Proving the Existence of Light, Sterile Neutrinos

W.C. Louis, LANL

March 21, 2012

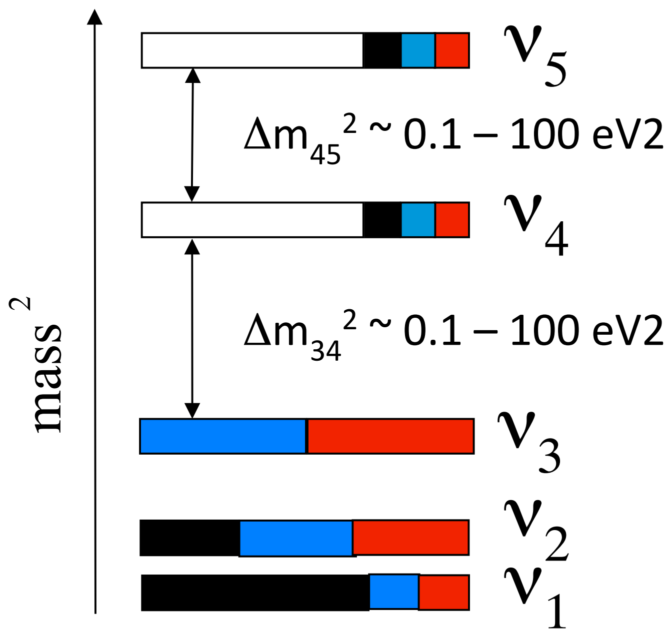
- Anomalies from Short-Baseline Neutrino Experiments
- 3+N Sterile Neutrino Models & ν_μ Disappearance
- Comparison of NC event rates from different detectors
- DIF Experiments (BooNE)
- DAR Experiments (OscSNS)
- Conclusion

Tantalizing 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.

Sterile Neutrinos

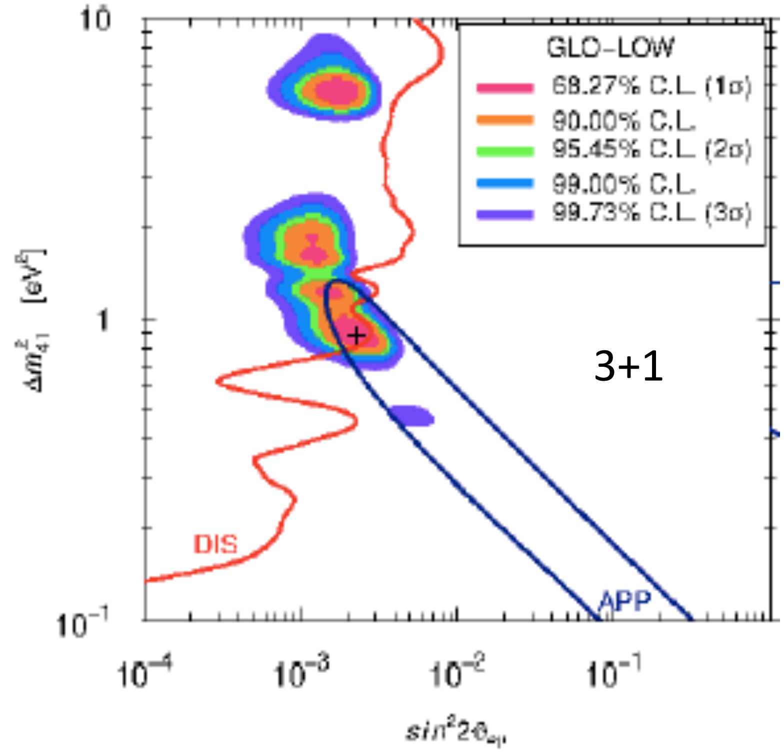


- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\nu_\mu \rightarrow \nu_e \neq \overline{\nu}_\mu \rightarrow \overline{\nu}_e$

3+N Global Fits to World ν Data

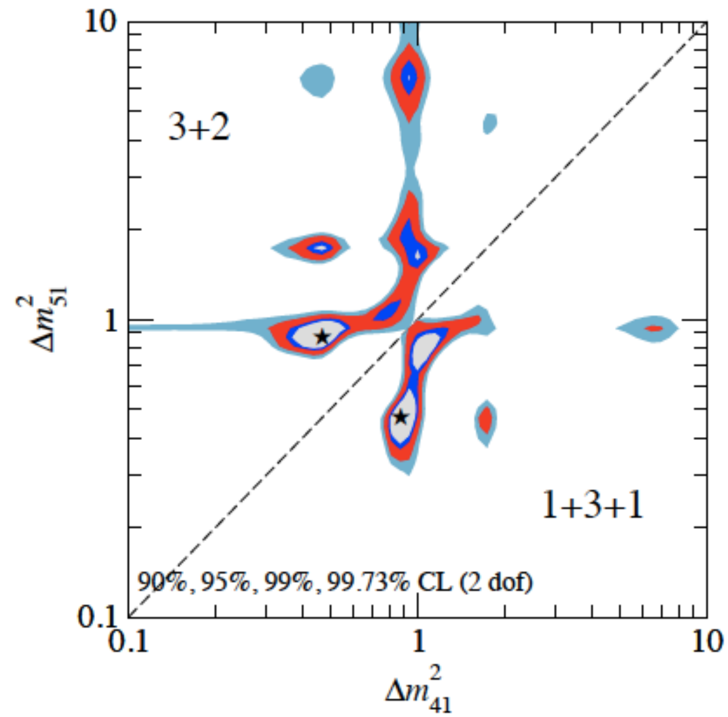
(Predict observable ν_μ disappearance)

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 Require Large ν_μ Disappearance Into Sterile Neutrinos!

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

Reactor Experiments: $P(\bar{\nu}_e \to \bar{\nu}_x) \sim 15\%$

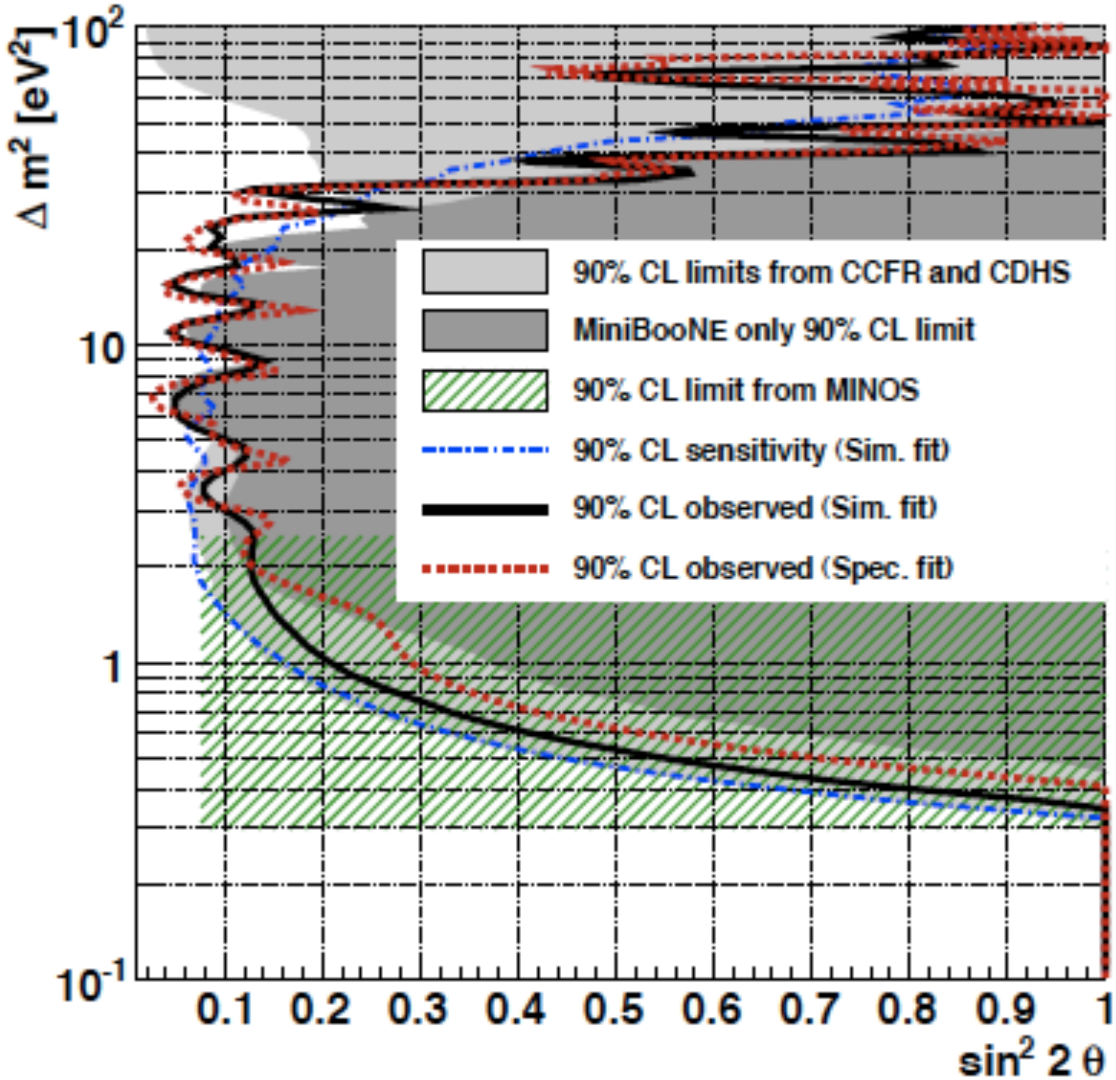
LSND/MiniBooNE: $P(\bar{\nu}_\mu \to \bar{\nu}_e) \sim 0.25\%$

