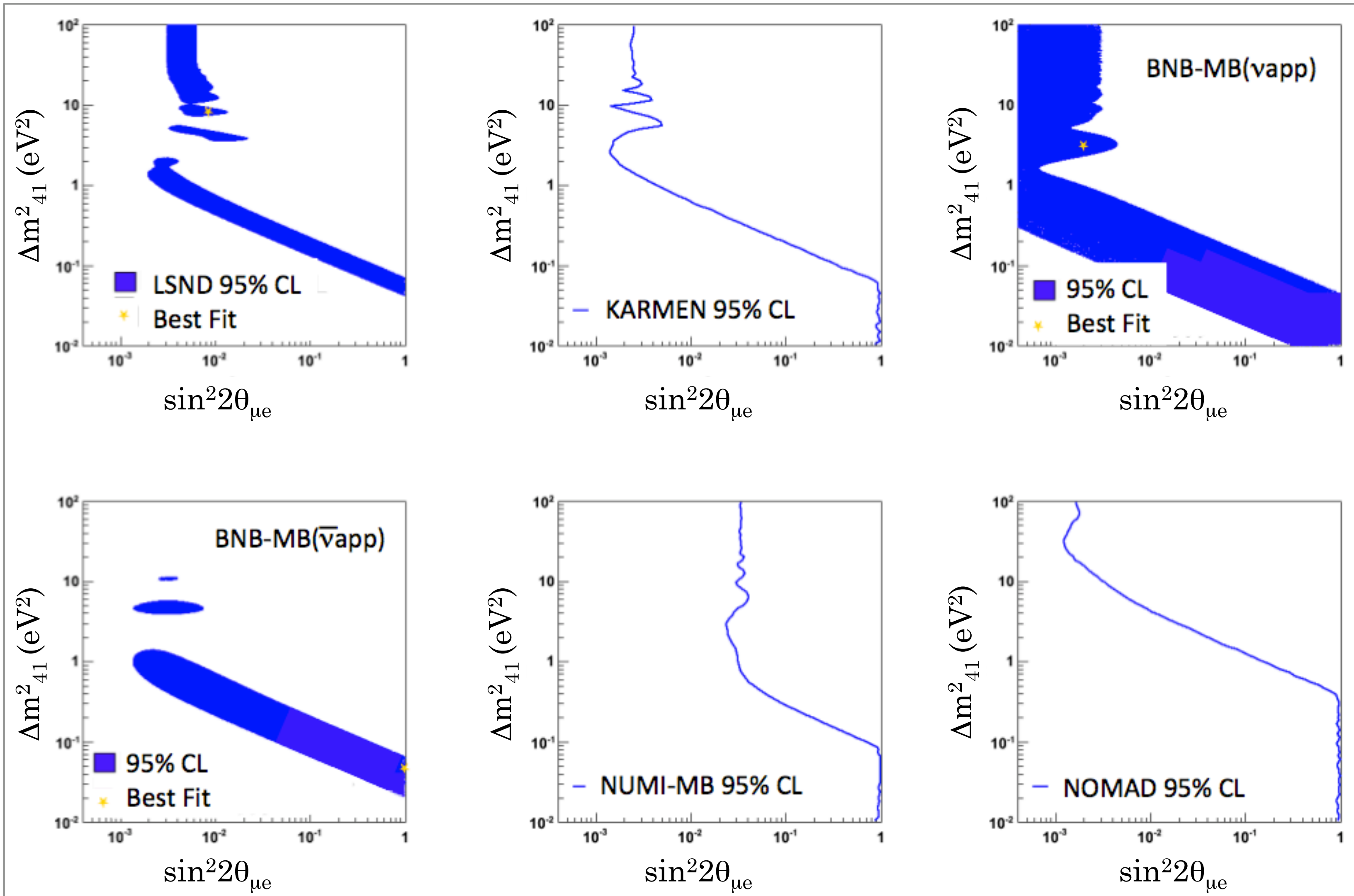
OVERVIEW OF CONSTRAINTS

- $\overset{(-)}{\nu}_e$ appearance
  - **LSND**
    [Phys. Rev. D 64, 112007 (2001)]
  - **MiniBooNE (BNB) $\bar{\nu}$ app**
    [hep-ex/1207.4809]
  - **MiniBooNE (BNB) ν app**
    [hep-ex/1207.4809]
  - **MiniBooNE (NuMI)**
    [Phys. Rev. Lett. 102, 211801 (2009)]
  - **NOMAD**
    [Phys. Lett. B 570, 19 (2003)]
  - **KARMEN**
    [Phys. Rev. D 65, 112001 (2002)]

Reviewed Anomalies
Null experiments with sensitivity to sterile neutrinos

Conrad et al, hep-ph/1207.4765

Overview of Constraints: (3+1) Appearance Data Sets



Conrad et al, hep-ph/1207.4765

Overview of Constraints

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- $\overset{(-)}{\nu}_e$ disappearance
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  - **Gallex/Sage** [Phys. Rev. D 78, 073009 (2008)]
  - **KARMEN/LSND xsec** [Phys. Rev. D 85, 013017 (2012)]

