A Proposal to Build a MiniBooNE Near Detector: BooNE

W.C. Louis & G.B. Mills, LANL

December 8, 2011

- Louis – Motivation for BooNE
- Mills – BooNE Proposal

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j \left|U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha j}\, U_{\beta j}\right| \sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

N	$\#\Delta m_{ij}^2$	$\#\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

Therefore, there needs to be ≥ 3 neutrino mixing for CP Violation!

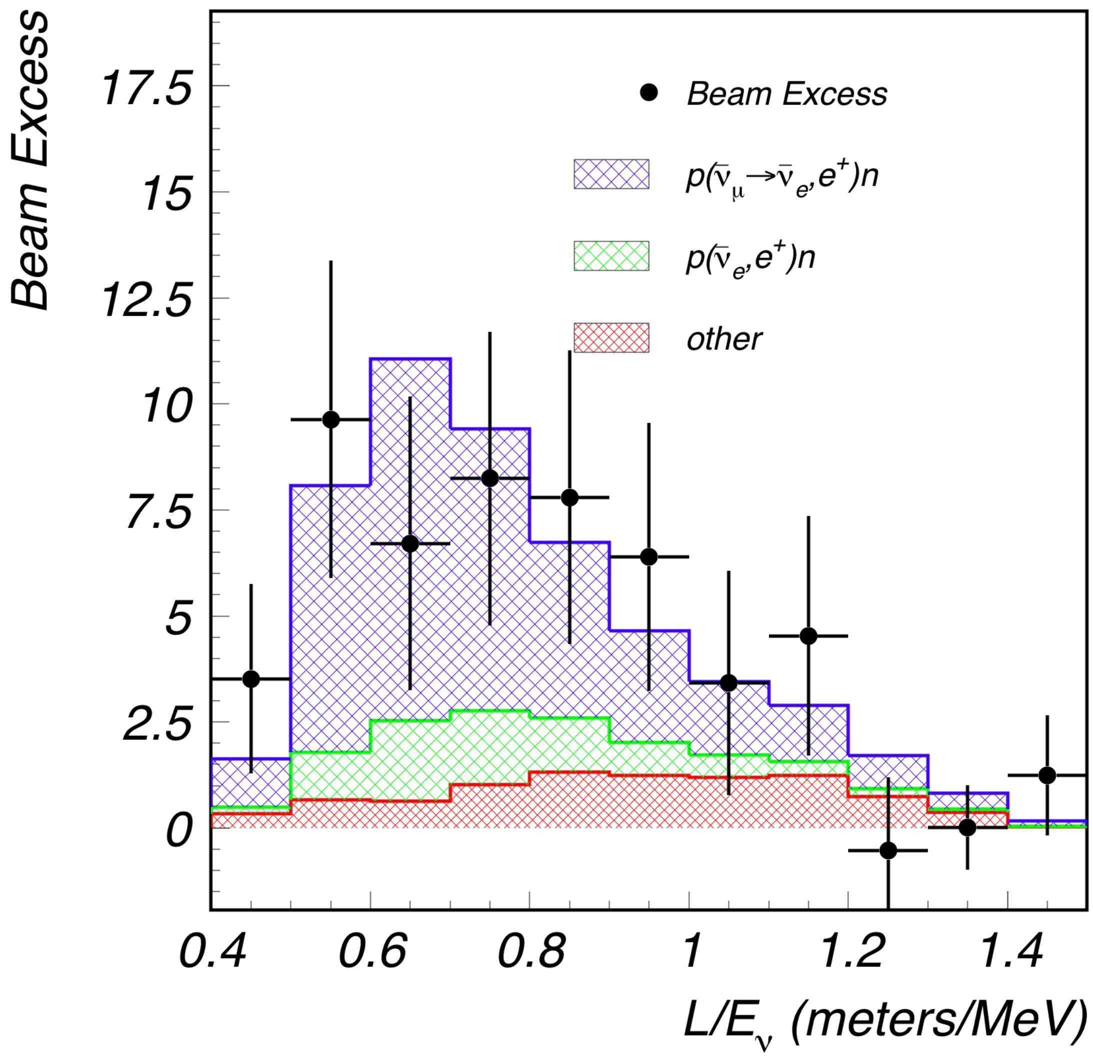
Tantalizing Results (Anomalies) from Short Baseline ν Experiments Not Explained by 3 ν

- LSND $\overline{\nu}_e$ Excess
- MiniBooNE ν_e Excess
- MiniBooNE $\overline{\nu}_e$ Excess
- Reactor $\overline{\nu}_e$ Anomaly
- Radioactive ν_e Source Anomaly

• These results (2-4 σ) all correspond to L/E ~ 1 and are not directly ruled out by any other experiment.

LSND Antineutrino Results

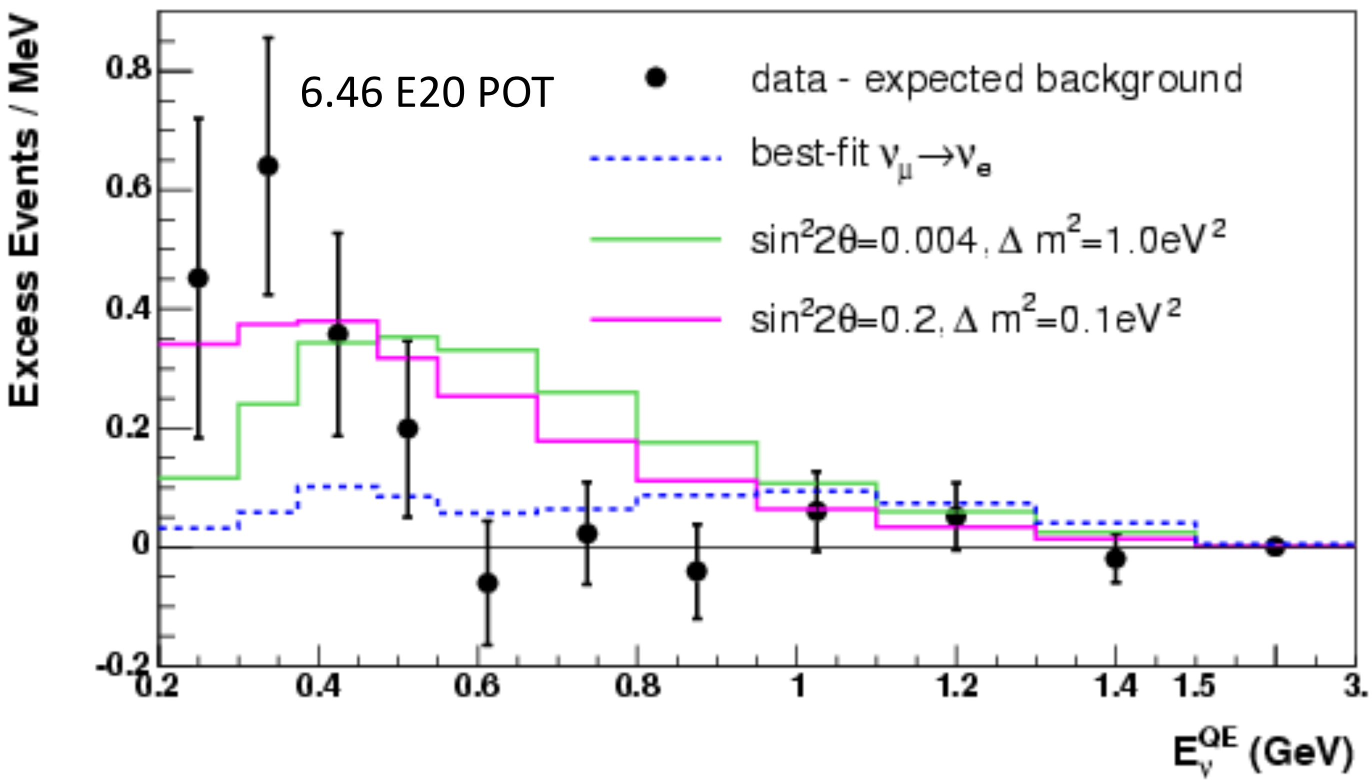
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)



3.8 σ excess of events

MiniBooNE Neutrino Results

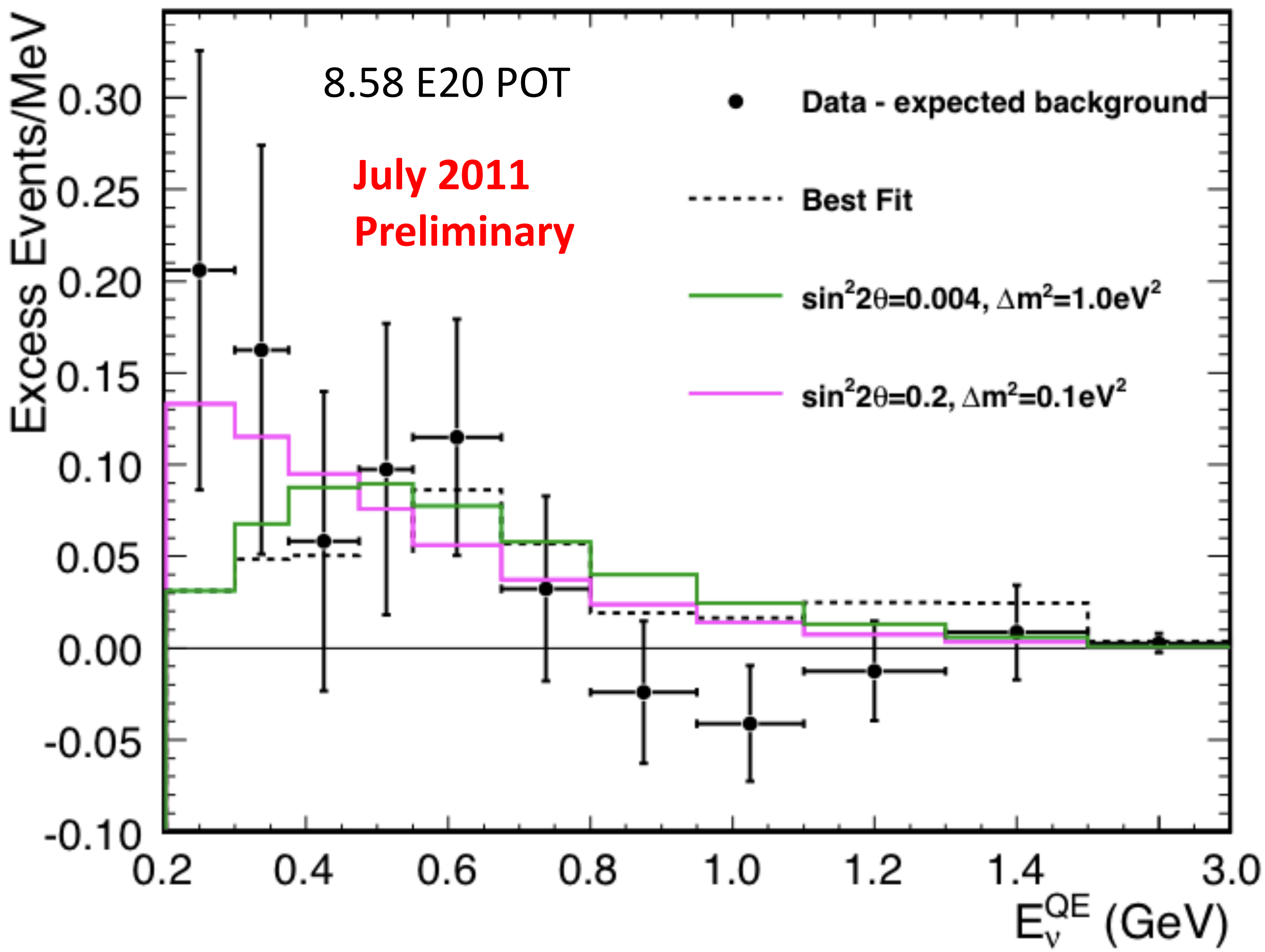
A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 102, 101802 (2009)