Therefore: **$P(\bar{\nu}_\mu \to \bar{\nu}_x) > 7\%$ (or $\sin^2 2\theta > 7\%$)**

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

SciBooNE/MiniBooNE ν_μ Disappearance Limits (Antineutrino Next)

arXiv:1106.5685



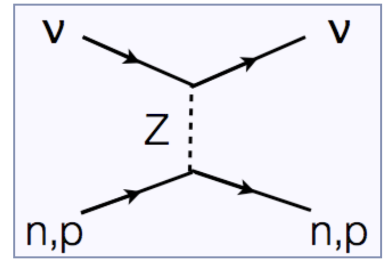
Question: How to prove the existence of light, sterile neutrinos?

Answer: Search for disappearance of a NC reaction in 2 detectors located at different distances!

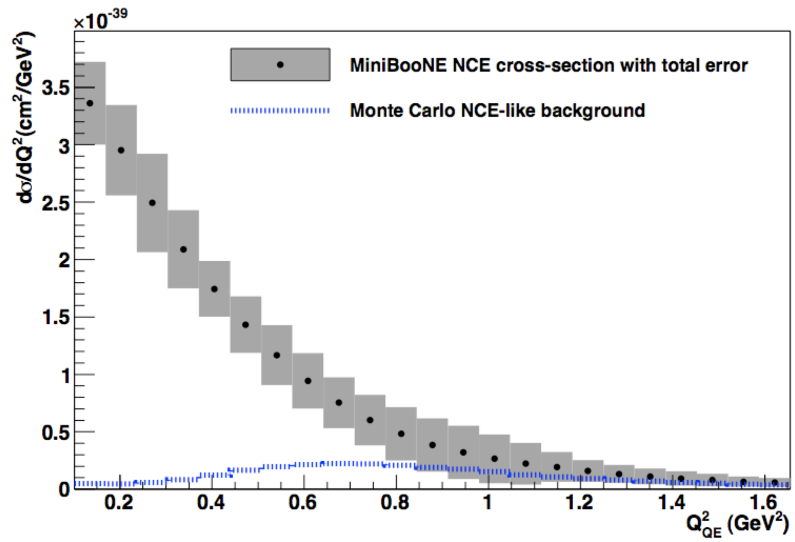
Neutrino Neutral Current Elastic

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



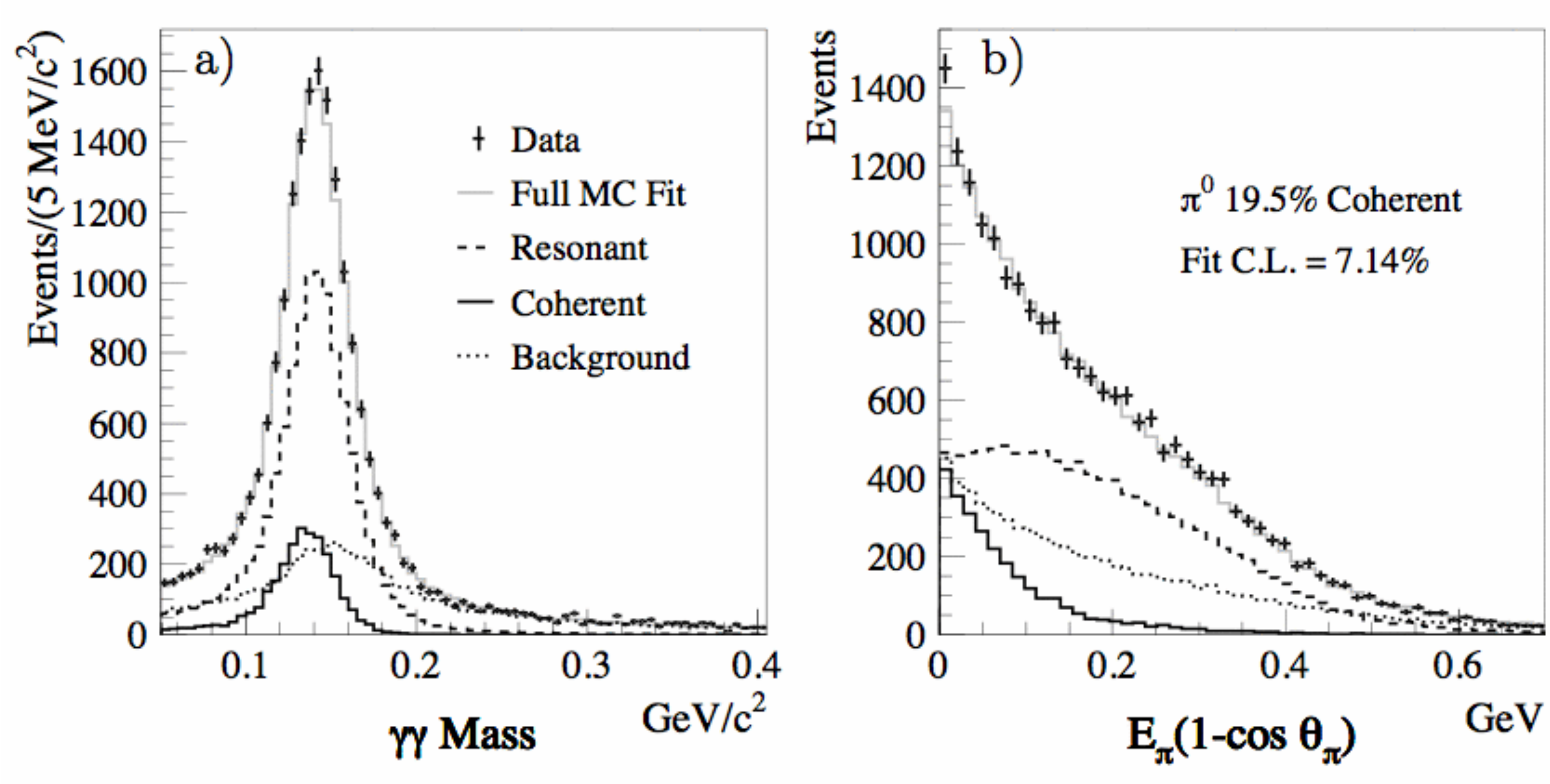
Ph.D. thesis, D. Perevalov, University of Alabama
Phys. Rev. D. **82**, 092005 (2010)

From D. Perevalov

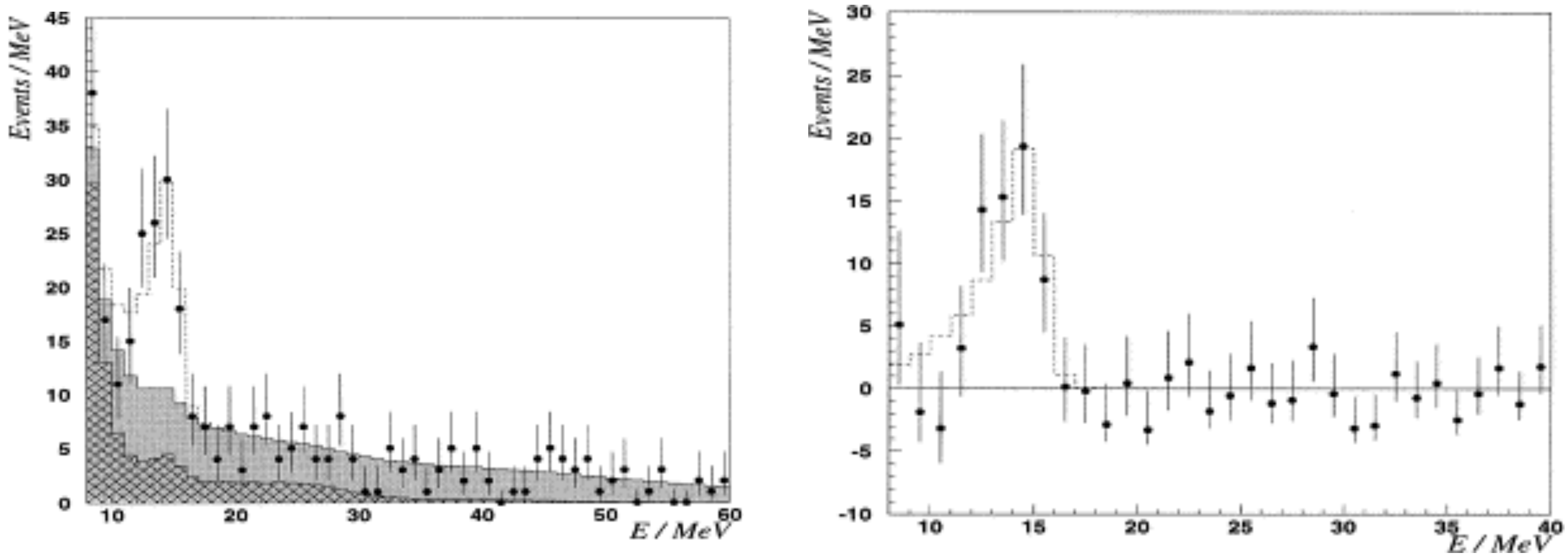
NCπ^0 Scattering

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

coherent fraction=19.5+-1.1+-2.5%



KARMEN Measurement of ν_μ C -> ν_μ C*(15.11)