Reviewed Anomalies
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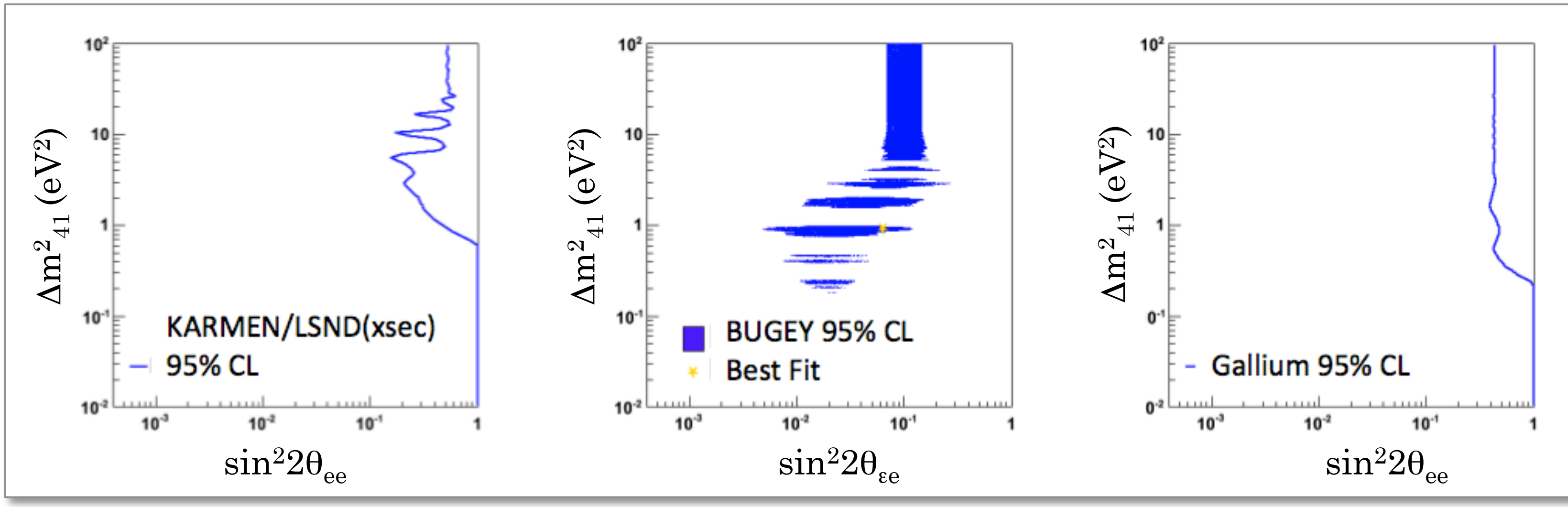
Conrad et al, hep-ph/1207.4765

Overview of Constraints: (3+1) ν_e Disappearance Data Sets



Overview of Constraints

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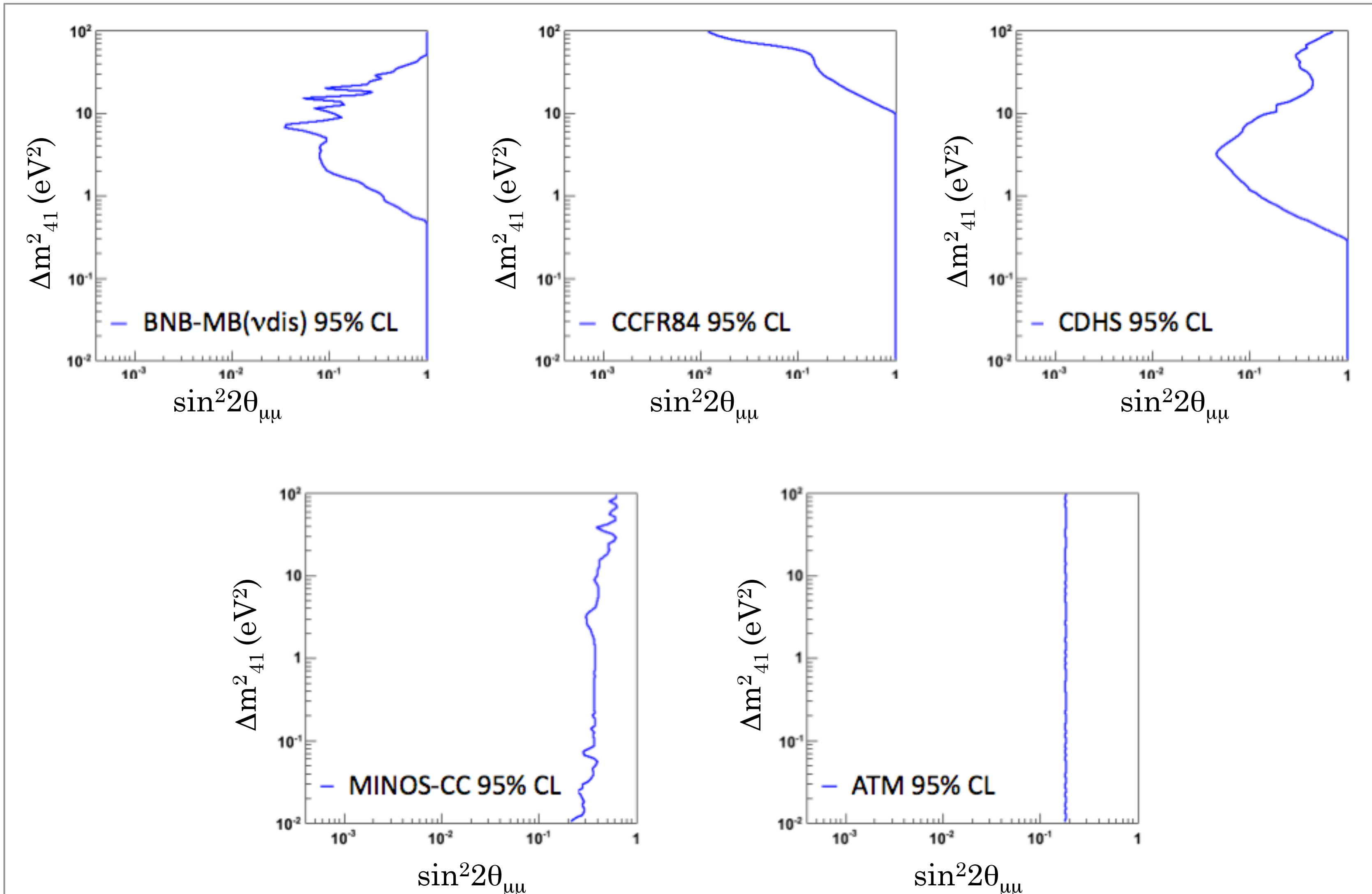
    [Phys. Rev. D 78, 073009 (2008)]
  - **KARMEN/LSND xsec**
    [Phys. Rev. D 85, 013017 (2012)]

- $\overset{(-)}{\nu}_\mu$ disappearance
  - **CCFR84**
    [Z. Phys. C 27, 53 (1985)]
  - **CDHS**
    [Phys. Lett. B 134, 281 (1984)]
  - **MINOS**
    [hep-ex/1202.2772 (2012), hep-ex/1108.1509 (2012)]
  - **MiniBooNE ν dis**
    [Phys. Rev. Lett. 103, 061802 (2009)]
  - **Atmospheric**
    [New J. Phys. 6, 122 (2004)]