3.0 σ excess of events from 200-1250 MeV

MiniBooNE Antineutrino Results

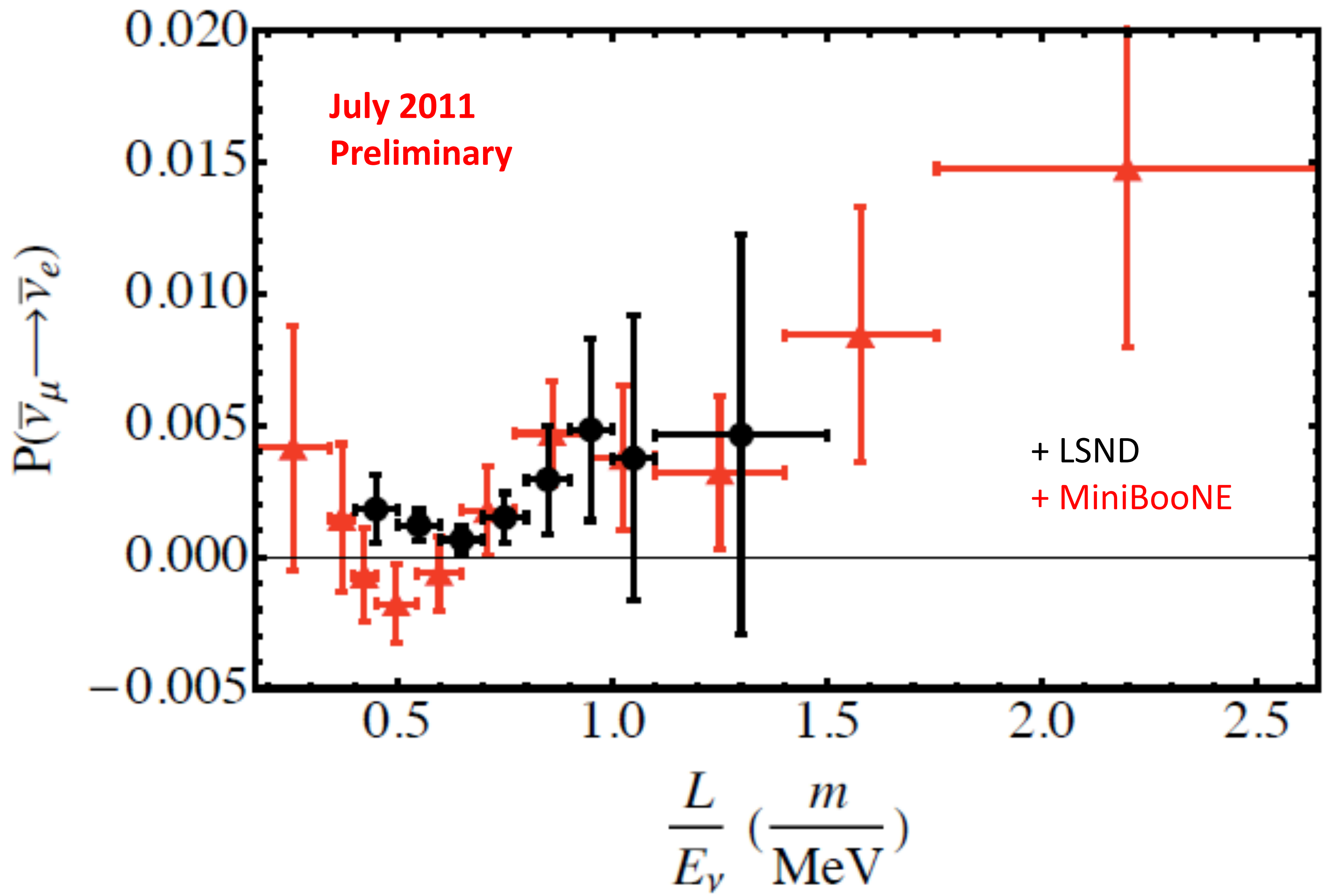
Updated from A. Aguilar-Arevalo et al., Phys. Rev. Lett. 105, 181801 (2010)



2.3 σ excess of events from 200-1250 MeV (so far)

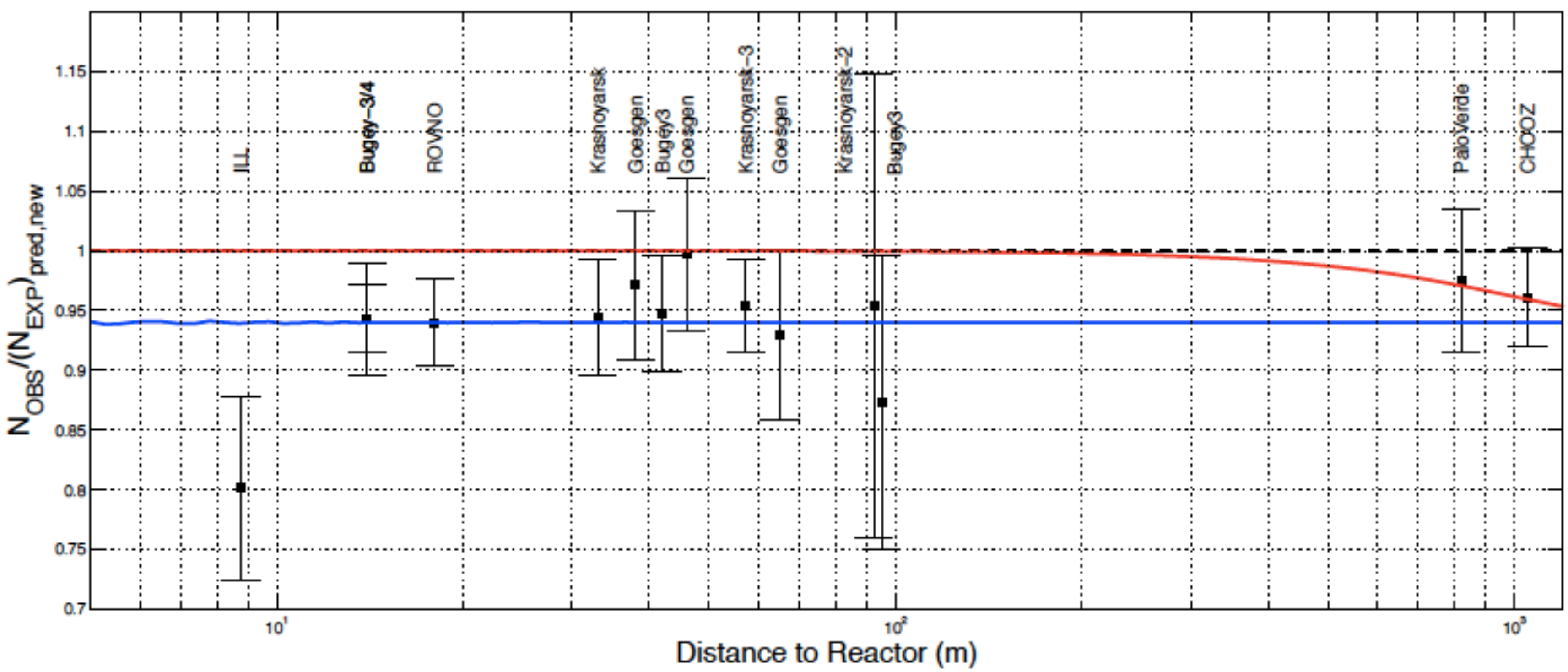
LSND vs MiniBooNE Antineutrino Results

Updated from A. Aguilar-Arevalo et al., Phys. Rev. Lett. 105, 181801 (2010)



Reactor Antineutrino Anomaly

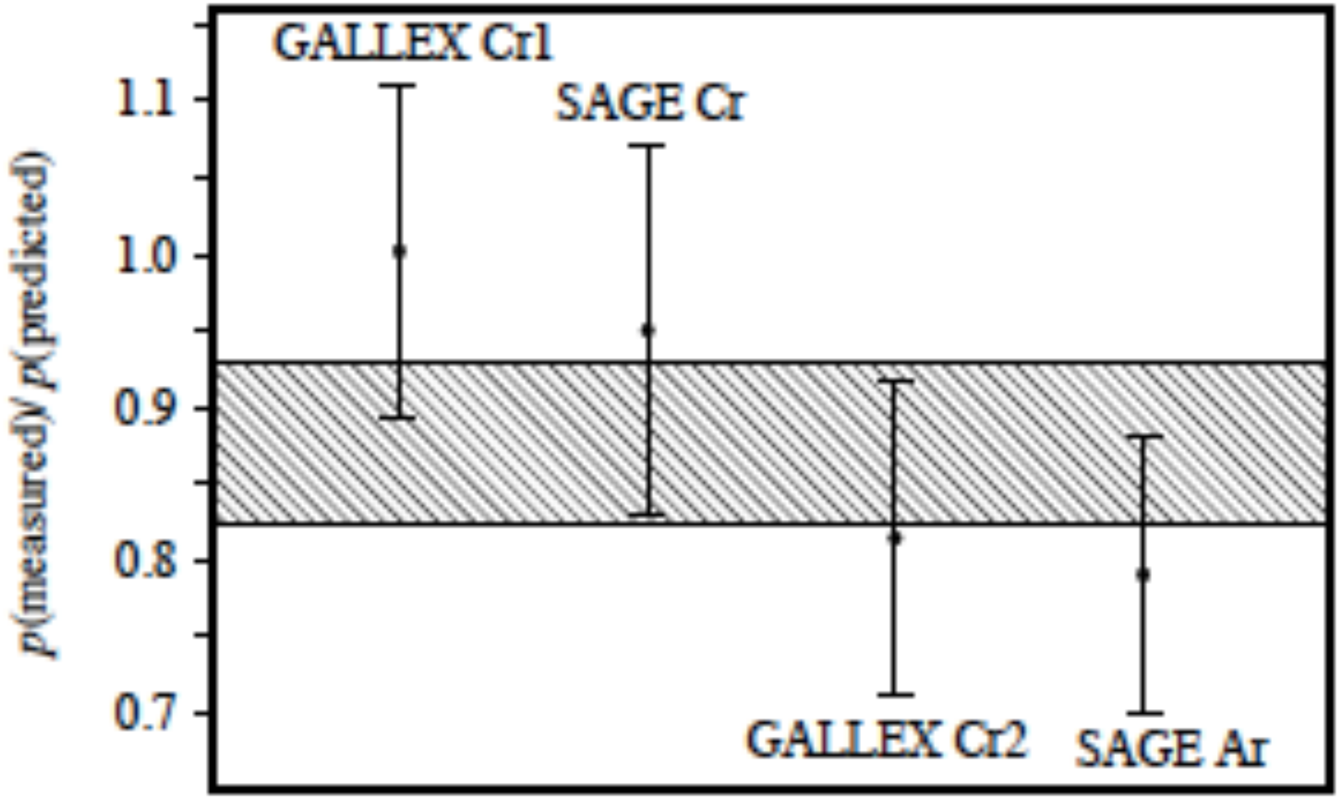
G. Mention et al., Phys.Rev.D83:073006,2011