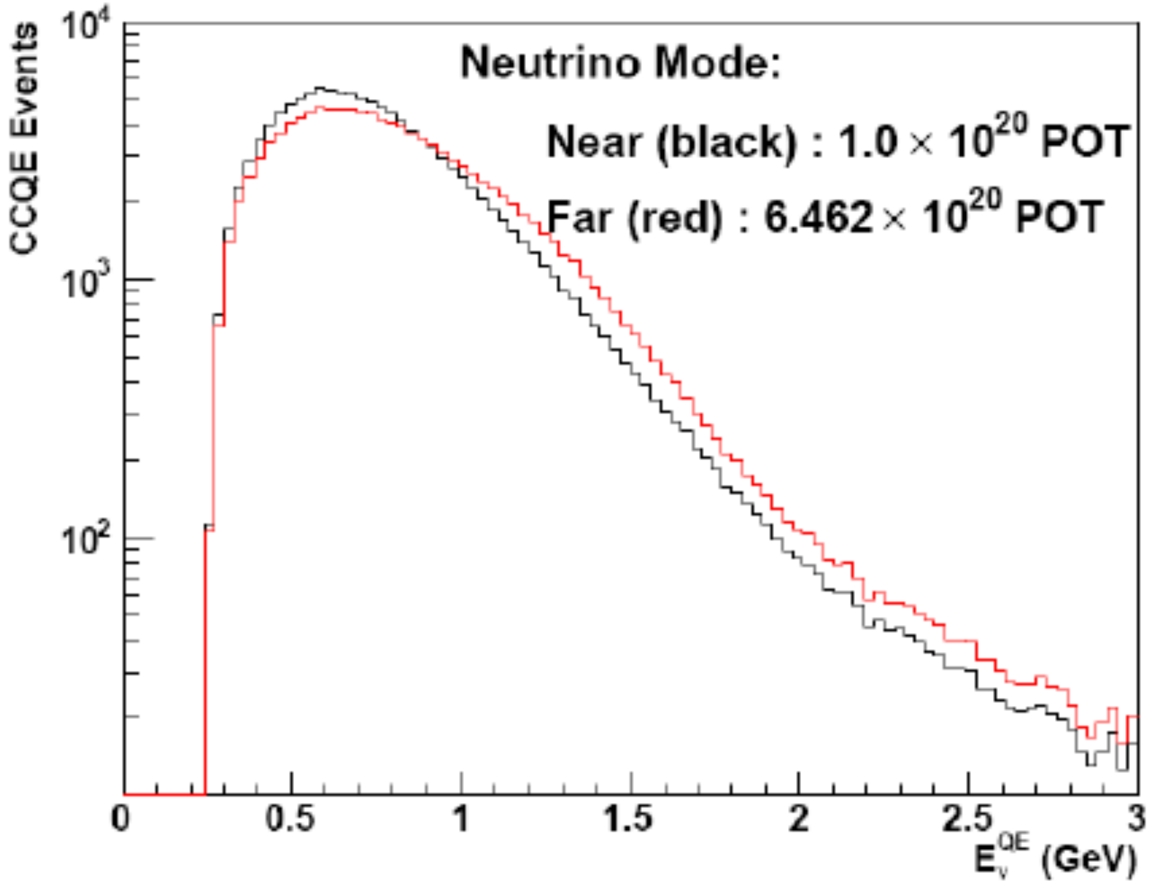


σ_{NC} = (3.2+-0.5+-0.4)x10^{-42} cm^2 (B. Armbruster et al., Phys. Lett. B423 (1998) 15)

σ_{NC} ~2.8x10^{-42} cm^2 (Kolbe, Langanke, & Vogel, Nucl. Phys. A652 (1999) 91)

BooNE: Two Mineral Oil Detectors (or Two LAr Detectors) at Different Distances on the BNB

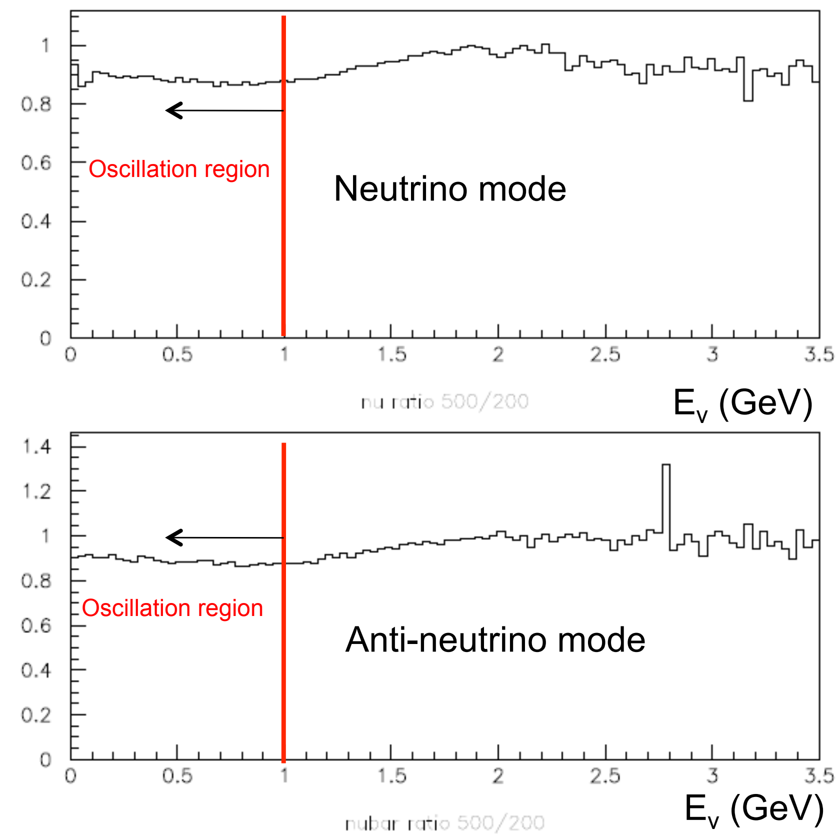
ν_μ Charged Current Event Rates Near and Far