Reviewed Anomalies
Null experiments with sensitivity to sterile neutrinos

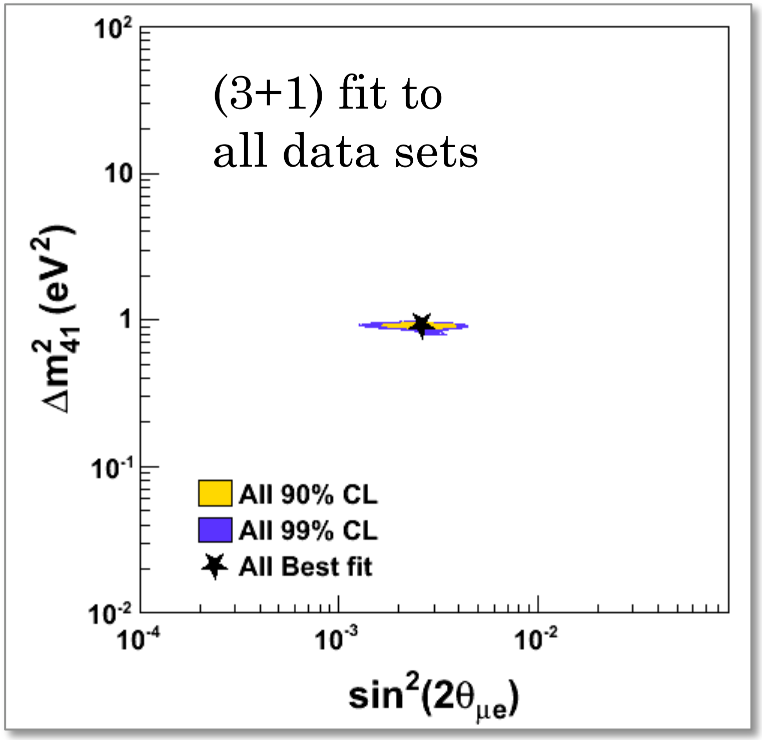
Conrad et al, hep-ph/1207.4765

Overview of Constraints: (3+1) ν_μ Disappearance Data Sets



(3+1): Global Fit

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



Compatibility among data sets included in the fit

Null χ^2 (dof)	Null gof	Best fit χ^2 (dof)	Best fit gof	PG χ^2 (dof)	PG
286.5 (240)	**2.1%**	233.9 (237)	**55%**	54 (24)	**0.043%**

COMPATIBILITY (PG) TEST

A measure of **how well the parameter regions** preferred by different subsets of data **overlap**

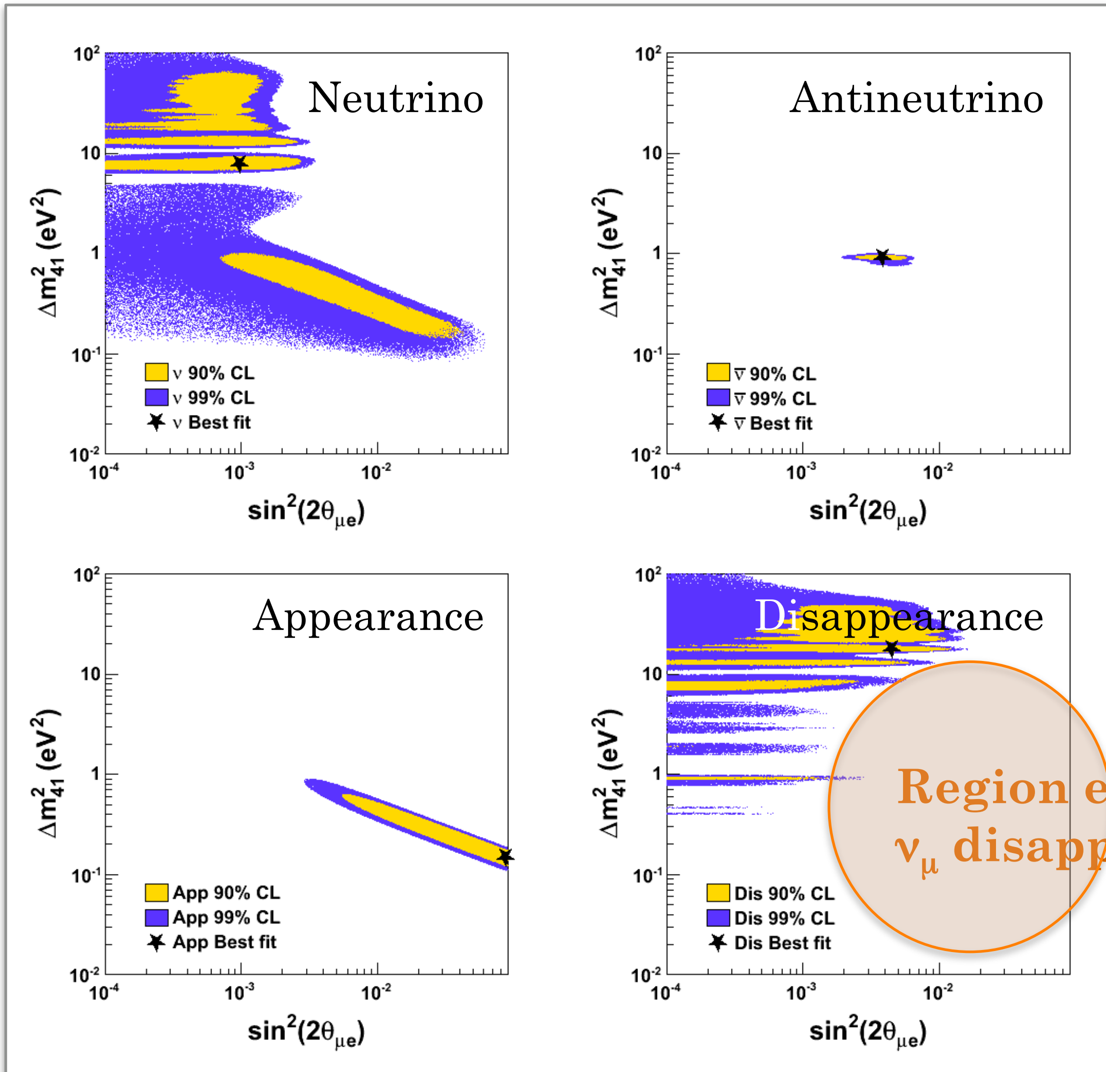
$$\chi^2_{PG} = \chi^2_{min,all} - \sum \chi^2_{min,i}$$