R=0.937+-0.027

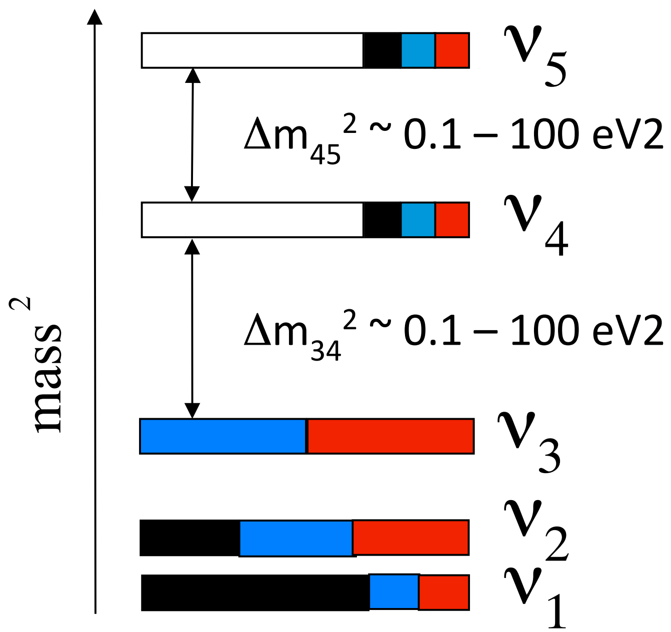
Radioactive Neutrino Source Anomaly

SAGE, Phys. Rev. C 73 (2006) 045805



R=0.86+-0.05

Sterile Neutrinos

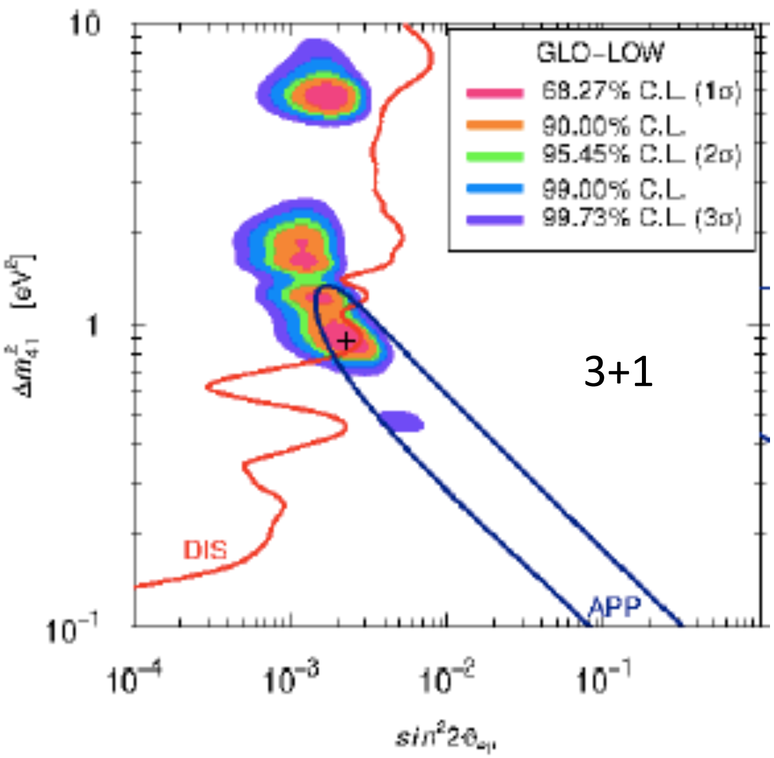


- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\nu_\mu \rightarrow \nu_e \neq \overline{\nu}_\mu \rightarrow \overline{\nu}_e$

3+N Global Fits to World ν Data

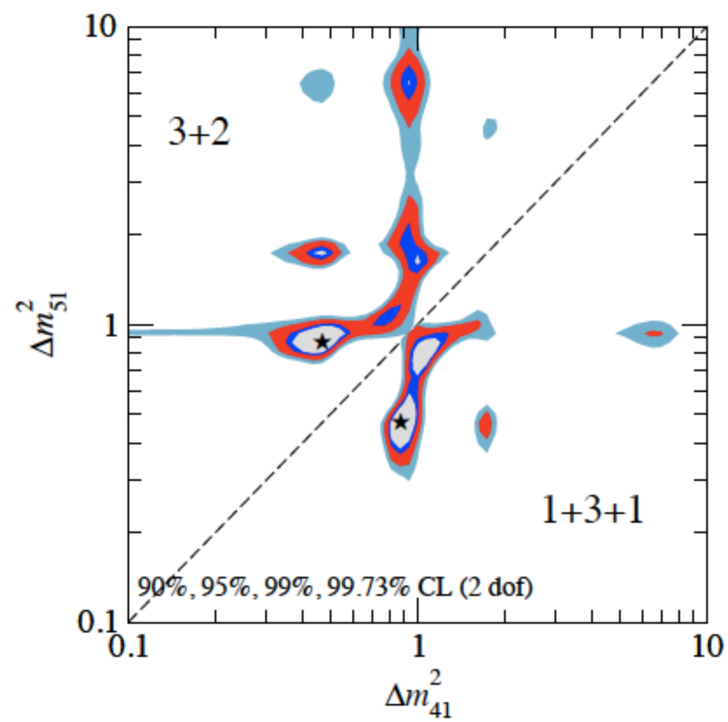
(Predict observable ν_μ disappearance)

all ν & $\bar{\nu}$



Giunti & Laveder, arXiv:1111.1069
(Some tension with ν_μ disappearance)
χ^2 = 152.4/144 DF (Prob = 30%)

all ν & $\bar{\nu}$



Kopp, Maltoni, & Schwetz,
Phys. Rev. Lett. 107, 091801 (2011)
χ^2 = 110.1/130 DF (Prob = 90%)

3+N Models Requires Large ν_μ Disappearance!

In general, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < ¼\, P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x)\, P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$

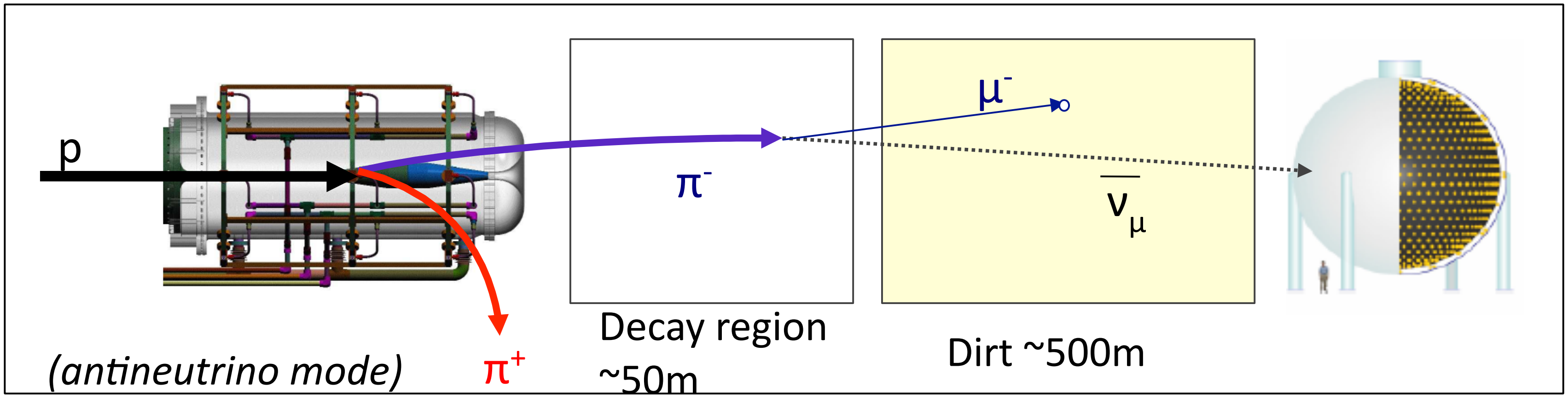
Reactor Experiments: $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) \sim 10\%$

LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

Therefore: **$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 10\%$ (or $\sin^2 2\theta > 10\%$)**

Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

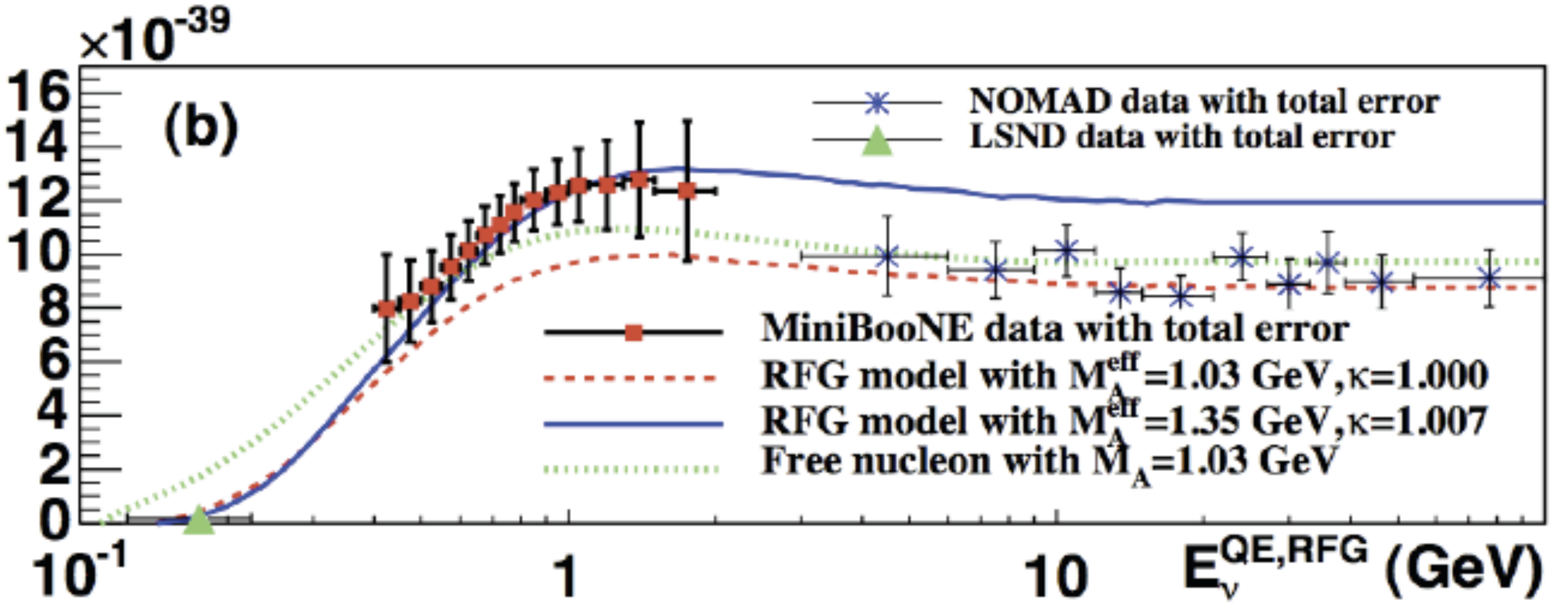
MiniBooNE Experiment



- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

ν_μ CCQE Scattering

A.A. Aguilar-Arevalo, Phys. Rev. D81, 092005 (2010).



Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}C)>6\ \sigma_{\nu\mu}(n)$

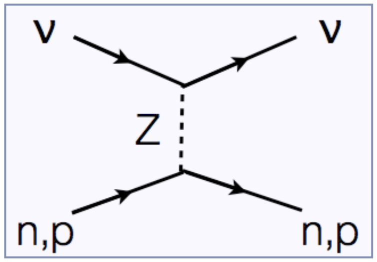
How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys.Rev.**C65,** 024002 (2002); Martini et al., PRC80, 065001 (2009).

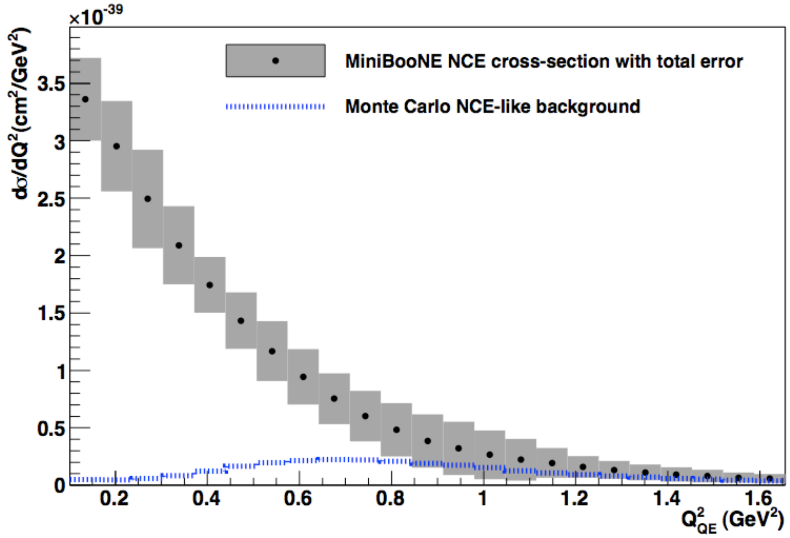
Neutrino Neutral Current Elastic

Phys.Rev.D82:092005,2010

- Neutral current elastic process probes similar formalism as charged-current quasi-elastic
  - sensitive to structure of both nucleon type.



- Protons fitter developed that reconstructs protons above Cherenkov threshold (T_p > 350 MeV)
- 94,531 events (~65% purity)
- Measured quantities:
  - $d\sigma/dQ^2$
  - Δs = 0.08+-0.26
  - M_A = 1.39+-0.11



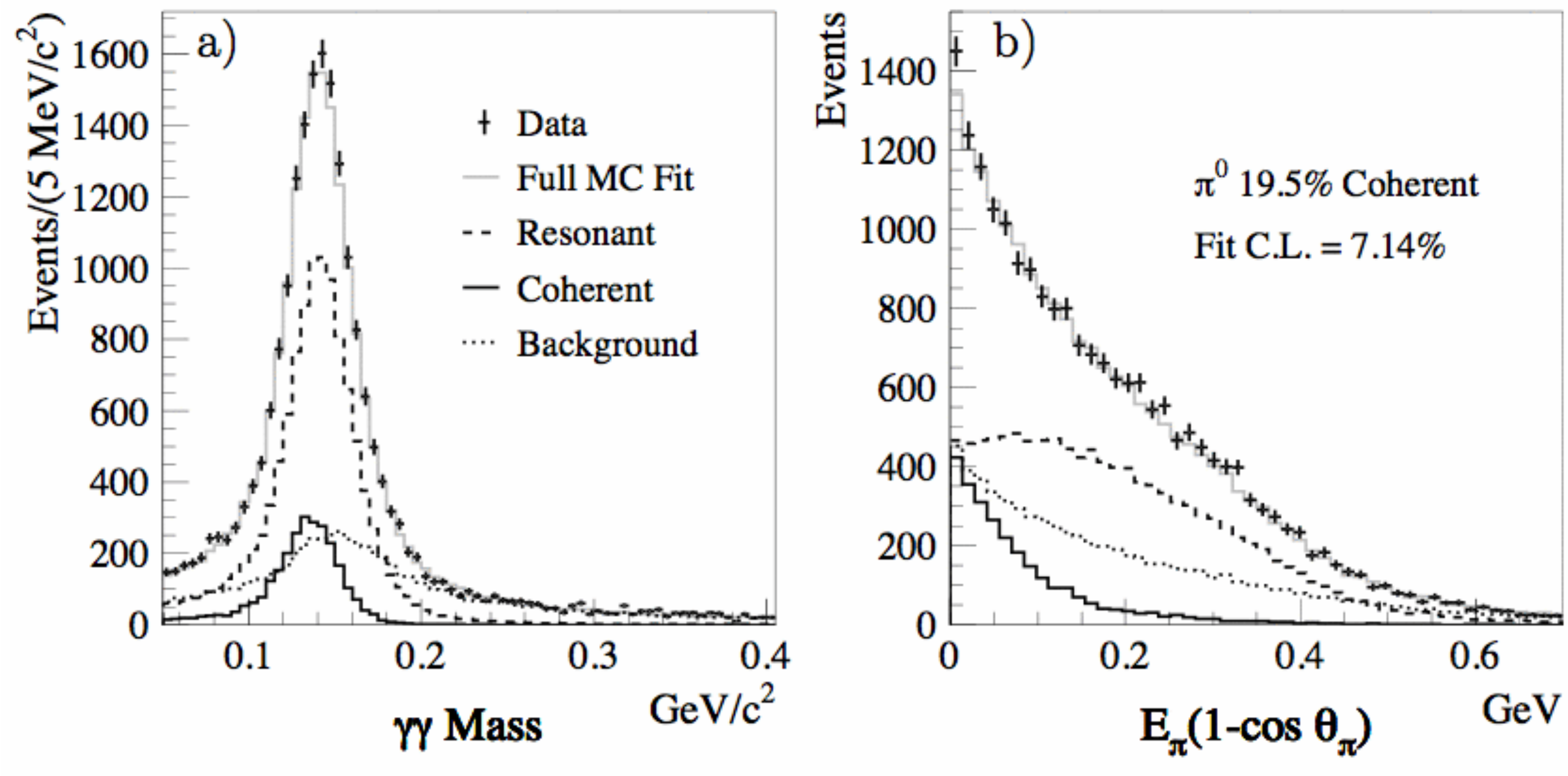
Ph.D. thesis, D. Perevalov, University of Alabama
Phys. Rev. D. **82**, 092005 (2010)