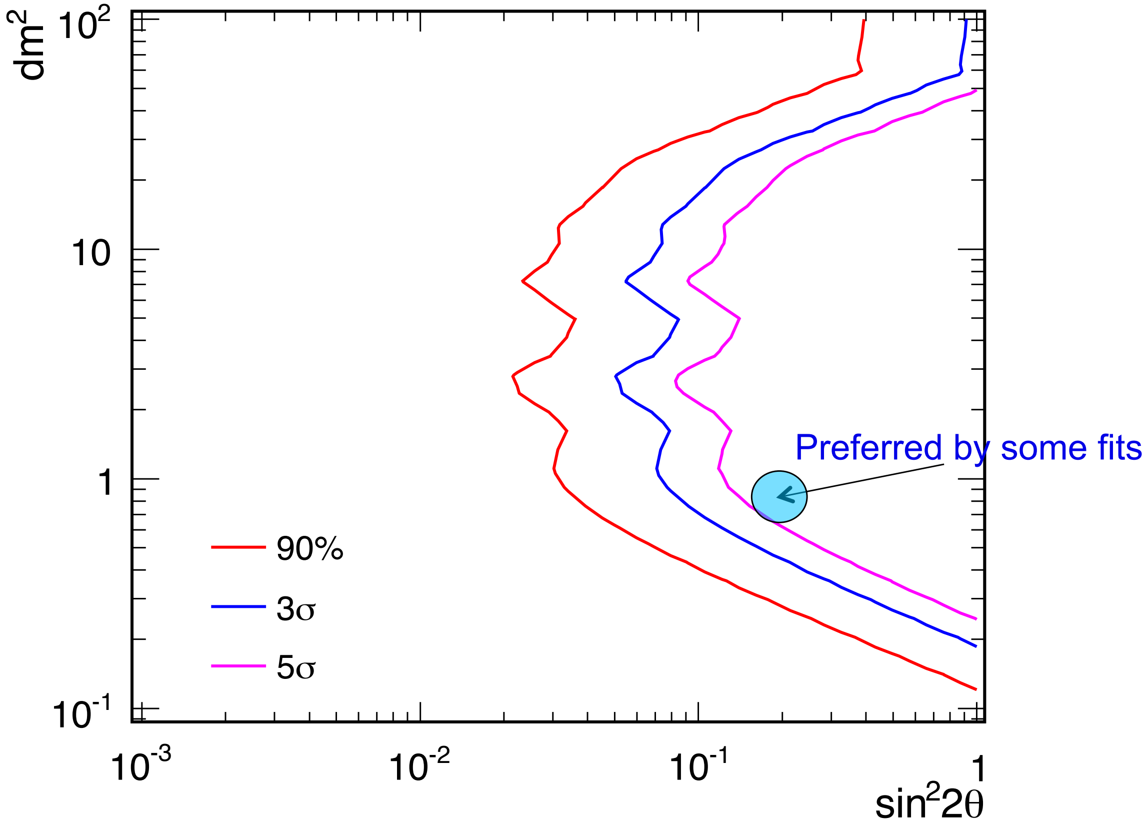
Quasi elastic event rates

Far to Near ν_e Flux Ratios at 200 m

MiniBooNE Far/Near fluxes
Scaled by $1/r^2$

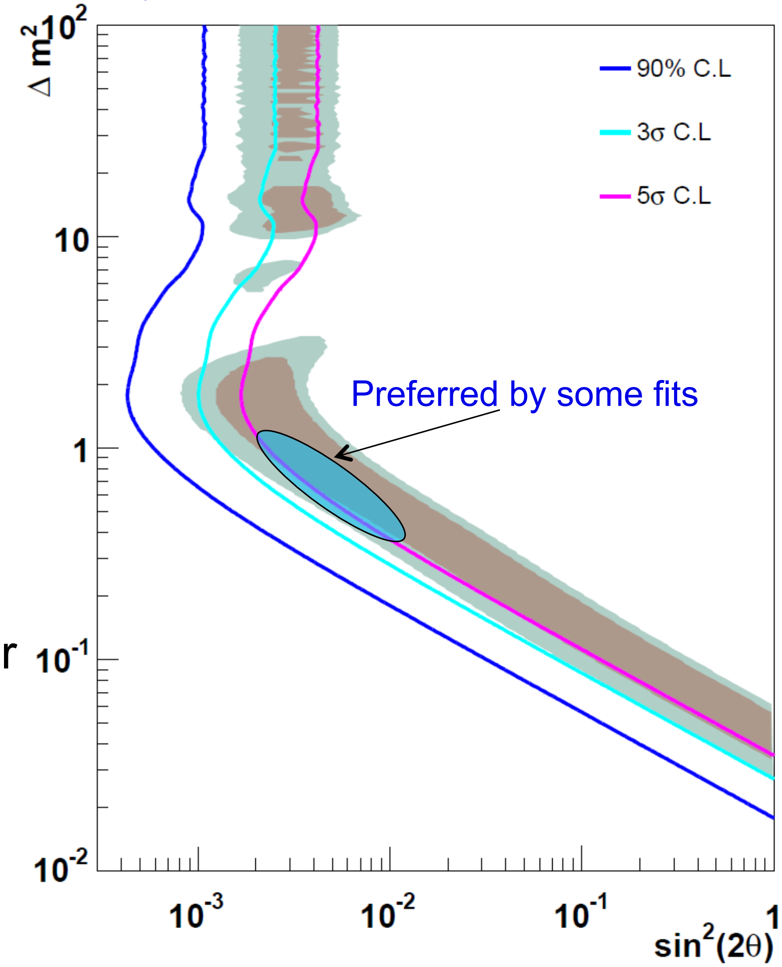


Neutrino Disappearance Sensitivity with Detector at 200 Meters



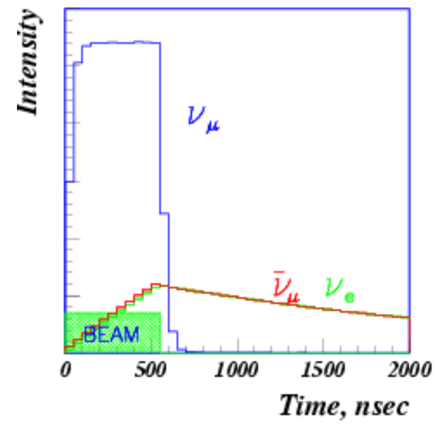
Sensitivity with Near/Far Comparison

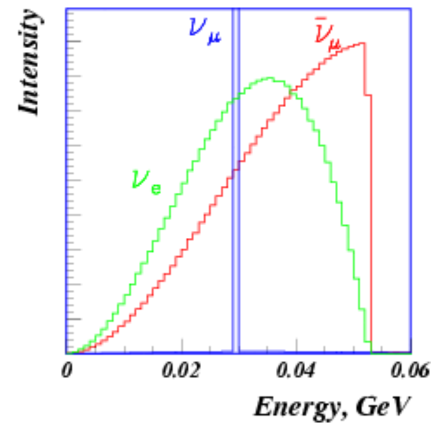
- Near/Far comparison sensitivity
  - ➢Near location at 200 meter
    - ✓ $1x10^{20}$ pot ~1 yr of running
  - ➢ Full systematic error analysis
    - ✓Flux, cross section, detector response



OscSNS at ORNL

- SNS spallation neutron source
- 1GeV protons @ 1.4MW
- Prolific source of neutrinos
- MiniBooNE-like detector at 60m





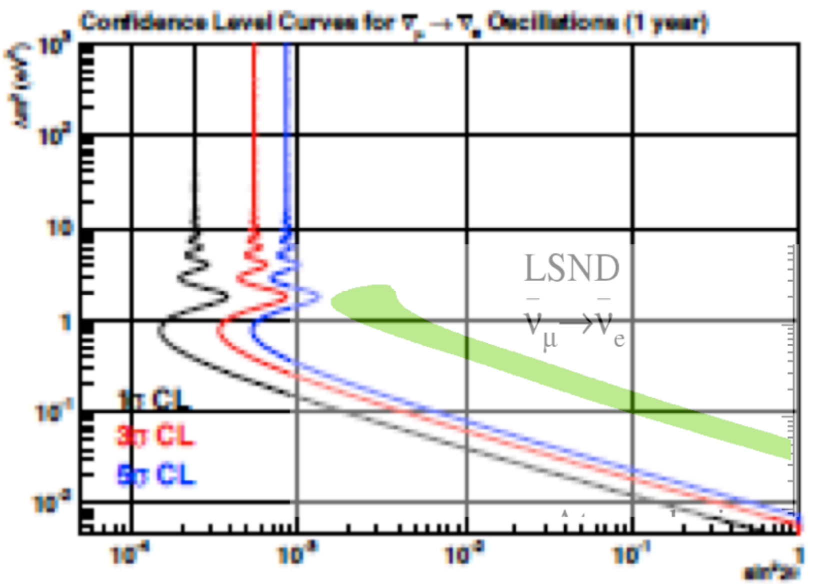
OscSNS would be capable of making precision measurements of $\bar{\nu}_e$ appearance & ν_μ disappearance and proving the existence of sterile neutrinos. (see Phys. Rev. D72, 092001 (2005)).

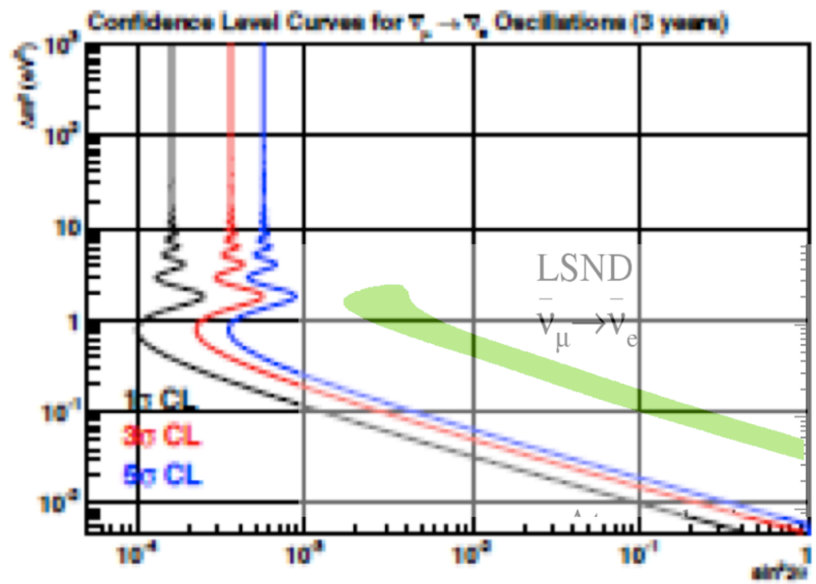
OscSNS Advantages Over Other Neutrino Oscillation Experiments