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

Unlike a χ^2 test, the PG test avoids the problem that a possible disagreement between data sets becomes diluted by data points which are insensitive to the fit

"Testing the statistical compatibility of independent data sets"
Maltoni & Schwetz, Phys. Rev. D68 (2003) 033020

(3+1): Incompatibilities



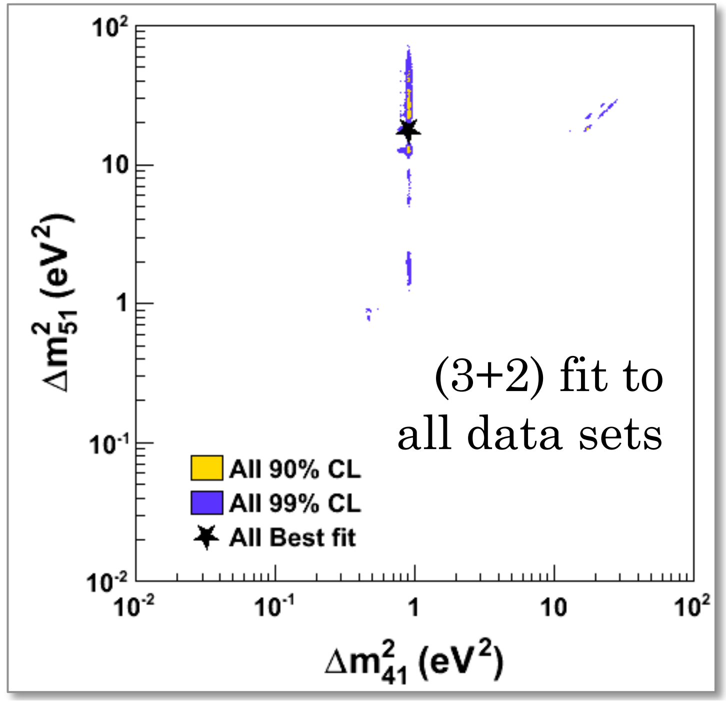
PG $(\nu,\bar{\nu})$ = 0.14%

PG (app,dis) = 0.013%

Region excluded from ν_μ disappearance experiments

(3+2): Global Fit & Incompatibilities

PG ($\nu,\bar{\nu}$) = 5.3%
PG (app,dis)= 0.0082%

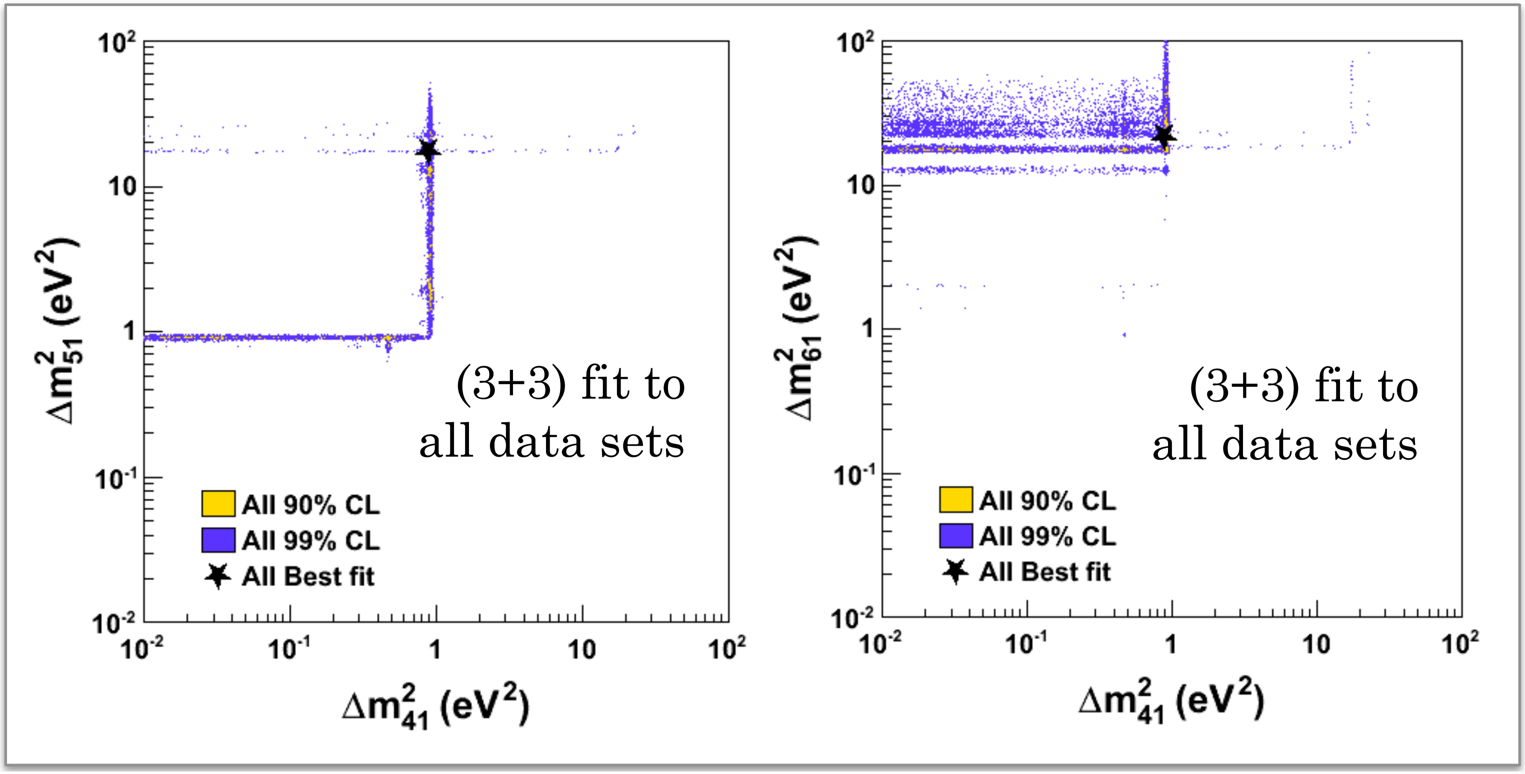


3+2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	ϕ_{54}
All	0.92	17	0.13	0.15	0.16	0.069	1.8π

Compatibility among data sets included in the fit

Null χ^2 (dof)	Null gof	Best fit χ^2 (dof)	Best fit gof	PG χ^2 (dof)	**PG**
286.5 (240)	**2.1%**	221.5 (233)	**69%**	63.8 (52)	**13%**