From D. Perevalov

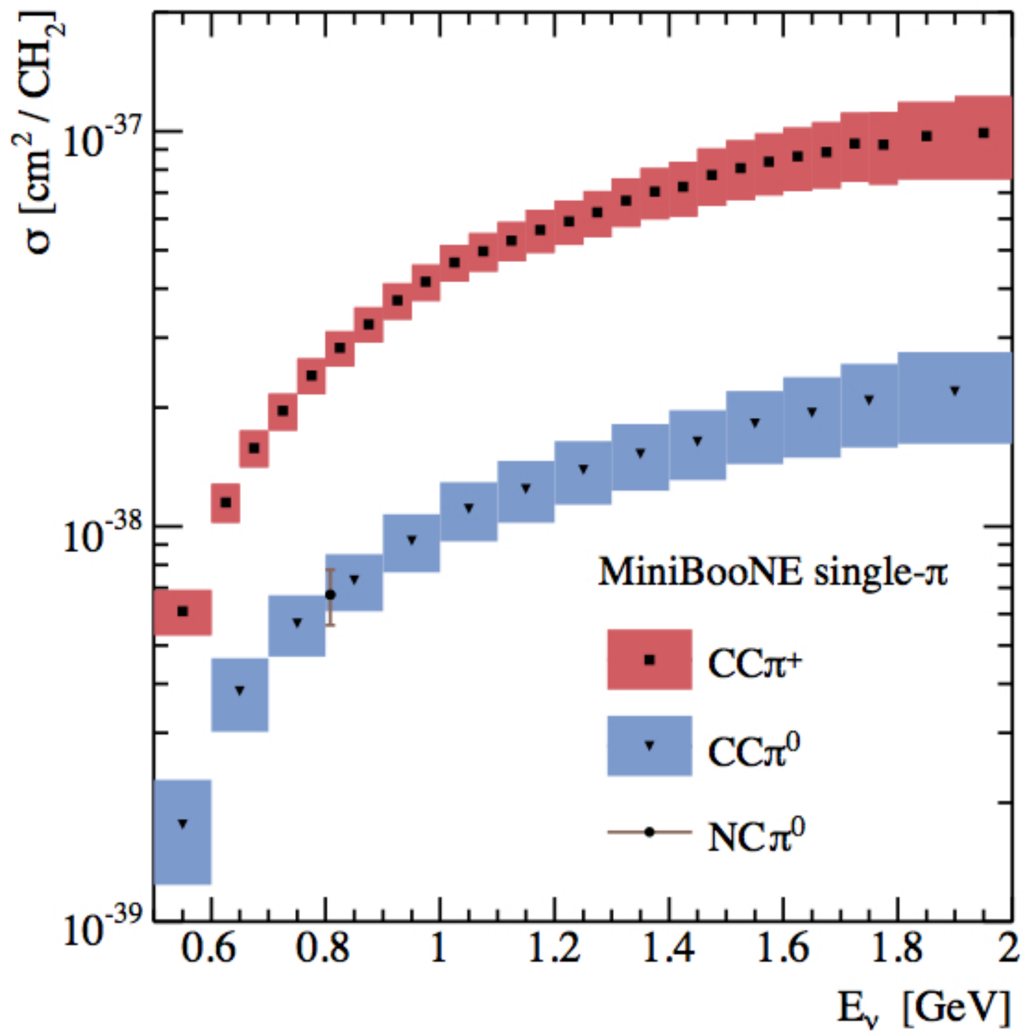
NCπ^0 Scattering

A. A. Aguilar-Arevalo et al., Phys. Lett. B 664, 41 (2008)

coherent fraction=19.5+-1.1+-2.5%



Single Pion Cross Sections

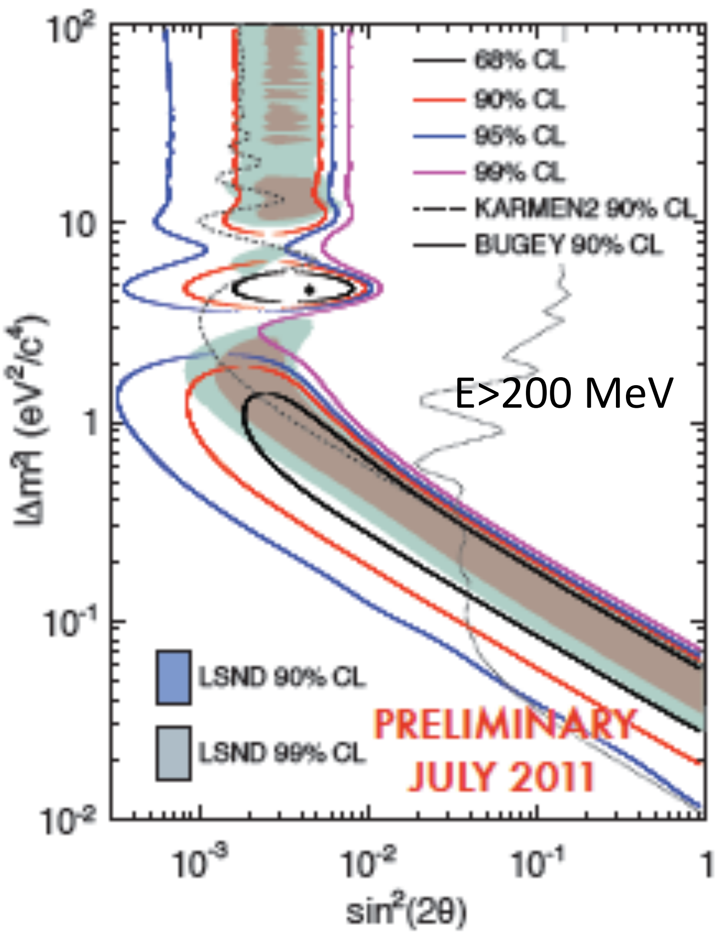


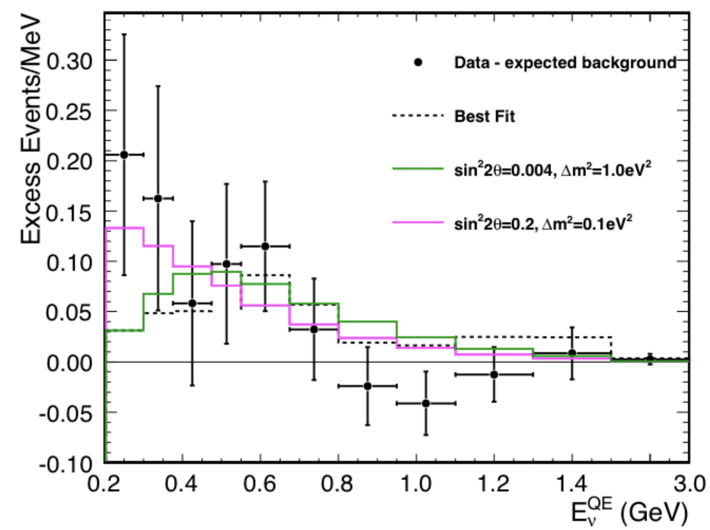
(R. Nelson, NuInt11)

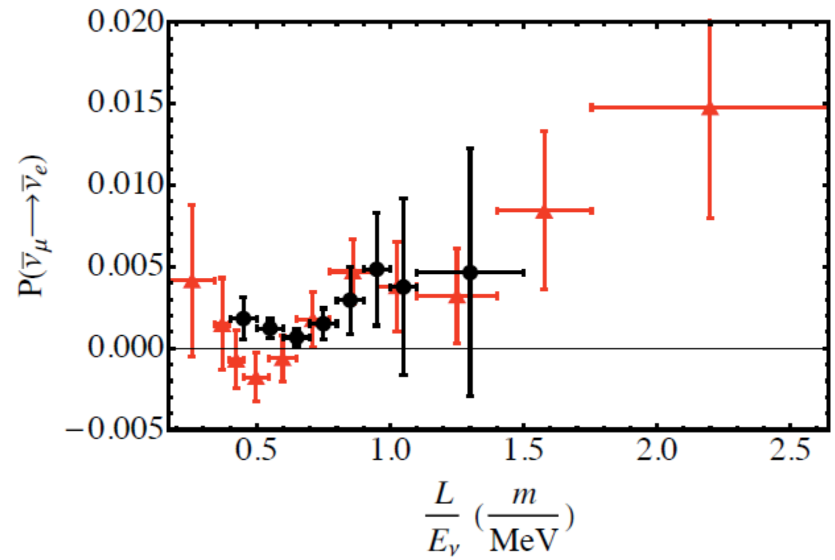
LSND & MiniBooNE Antineutrino Results

Neutrino/Antineutrino joint analysis is underway

Updated from A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 105, 181801 (2010)







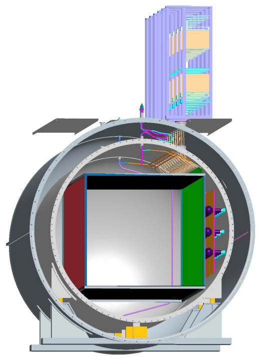
BooNE: Near Detector at ~200 m

Uncertainties Resolved By BooNE

- Short baseline ν_e and $\overline{\nu}_e$ appearance
- Short baseline CP violation
- Short baseline ν_μ and $\overline{\nu}_\mu$ disappearance
- Existence of sterile neutrinos by comparing NCπ^0 and NCElastic reactions in near and far detectors
- The 3+N interpretation of the LSND signal
- Incidentally, knowledge of the ν flux for all BNB experiments.

Competition for BooNE

- MicroBooNE is complementary to BooNE; MicroBooNE will determine whether the MiniBooNE ν excess is due to electron events or gamma events, while BooNE will determine whether the ν and $\overline{\nu}$ excesses are due to neutrino oscillations and whether there is short baseline CP violation in the lepton sector.
- ICARUS at CERN is competition to BooNE; however, BooNE can obtain a definitive result prior to ICARUS (significant result after one year of data taking).



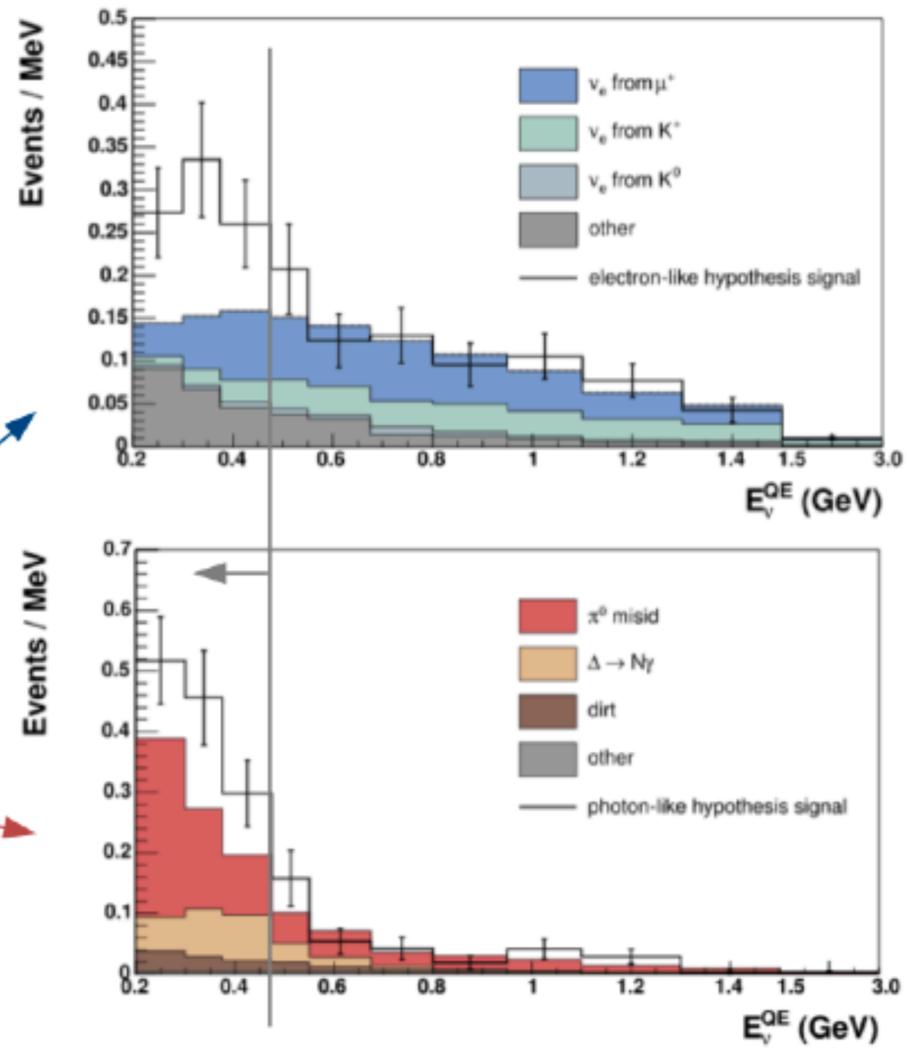
MicroBooNE at FNAL

MicroBooNE sensitivity to low energy excess:

(neutrino running,
- 70 ton fiducial volume,
- x2 higher PID efficiency than MiniBooNE,
- 3% mis-ID,
- 6.0e20 POT)

Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7σ stat. significance

Photon-like hypothesis:
36.8 excess events
78.9 background events
4.1σ stat. significance



ICARUS at the CERN PS

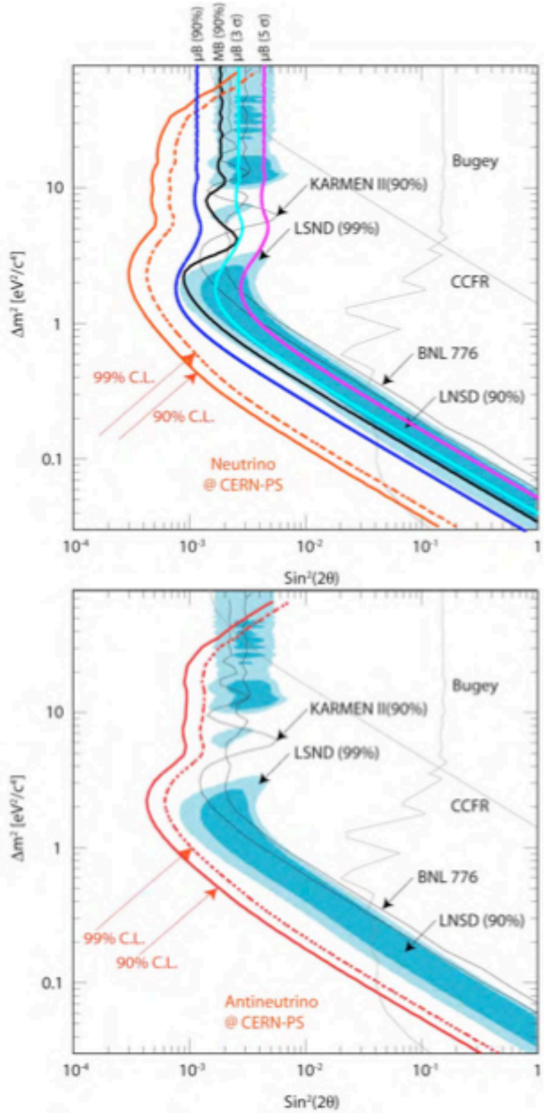


Figure 25. Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (top) and anti-neutrino (bottom) for 2.5 10^{20} pot and 5.0 10^{20} pot respectively. The LSND allowed region is fully explored in both cases.

Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

600 ton ICARUS at 850 m

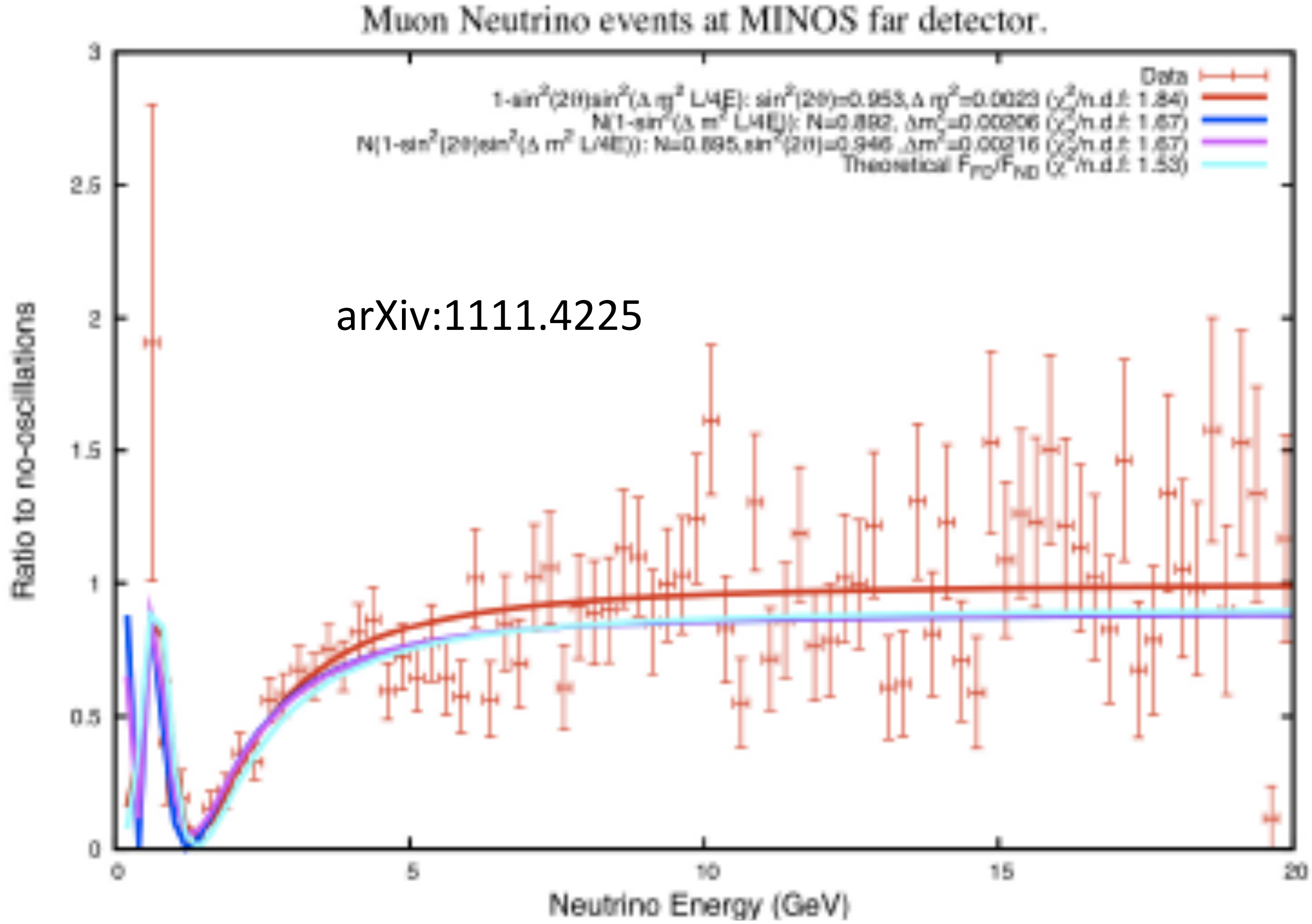
150 ton LAr at 127 m

Summary

- There are anomalies in short baseline ν experiments that cannot be explained by the 3 ν paradigm and that suggest the existence of sterile ν.
- The world neutrino & antineutrino data can be fit to a 3+1 oscillation model with $\Delta m^2 \sim 1\ eV^2$, although there is some tension with ν_μ disappearance. This model predicts observable (10%) ν_μ disappearance. (Other possibilities include, e.g., sterile ν decay and Lorentz Violation.)
- The world neutrino + antineutrino data fit even better to a 3+2 oscillation model with CP Violation.
- BooNE can measure neutrino oscillations with high significance (>5σ) and prove that sterile neutrinos exist!
- Short baseline oscillations affect (and are complementary to) long baseline ν experiments and the measurement of θ_{13} and δ (arXiv:1111.4225).