- Well understood ν flux
- Well understood ν cross sections
- Low duty factor
- Absence of nuclear effects
- Very low backgrounds (< 0.1%)
- Beam comes for free from the SNS
- SNS runs more than ½ the year

OscSNS at ORNL

- $\bar{\nu}_e$ appearance sensitivity for 1 & 3 years of running

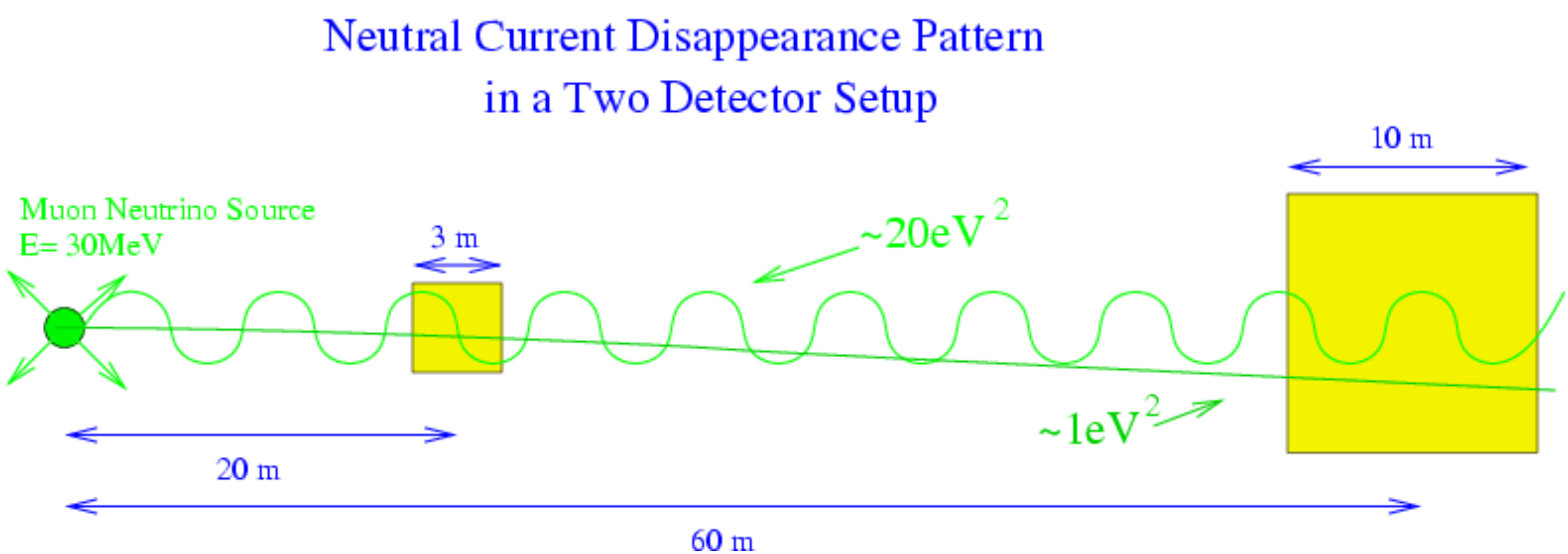




Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:

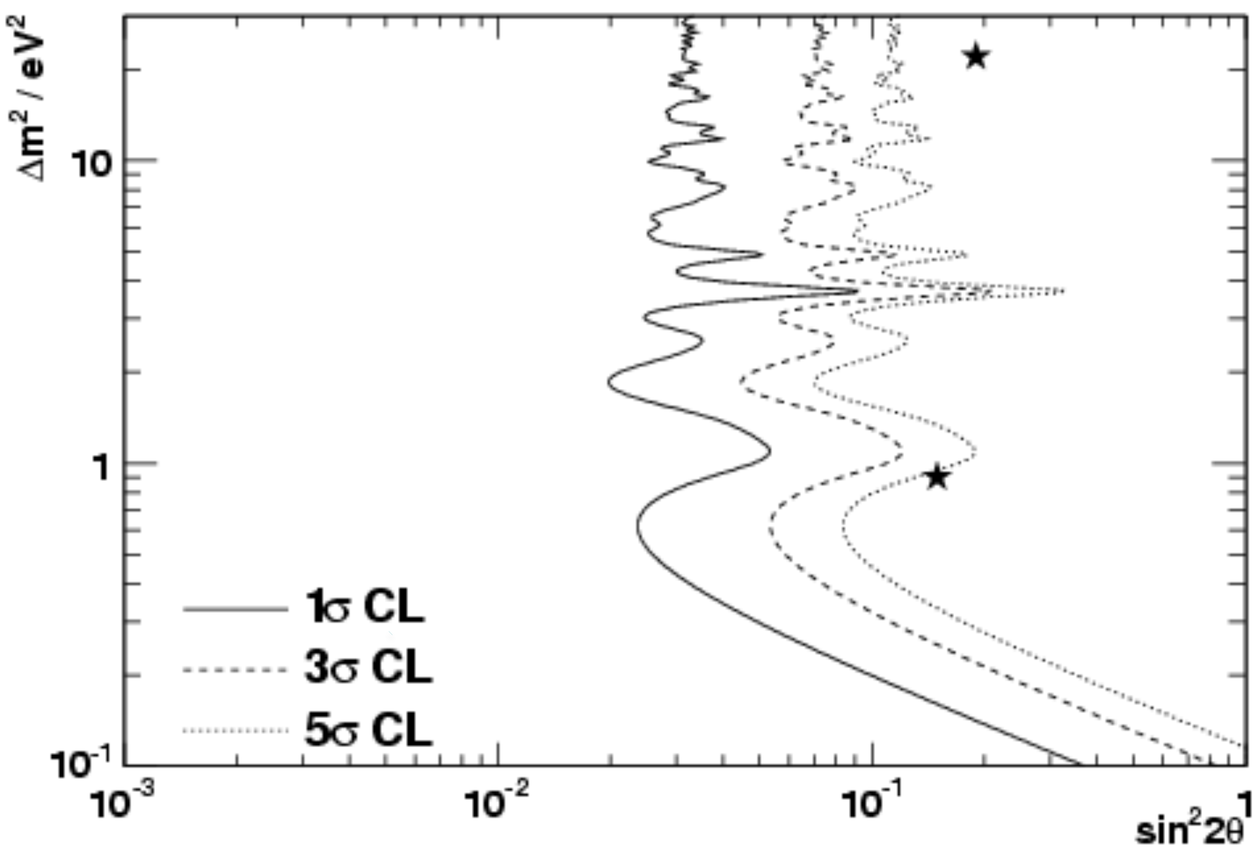
ν_μ C -> ν_μ C*(15.11)

Garvey et al., Phys. Rev. D72 (2005) 092001



Measurement of Oscillation Parameters with Two Detectors

ν_μ disappearance



Goals of the BooNE & OscSNS Experiments

- Prove the existence of sterile neutrinos by comparing NC reactions in near and far detector
- Short baseline ν_e and $\bar{\nu}_e$ appearance
- Short baseline CP violation
- Short baseline ν_e, ν_μ and $\bar{\nu}_\mu$ disappearance
- The resolution of the current short-baseline anomalies

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 fairly well to a 3+N oscillation model with large ν_μ disappearance (>7%).