(3+3): Global Fit



3+3	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_{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

Compatibility among
data sets included in the fit

Null χ^2 (dof)	Null gof	Best fit χ^2 (dof)	Best fit gof	PG χ^2 (dof)	PG
286.5 (240)	**2.1%**	218.2 (228)	**67%**	68.9 (85)	**90%**

Conrad et al, hep-ph/1207.4765

(3+3): Incompatibilities

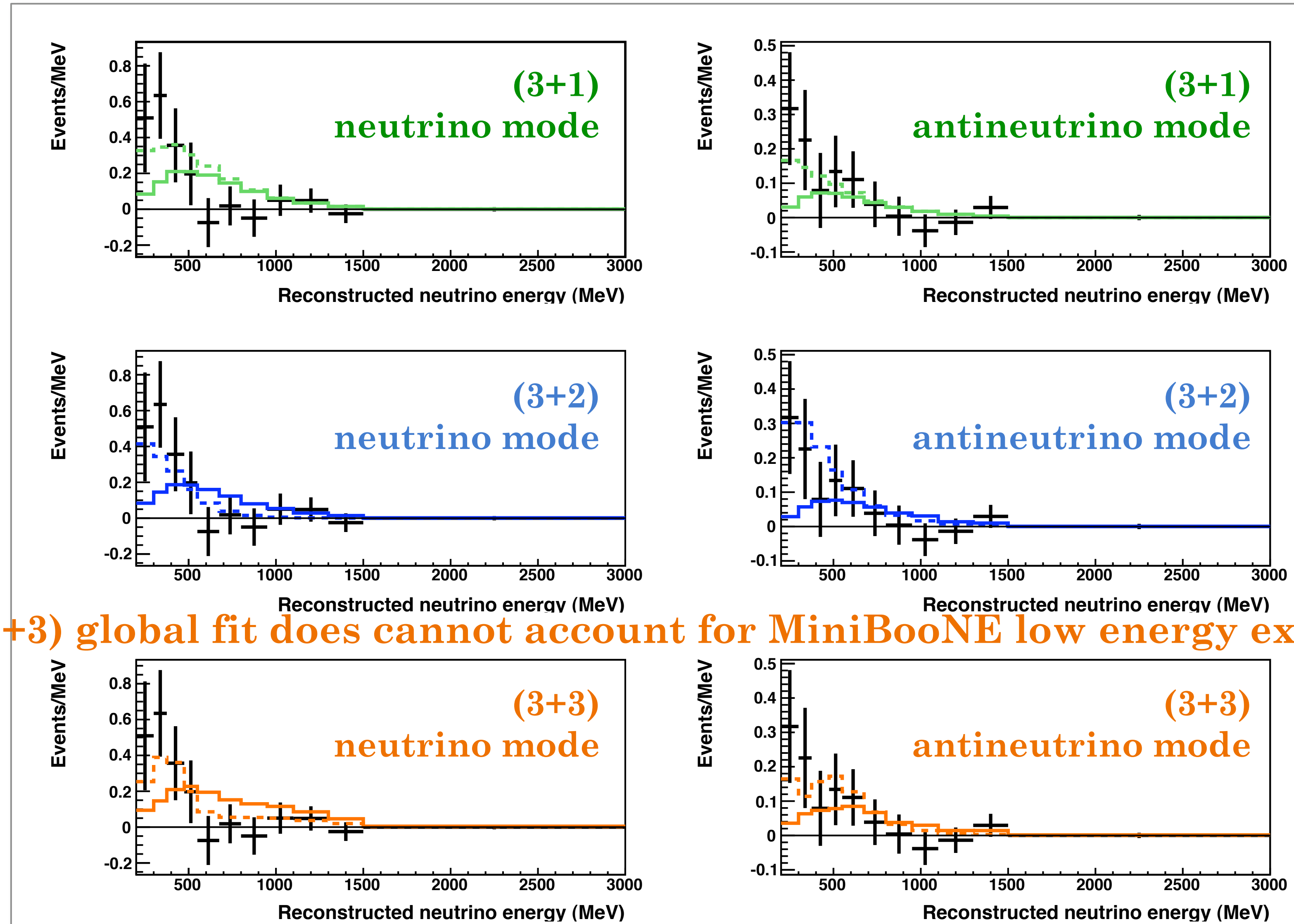
	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\overline{\nu}$	90.6 (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%

Appearance and disappearance data sets still incompatible even under a (3+3) scenario

(3+3): Incompatibilities

All SBL
App SBL

- Appearance fits largely driven by MiniBooNE:



(3+3) global fit does cannot account for MiniBooNE low energy excess

SUMMARY OF GLOBAL FITS

- **(3+0):** Solar and atmospheric Δm^2 already saturate three known neutrino spectrum
  - Need to add at least one sterile neutrino
- **(3+1):** It has been known for a while that (3+1) fits are not a good description of world data
  - Cannot explain differences in ν_e vs ν_e appearance signals
  - Cannot explain lack of ν_μ disappearance observations at $\Delta m^2 \sim 1$ eV^2
- **(3+2):** It has been realized recently that a second sterile neutrino helps somewhat
  - CP violation helps recover compatibility among appearance experiments
  - But appearance and disappearance experiments remain incompatible
- **(3+3):** Adding a third neutrino improves the quality of global fits but does not resolve the tension between appearance and disappearance experiments, and does not explain the MiniBooNE low energy excess

Global Fits to Sterile Neutrino Oscillations: Caveats and Limitations

- Appearance searches assume no disappearance
  - This is an incorrect assumption, given best fit parameters extracted in global fits
  - This may resolve some tension seen in the MiniBooNE appearance data sets, if one allows for ν_e background disappearance

- Need a more advanced statistical and systematic treatment of data sets
  - Compatibility measure needs to be verified with fake data and frequentist studies
  - Need better treatment of systematic correlations between data sets
  - This is a challenging step, but necessary for definitive statements on these models

What's Next?

- Establishing the existence of sterile neutrinos would be a major result for particle physics!