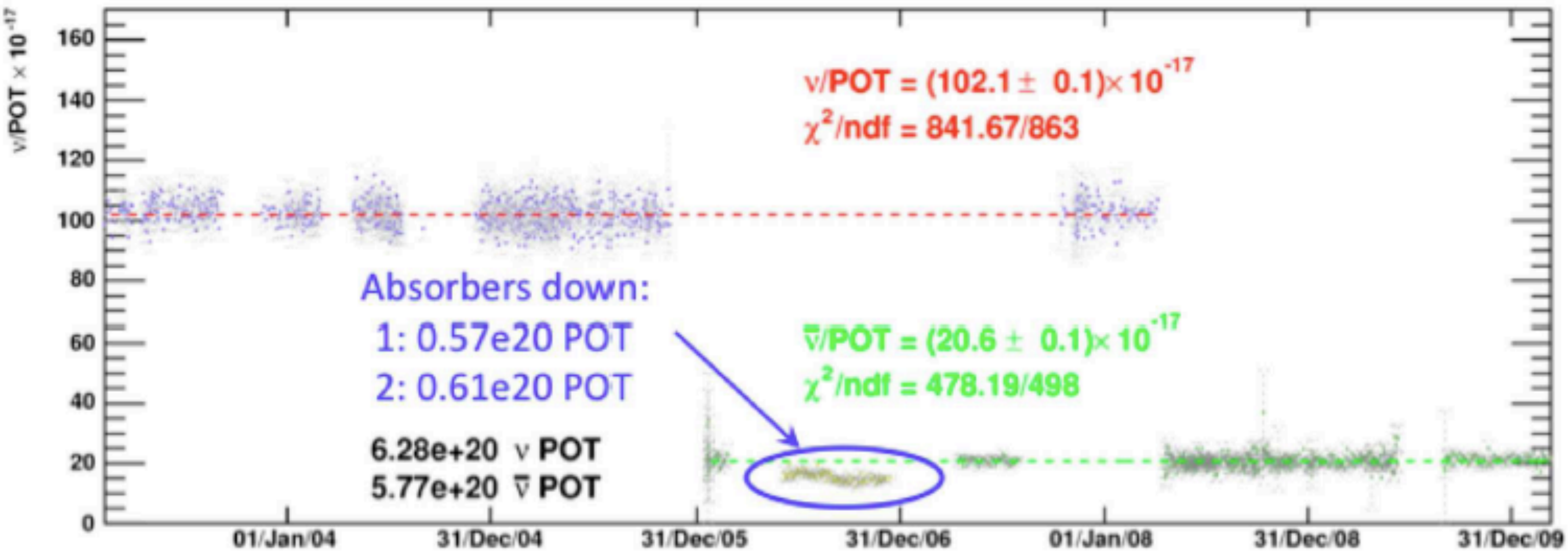
Backup

Fitting MINOS data for ν_μ Disappearance

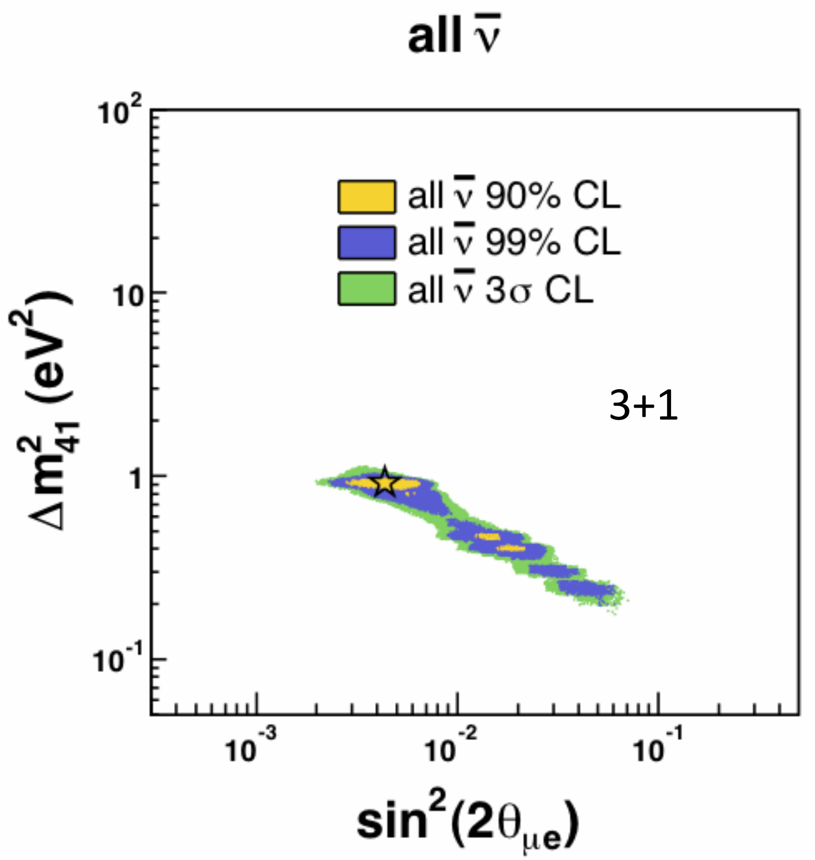


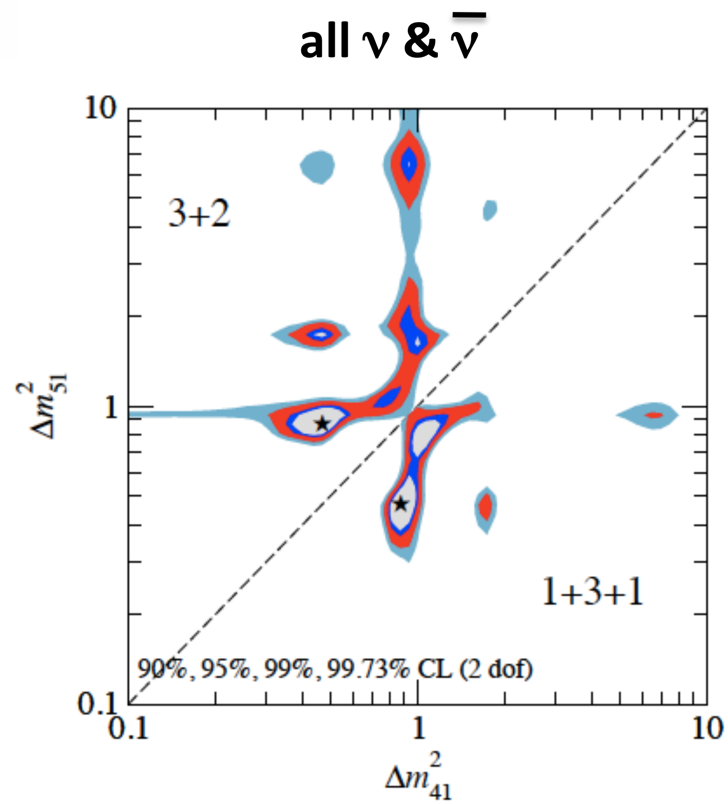
Case	$\Delta m^2 (10^{-3} eV^2)$	$\sin^2 2\vartheta_\mu$	$\mathcal{N}_\mu$	χ^2/n.d.f
I	2.31 ± 0.10	0.953 ± 0.04	$1^\dagger$	1.65
II	2.07 ± 0.09	$1^\dagger$	0.895 ± 0.03	1.48
III	2.17 ± 0.13	0.946 ± 0.048	0.897 ± 0.03	1.48
$\mathcal{R}_{\mu\mu}$	–	–	–	1.53

MiniBooNE Event Rate/POT Has Been Very Stable Over the Life of the Experiment



3+N Global Fits to World ν Data





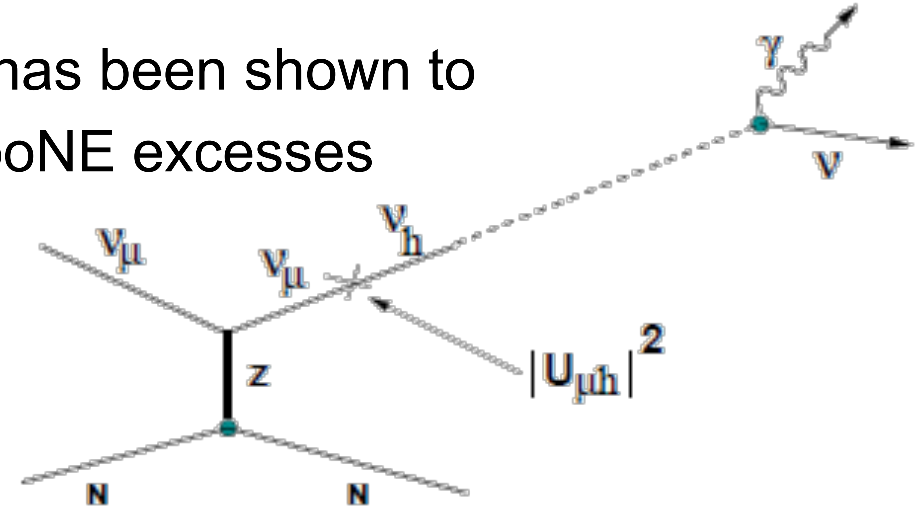
Updated from G. Karagiorgi et al., PRD80, 07300 (2009)

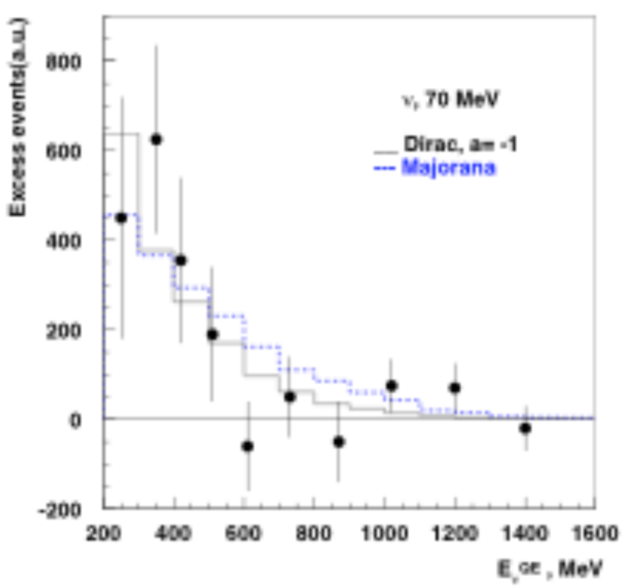
Kopp, Maltoni, & Schwetz, Phys. Rev. Lett. 107, 091801 (2011)

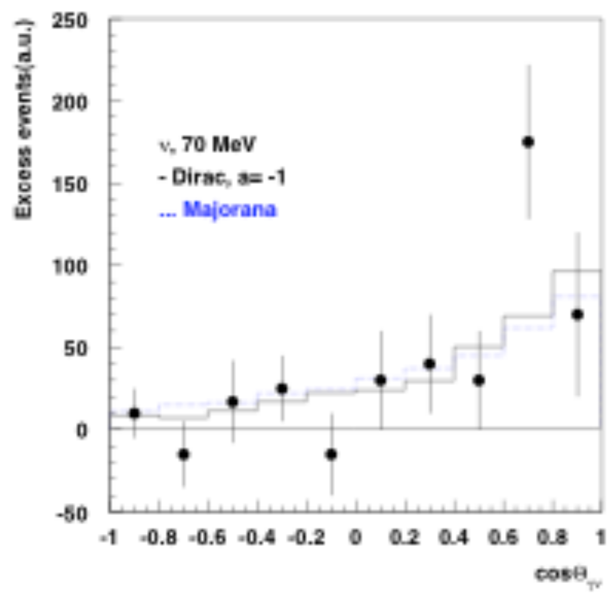
Sterile ν Decay

- The decay of a ~50 MeV sterile ν has been shown to accommodate the LSND & MiniBooNE excesses
  - **Gninenko, PRL 103, 241802 (2009)**

    arXiv:1009.5536







Lorentz Violation?

Lorentz- and CPT-violating models for neutrino oscillations

Jorge S. Díaz and V. Alan Kostelecký
Physics Department, Indiana University, Bloomington, IN 47405, U.S.A.
(Dated: IUHET 561, August 2011)

A class of calculable global models for neutrino oscillations based on Lorentz and CPT violation is presented. One simple example matches established neutrino data from accelerator, atmospheric, reactor, and solar experiments, using only two degrees of freedom instead of the usual five. A third degree of freedom appears in the model, and it naturally generates the MiniBooNE low-energy anomalies. More involved models in this class can also accommodate the LSND anomaly and neutrino-antineutrino differences of the MINOS type. The models predict some striking signals in various ongoing and future experiments.