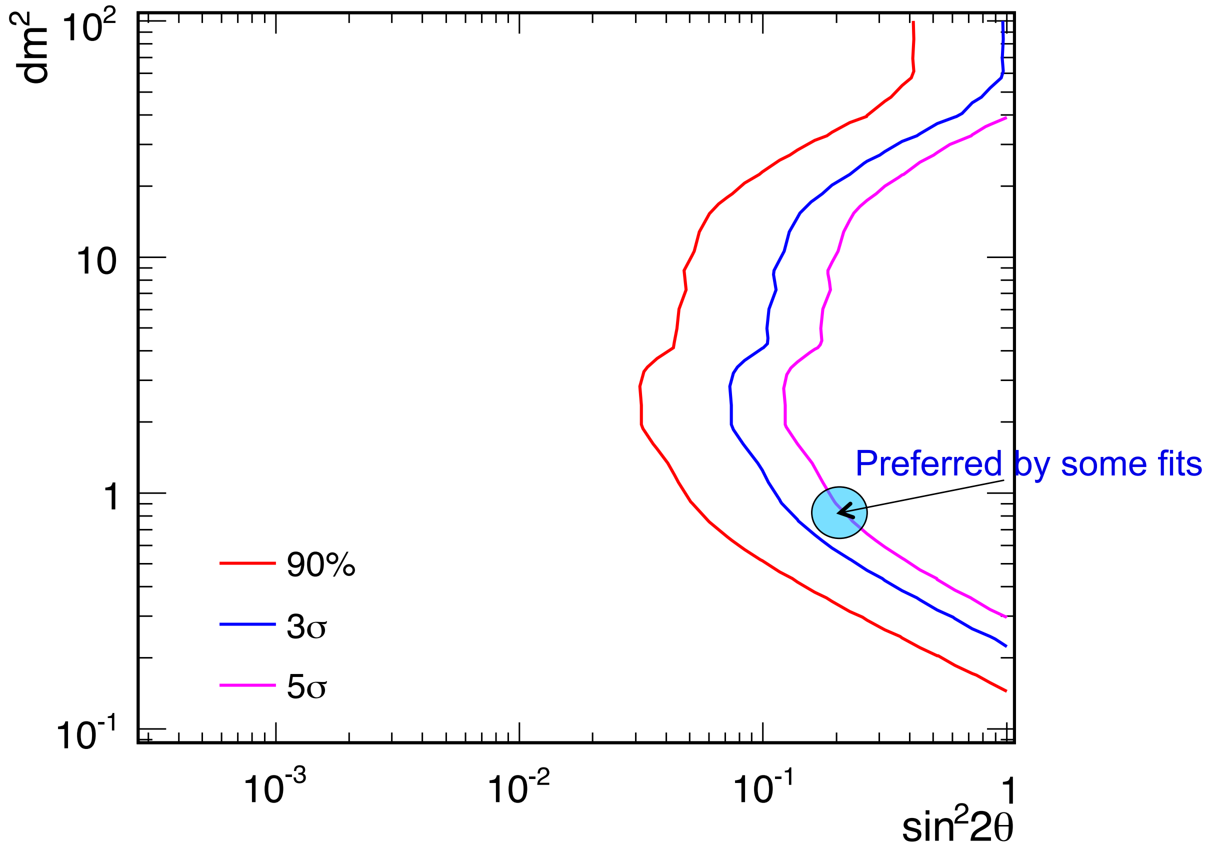
• The existence of light, sterile neutrinos can be proven by measuring the ratio of NC event rates in two different detectors.

• DIF (BooNE) & DAR (OscSNS) experiments 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).

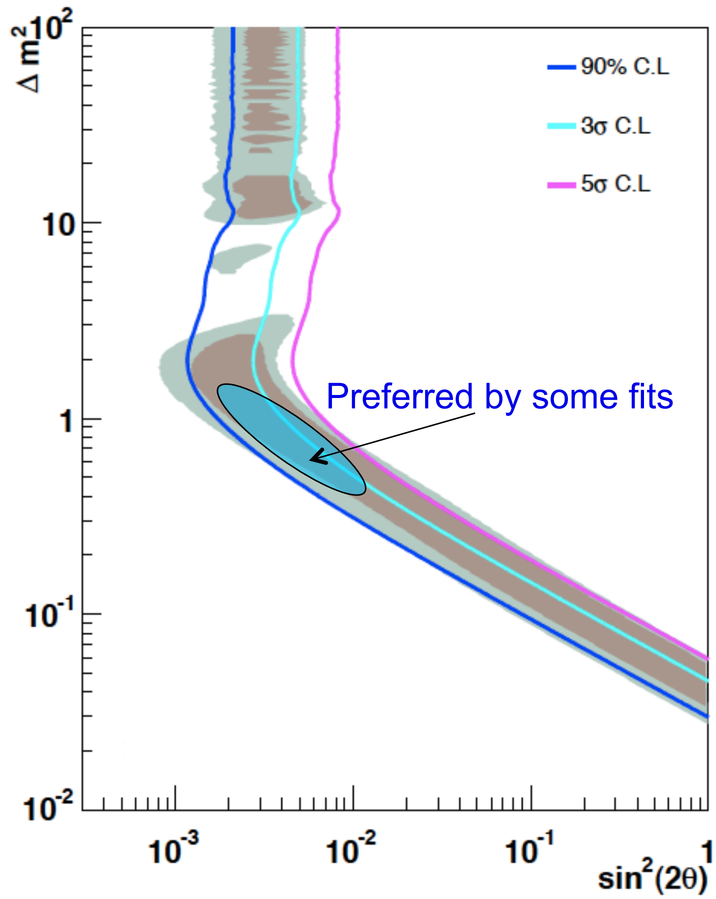
Backup

Antineutrino Disappearance Sensitivity with Detector at 200 Meters



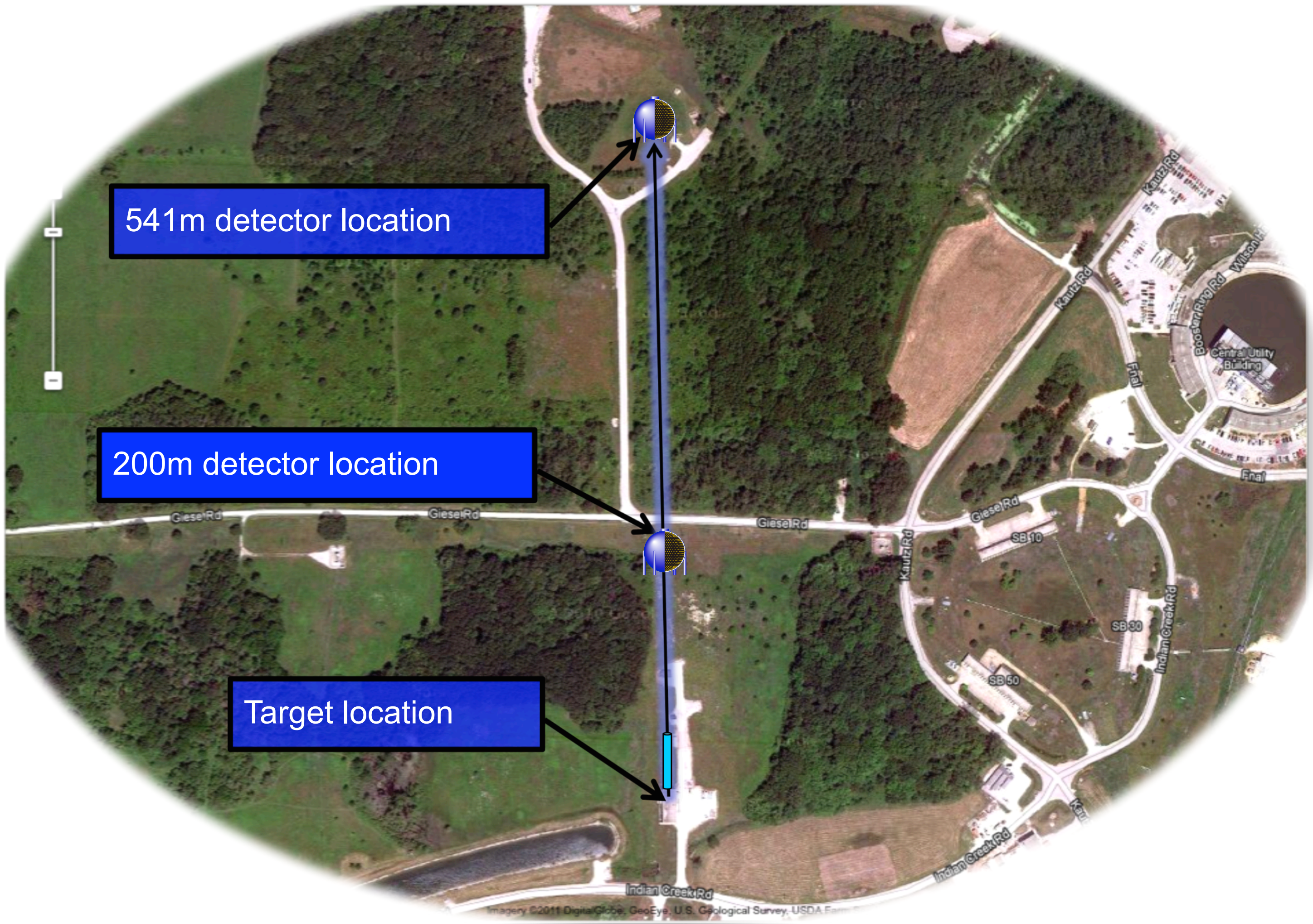
Sensitivity with Near/Far Comparison Anti-nu Mode

- Near/Far comparison sensitivity
  - ➢Near location at 200 meter
    - ✓ 1×10^{20} pot ~1 yr of running
  - ➢ Full systematic error analysis
    - ✓Flux, cross section, detector response




Pine St
United States Government
Pine St
Pine St
Lederman Science Center
Kirk Rd
Kautz Rd
Niu Institute Neutron Therapy
Fermi National Lab Library
Central Utility Building
Booster Ring Rd
Outer Ring Rd
Giese Rd
Giese Rd
Giese Rd
SB 10
SB 30
SB 50
Indian Creek Rd
Kautz Rd
Holter Rd
Indian Creek Rd
Indian Creek Rd
Kirk Rd
Outer Ring Rd
Holter Rd

New Location at 200 meters



OscSNS $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Experiment vs LSND

(assuming $\Delta m^2 < 1\ eV^2$)

- More Detector Mass (x5)
- Higher Intensity Neutrino Source (x2)
- Lower Duty Factor (x100) (less cosmic background)
- No DIF Background (backward direction)
- Lower Neutrino Background (x4) (60m vs 30m)
- Better Signal/Background (x4)
- For LSND parameters, expect ~350 ν_e oscillation events & <50 background events per year!