- Several hints exist in the $\Delta m^2 \sim 1$ eV^2 region
  - They come from ν_e appearance and disappearance experiments
  - Some tension with lack of ν_μ disappearance signals

- Current SBL landscape prompts the **consideration of new proposals and ideas for sterile neutrino searches…**

Backup slides

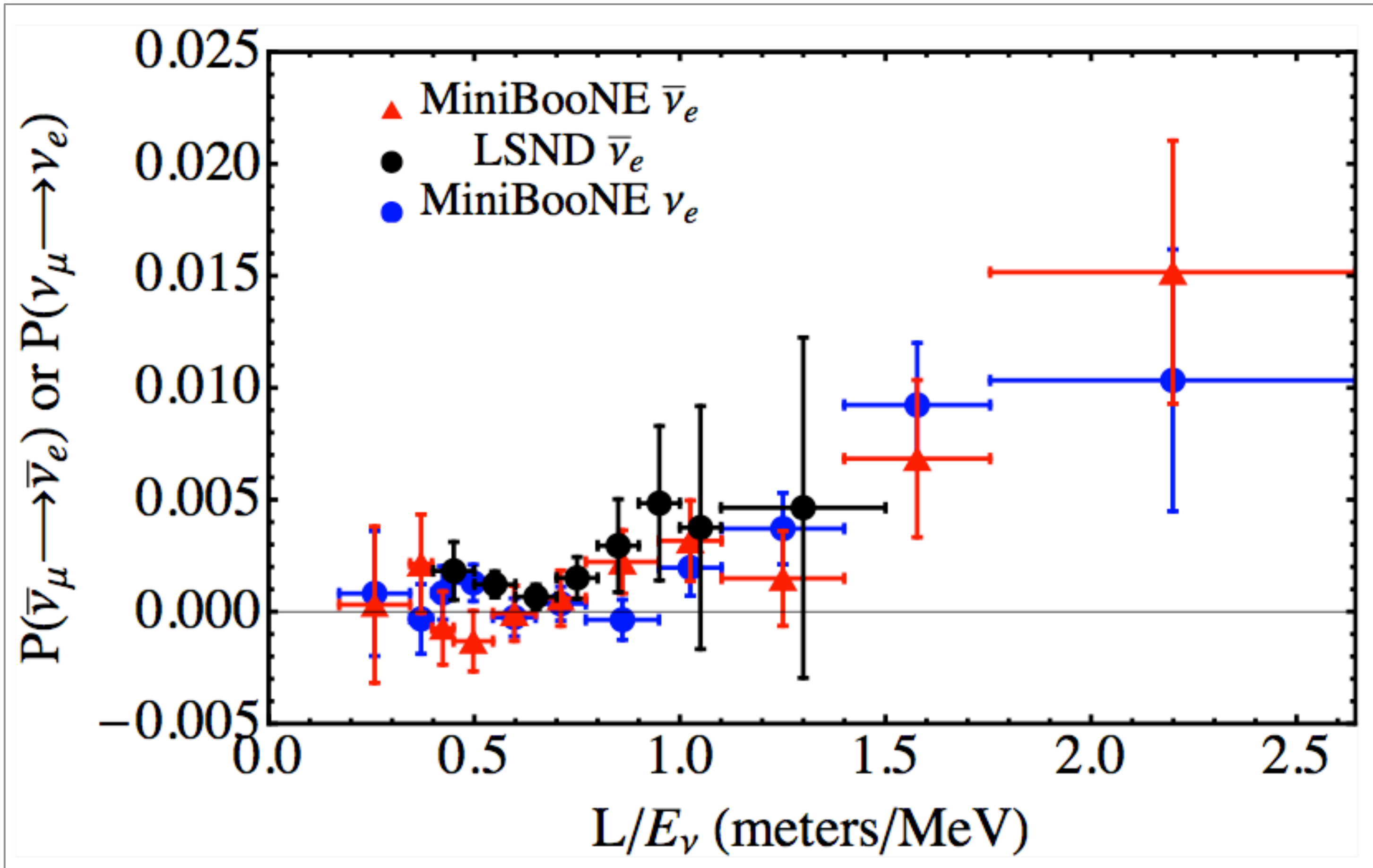
Summary of "Anomalies": MiniBooNE

MiniBooNE search for ν_e (or $\bar{\nu}_e$) appearance in a pure ν_μ (or $\bar{\nu}_\mu$) beam:

- MiniBooNE has very good ν_μ versus ν_e event identification using:
  - Cherenkov ring topology, scintillation to cherenkov light ratio, and μ-decay Michel tag
- All backgrounds constrained by data
  - Intrinsic ν_e in the beam: from μ decay, constrained by observed ν_μ events
  - Particle misidentification in detector: from NC π^0 production or $\Delta \rightarrow N\gamma$, constrained by observed $\pi^0 \rightarrow \gamma\gamma$ events
  - Measured neutrino contamination in antineutrino mode running ($22 \pm 5\%$)
- Simultaneous fit to ν_e and ν_μ events
  - Reduces flux, cross section, and energy reconstruction uncertainties
- Systematic error on background $\approx 10\%$ (energy dependent)

MiniBooNE June 2012 results → hep-ex/1207.4809

SUMMARY OF "ANOMALIES": MINIBOONE AND LSND



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Global Fits: Analysis Method

- Model parameters
  - Approximate $m_1 \approx m_2 \approx m_3 << m_4, m_5, m_6$
  - Three independent mass splittings: Δm^2_4, Δm^2_5, Δm^2_6
  - Six moduli: $|U_{e4}|$, $|U_{\mu 4}|$, $|U_{e5}|$, $|U_{\mu 5}|$, $|U_{e6}|$, $|U_{\mu 6}|$
  - Three CPV phases: $\phi_{54} = \arg(U_{e5} U^*_{\mu 5} U^*_{e4} U_{\mu 4})$, ϕ_{64}, ϕ_{65}
- Fit method
  - Generate masses and mixing parameters by importance sampling:
    $0.01\text{eV}^2 \leq \Delta m^2_{41}, \Delta m^2_{51}, \Delta m^2_{61} \leq 100\text{eV}^2$
    $\Delta m^2_{61} \geq \Delta m^2_{51} \geq \Delta m^2_{41}$
    $|U_{e4}|$, $|U_{\mu 4}|$, $|U_{e5}|$, $|U_{\mu 5}|$, $|U_{e6}|$, $|U_{\mu 6}|$ according to unitarity constraints
    CP violation: allow ϕ_{54}, ϕ_{64}, ϕ_{65} to vary within $(0,2\pi)$
  - Minimize $\chi^2 = \Sigma_i \chi^2_i$, i = dataset (LSND, KARMEN, etc…)
    using a **Markov chain**:
    Model acceptance probability:
    $P(x_i \rightarrow x_{i+1}) = \min\{1, \exp[-(\chi^2_{i+1} - \chi^2_i)/T]\}$
    $x_{i+1} = x_i + e$
- Determine allowed regions by Gaussian approximation, and marginalize (2 dof) over 2 parameters at a time