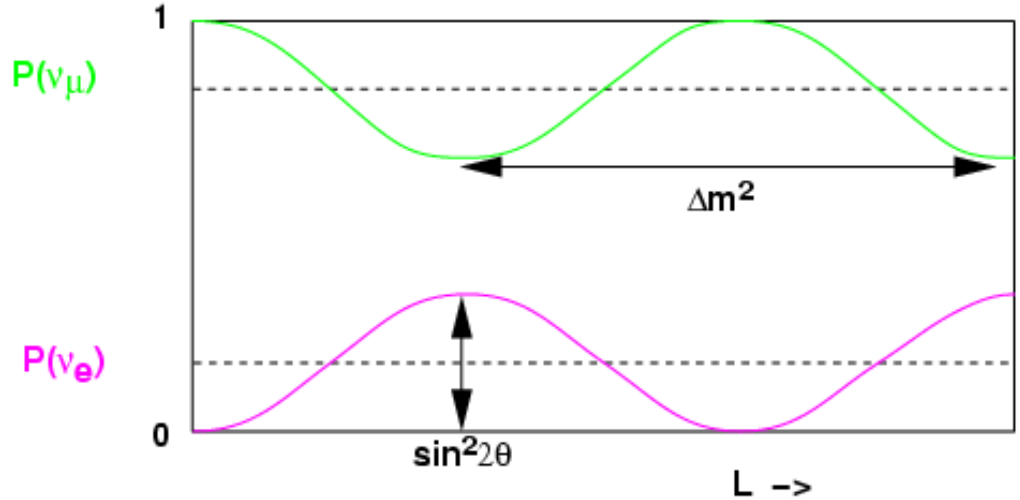
arXiv: 1108.1799

Neutrino Oscillations

Weak Eigenstates | **Eigenstates of Propagation**

$\nu_\mu = \cos\Theta\, \nu_1 + \sin\Theta\, \nu_2$

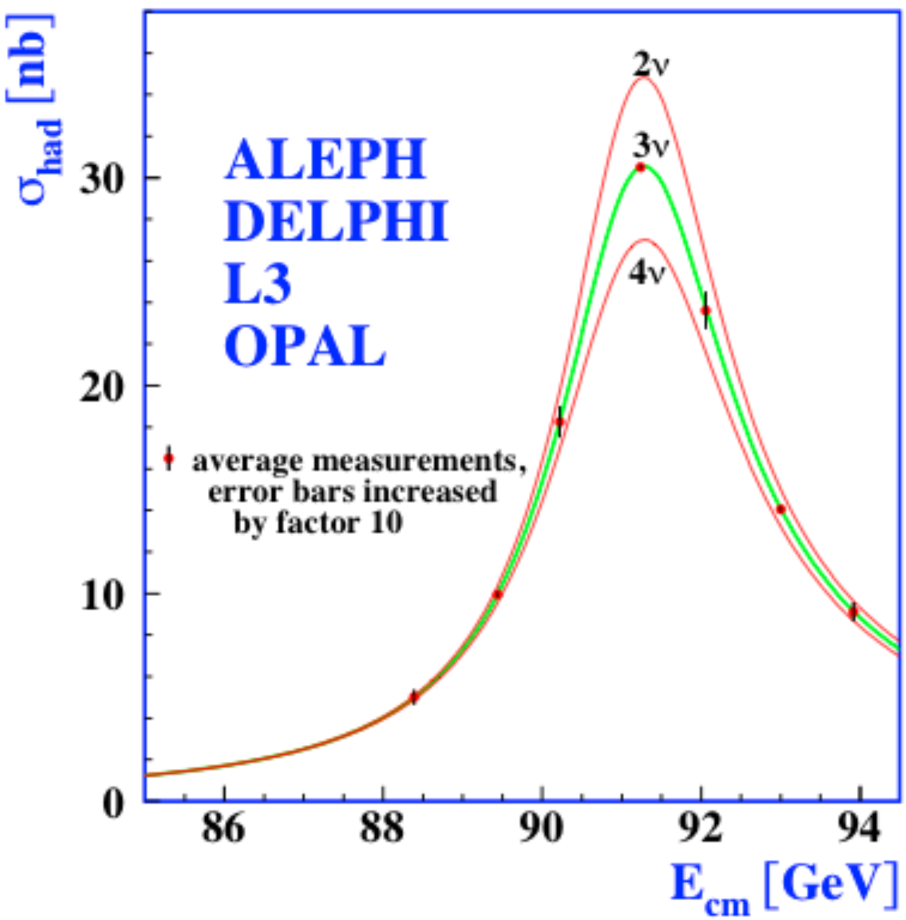
$\nu_e = -\sin\Theta\, \nu_1 + \cos\Theta\, \nu_2$



$$P_{\nu_\mu \to \nu_e} = \sin^2(2\Theta)\ \sin^2(1.27\, \Delta m^2\, L/E_\nu)$$

$\Delta m^2 = m_2^2 - m_1^2$ in eV^2, L in meters, E_ν in MeV

LEP Experiments at CERN: 3 Active Neutrinos!

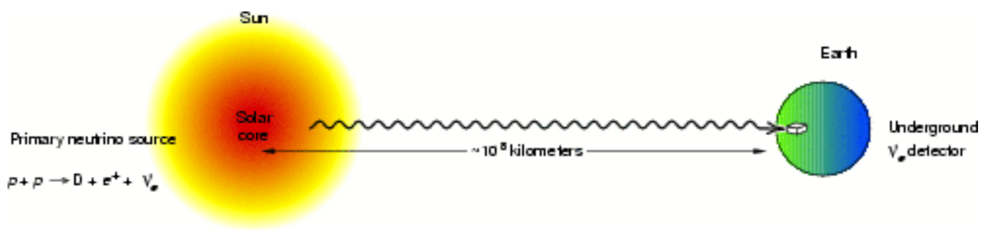


arXiv:hep-ex/0509008v3

The LEP experiments have measured the number of light, active neutrinos to be 3. Therefore, any additional neutrinos would need to be **sterile**.

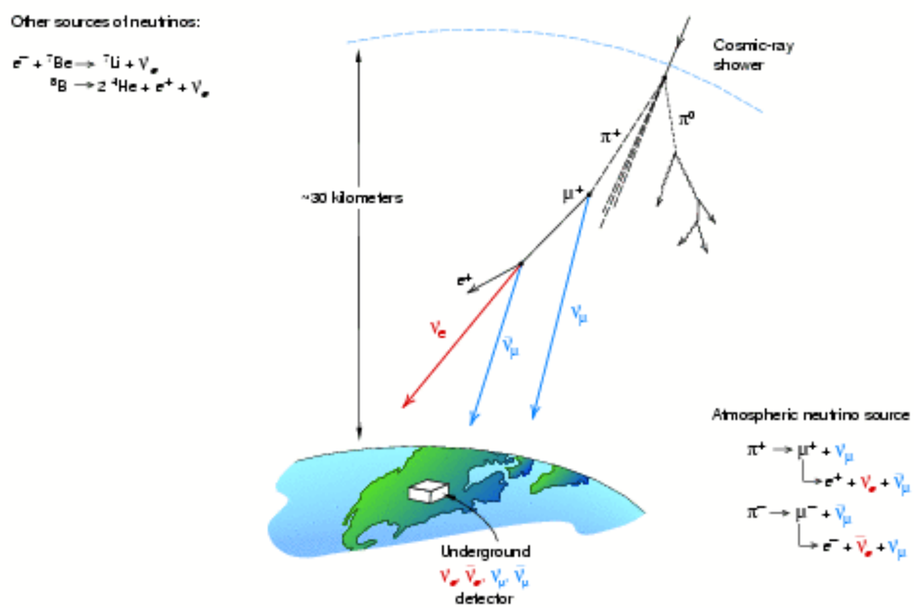
Sterile neutrinos would interact by Gravity but not by the Strong, Electromagnetic, or Weak Interactions.

Evidence/Observation of ν Oscillations



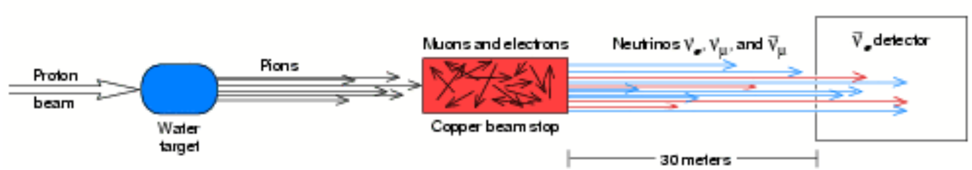
SuperK, SNO, KamLAND

$\Delta m^2 \sim 0.00007\ eV^2$



SuperK, K2K, MINOS, OPERA

$\Delta m^2 \sim 0.002\ eV^2$



LSND, MiniBooNE, Reactor ν

$\Delta m^2 \sim 1\ eV^2$

LSND $\bar{\nu}_e$ Background Estimates

Estimate	$\bar{\nu}_e/\bar{\nu}_\mu$	$\bar{\nu}_e$ Bkgd	LSND Excess
LSND	0.086%	19.5+-3.9	87.9+-22.4+-6.0
HARP-CDP	0.104%	23.6+-4.7	83.8+-22.4+-6.5

All $\bar{\nu}_e$ background estimates assume a 20% error. Note that the $\bar{\nu}_e/\bar{\nu}_\mu$ ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001)

HARP-CDP Paper: arXiv:1110.426, with mistakes corrected; however, there is still a problem with an overestimate of the DIF fluxes, which can cause an overestimate of the nuebar intrinsic background.

Mistakes in arXiv:1110.4265

(1) The paper multiplies the intrinsic nuebar background by a factor of 1.6, which is the ratio of "Emulation"/"Best Estimate" nuebar in Table 15. However, this neglects the fact that the paper overestimates the DAR fluxes and one should, therefore, normalize to the nue flux. Thus, the paper instead should use a factor of 1.21, which is the ratio of "Emulation"/"Best Estimate" nuebar/numubar in Table 15. This increases the intrinsic nuebar background by 4.1 events instead of 11.7 events.

(2) In Table 15 the pi+ and pi- DIF fluxes are factors of 3.3 and 2.5 higher in the "Best Estimate" than in the LSND publication. However, LSND made high statistics measurements of numu and numubar scattering (PRC 66, 015501-1), and the paper's "Best Estimate" fluxes are wrong. For example, for numubar + p -> mu+ n scattering, LSND observes 214+-35 events, which are consistent with the LSND flux estimate and a factor of 3.3 lower than the paper's flux estimate. For numu + C -> mu- +Ngs, LSND observes 66.9+-9.1 events, which are consistent with the LSND flux estimate and a factor of 2.5 lower than the paper's flux estimate. Therefore, it is clear that the paper is overestimating the DIF flux by factors of 2.5-3.3. Does this mean that the paper's intrinsic nuebar background estimate should be reduced by a factor of 3.3?

(3) The T_mu<3 MeV cut is not a hard cutoff. Rather, LSND still observes some muons down to 2 MeV or lower, especially because the energy lost by the recoil neutron is included. Also, LSND checked the background estimate by extrapolating the observed nhit distribution down to zero. Therefore, LSND is confident about the background estimate of 10.5+-4.6, and the paper's background estimate of 13.8+-8.2 is not correct.

(4) The 12Ngs beta decays that mimic 2.2 MeV gammas are very small (~0.2 events just to pass the minimal cuts). Indeed, LSND determined that the R distribution of 12Ngs events looks indistinguishable from the R distribution of 12N inclusive events without a beta. The paper's estimate of 2.3 events is overestimated, partly because a 2.2 MeV electron produces more PMT hits than a 2.2 MeV gamma. A 2.2 MeV gamma produces the same number of PMT hits as an ~1-1.5 MeV electron.

Therefore, if the problem with the DIF fluxes is ignored, the paper's excess should be 83.7+- 23.2 events, which agrees well with the LSND estimate of 87.9+-23.2 events. However, if the paper's intrinsic nuebar flux is reduced by a factor of 3.3 to make the DIF estimates agree with LSND data, then the paper's excess increases to 100.2+-23.2 events.