BooNE Cost Estimate

- Based on as-built MiniBooNE costs
  - 28% contingency added
  - 3%/year escalation assuming 2013 start

Item	Cost ($K)
Tank	265.3
Support Structure	28.1
PMTs	2768.9
Preamps	30.6
Electronics	355.5
DAQ	67.2
Conventional Construction	4212.0
Plumbing	25.9
Oil	1283.6
Total	9037.2

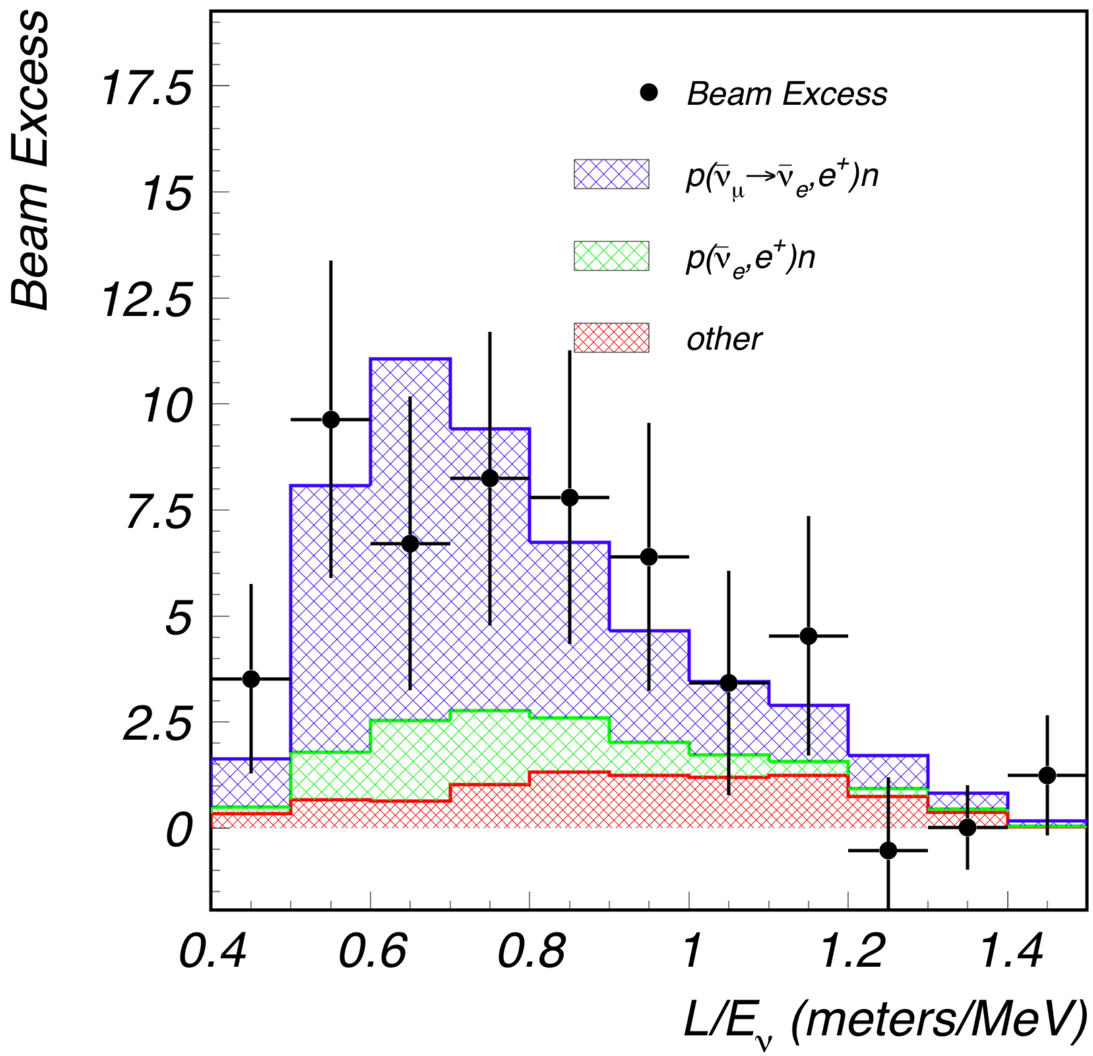
BooNE Schedule

- Project is ideal for fast-tracking
  - Much of the original design could be used
  - Well known performance characteristics
  - Have complete simulation/analysis software in-hand

Milestone	Date
CD-0	3/26/12
CD-1	7/17/12
CD-2	9/26/12
CD-3 Construction Start	5/24/13
Tank Complete	8/1/13
Conventional Construction Complete	12/3/13
Electronics Complete	10/19/13
DAQ Start	5/24/13
PMTs Installed	4/24/14
CD-4	5/26/14

LSND Antineutrino Results

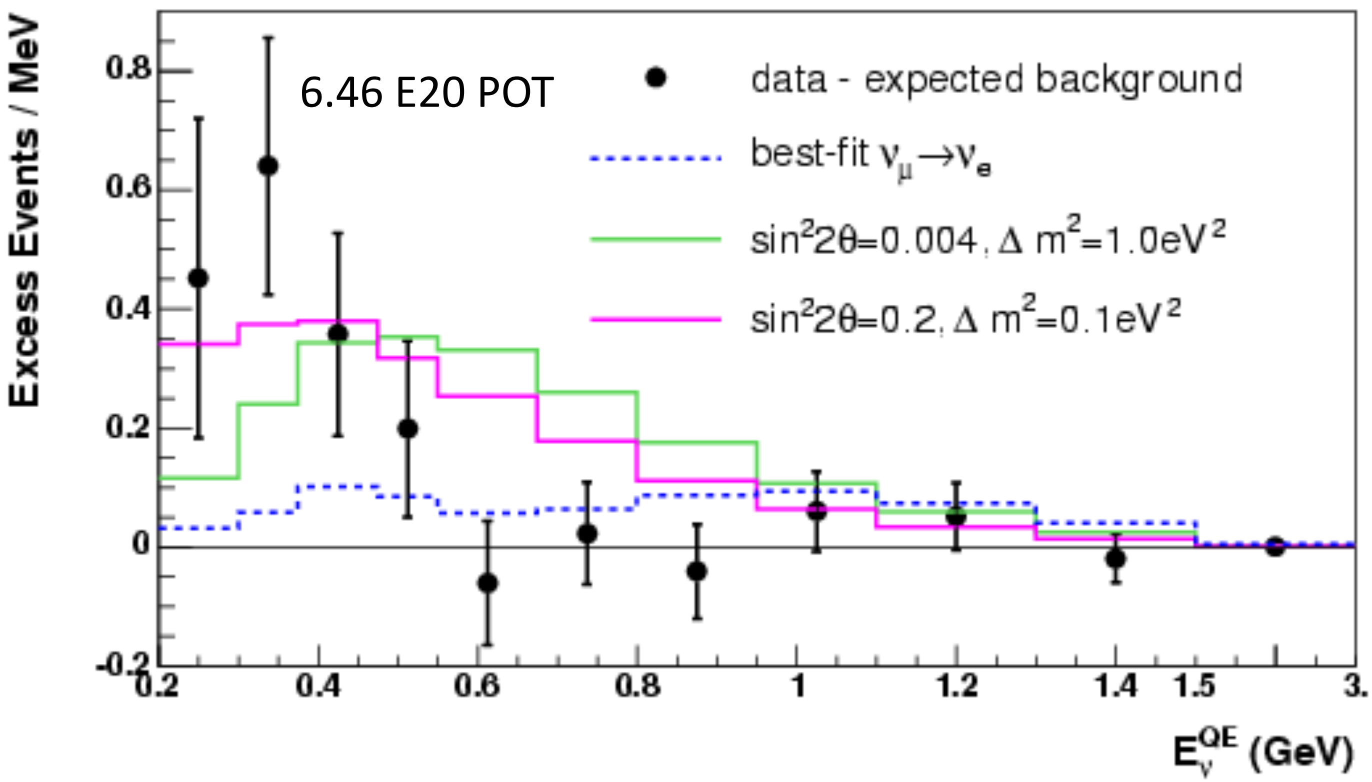
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)