Conrad et al, hep-ph/1207.4765

Global Fits: Analysis Method

(3+3) appearance probability:

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

(3+3) disappearance probability:

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

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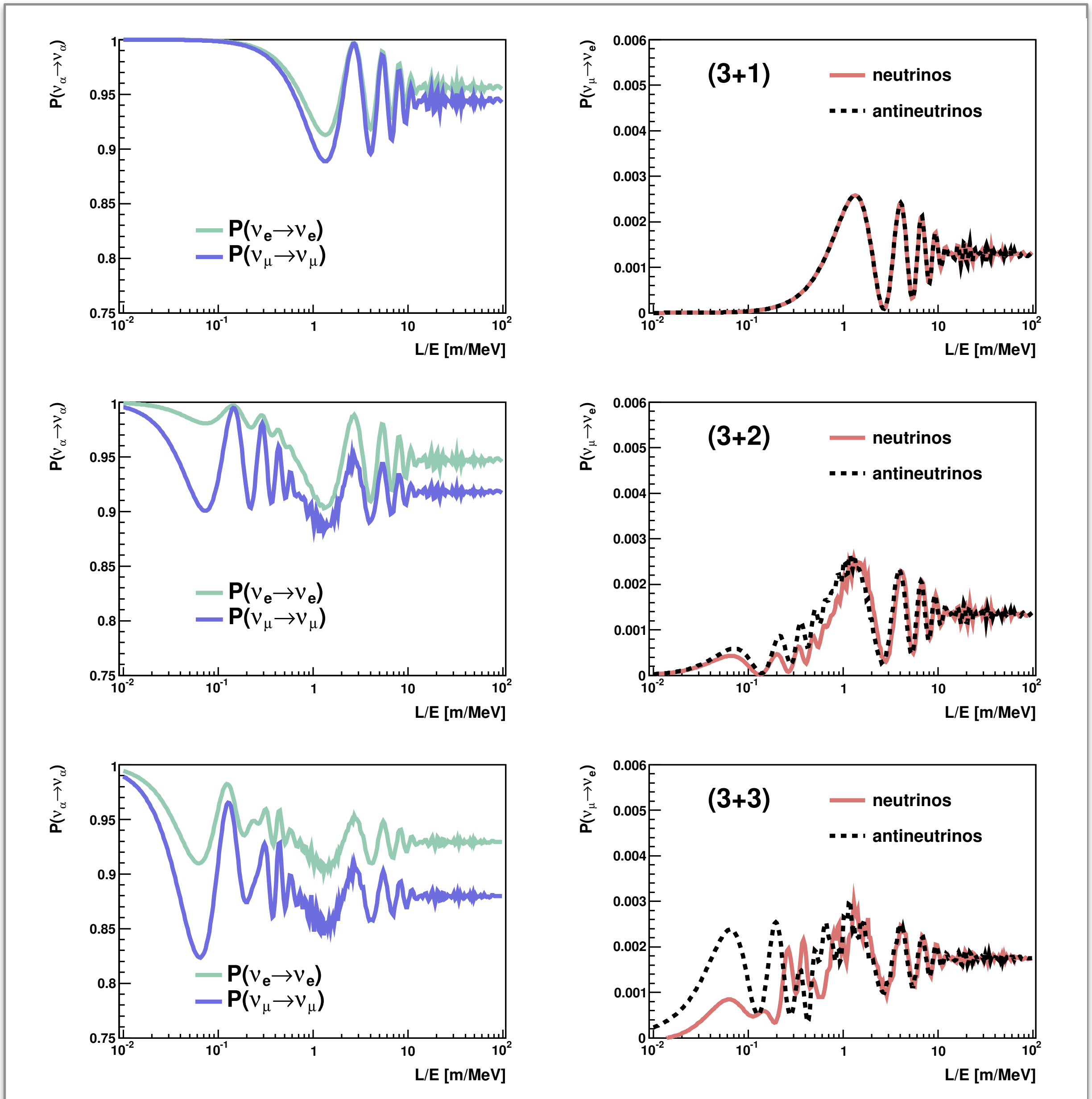
	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+1						
All	233.9 (237)	286.5 (240)	55%	2.1%	54.0 (24)	0.043%
App	87.8 (87)	147.3 (90)	46%	0.013%	14.1 (9)	12%
Dis	128.2 (147)	139.3 (150)	87%	72%	22.1 (19)	28%
ν	123.5 (120)	133.4 (123)	39%	25%	26.6 (14)	2.2%
$\overline{\nu}$	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%

Conrad et al, hep-ph/1207.4765

Global Fit Oscillation Probabilities



ALTERNATIVE SCENARIOS

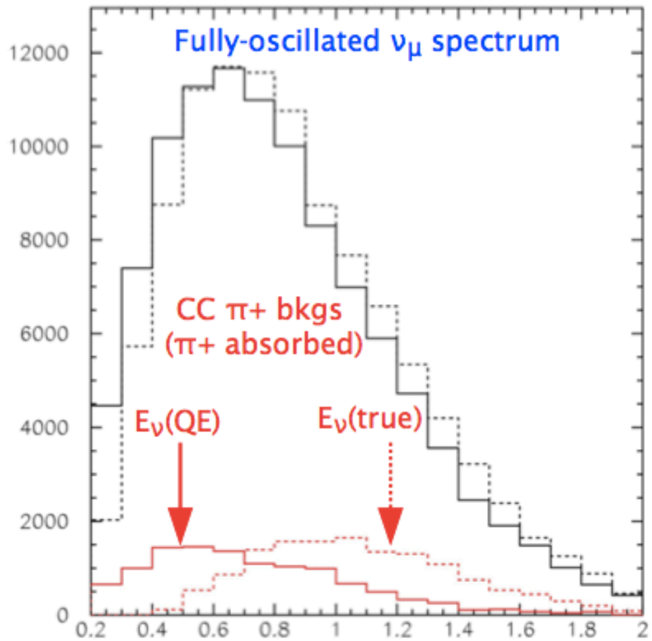
- An incomplete list:
  - 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 03
  - 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
  - Exotic muon-decay Babu, Pakvasa 02
  - CPT viol. quantum decoherence Barenboim, Mavromatos 04
  - Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
  - mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
  - shortcuts of sterile ν s in extra dim Paes, Pakvasa, Weiler 05
  - decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 10
  - 2 decaying sterile neutrinos with CPV Palomares-Riuz, Pascoli, Schwetz 05
  - energy dependent quantum decoherence Farzan, Schwetz, Smirnov 07
  - sterile neutrinos and new gauge boson Nelson, Walsh 07
  - sterile ν with energy dep. mass or mixing Schwetz 07
  - sterile ν with nonstandard interactions Akhmedov, Schwetz 10; Conrad, GK, Shaevitz, 12
- Most of these involve sterile neutrinos
- Most of these have problems with some existing experimental data

Possible Bias in Calculated Neutrino Energy

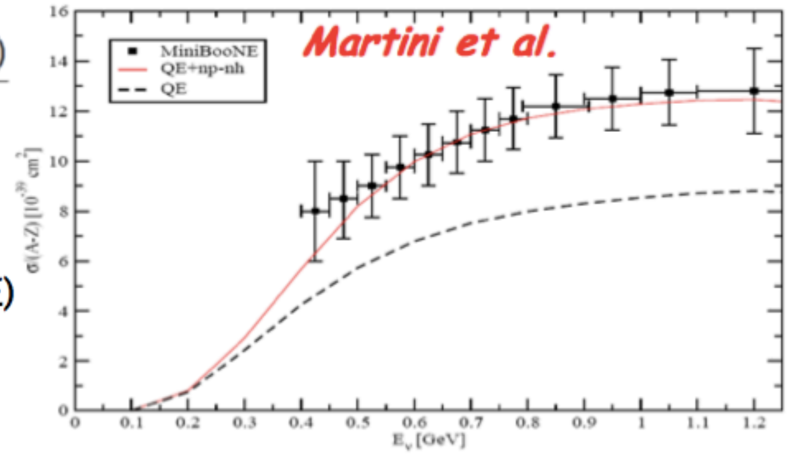
Reconstructed energy of MiniBooNE events assumes CCQE kinematics:

$$E_\nu = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2\left[(M_n - E_B) - E_\mu + p_\mu \cos\theta_\mu\right]}$$

- Additional participants other than the outgoing lepton and struck nucleon will cause events to reconstruct at lower E_ν(QE)

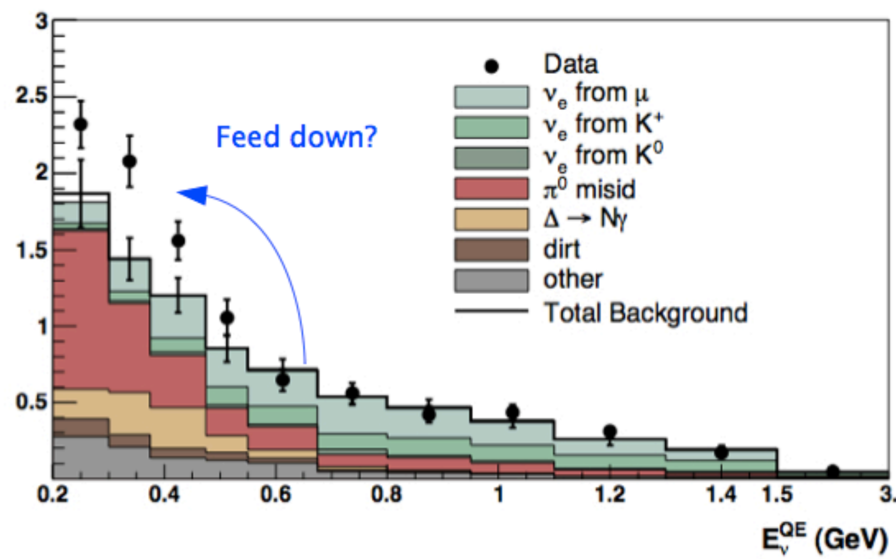


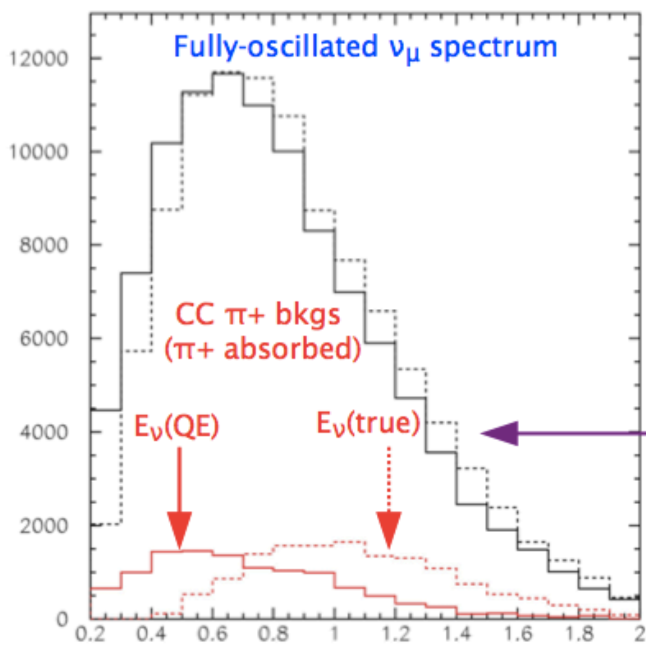
Martini *et al.*, PRC **80**, 065001 (2009)



- MiniBooNE finds a cross-section for ν_μ CCQE that is 20-30% higher than expected
- Number of theorists suggesting this could arise from multi-nucleon correlations, observed many years ago in e-scattering
- Could help explain why MB xsec is higher than free nucleon, differences between expts where event selection can depend on final state nucleons

Bias Could Shift Events to Lower Energy But …





- Means a fraction of oscillated ν_e could be misreconstructed (similar to CCπ+ case)
- Could feed down help relax tension between low and mid range energies?
- Possible, but MiniBooNE corrects sig/bkg predictions based on the measured ν_μ spectrum
- Studies where we double the π+ absorption rate, and then retune sig/bkg predictions to match to CCQE…negligible impact