3.8 σ excess of events

MiniBooNE Neutrino Results

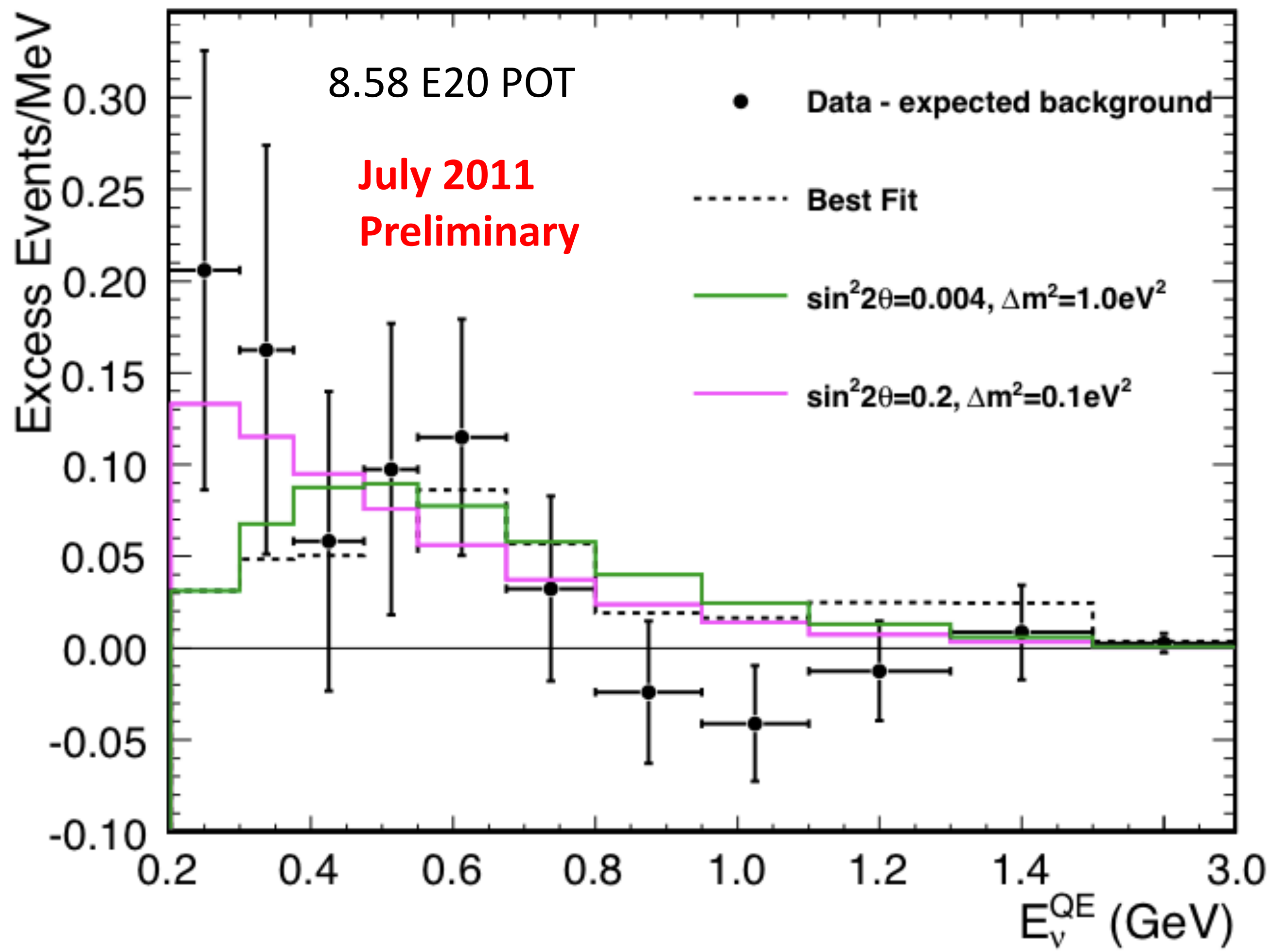
A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 102, 101802 (2009)



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)

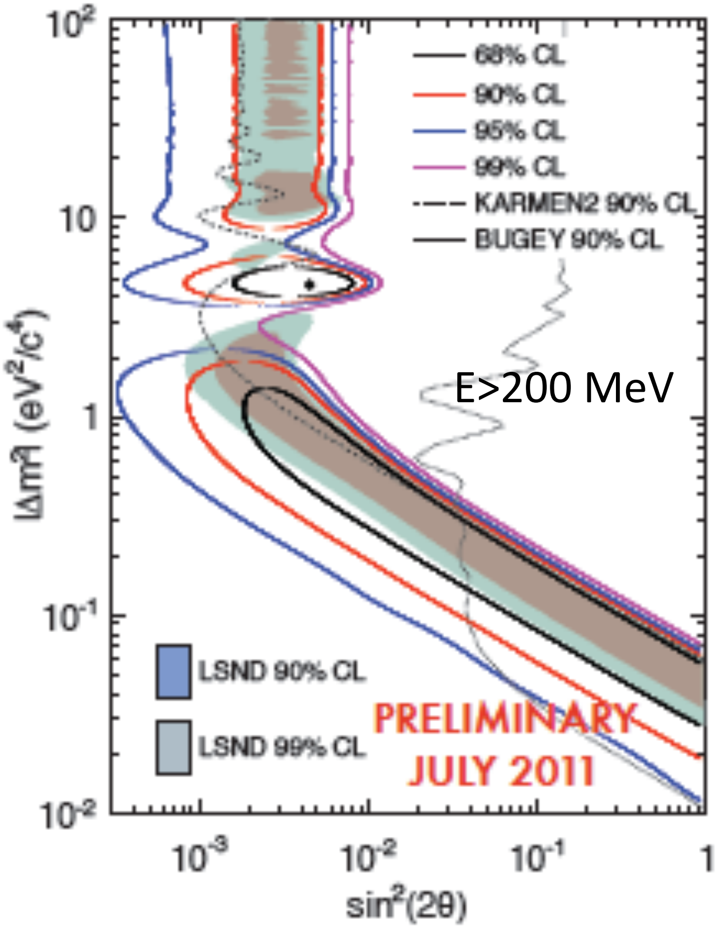


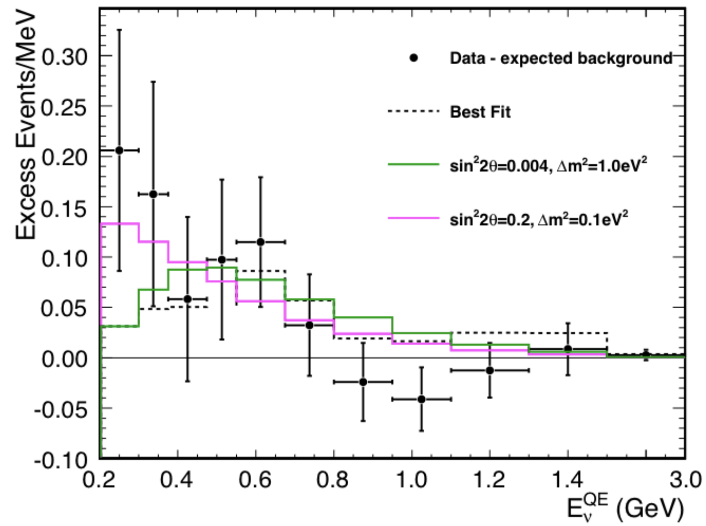
2.3 σ excess of events from 200-1250 MeV (so far)

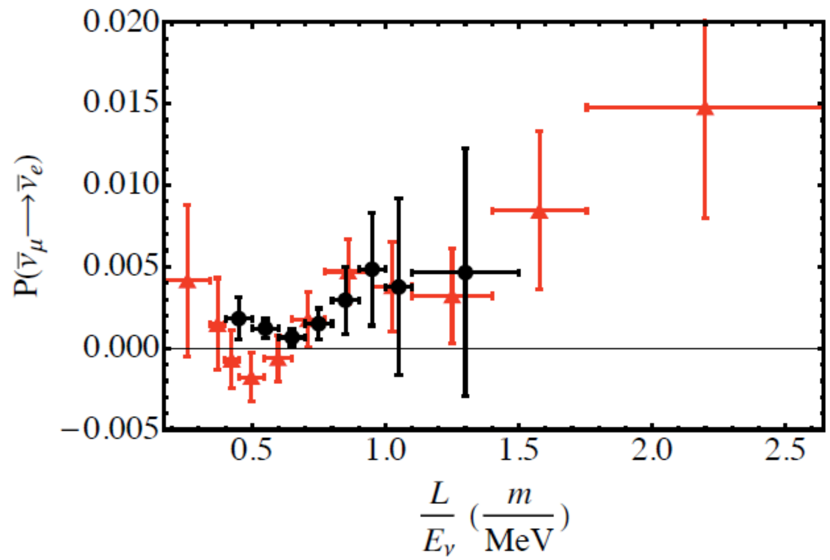
LSND & MiniBooNE Antineutrino Results

Neutrino/Antineutrino joint analysis is underway

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

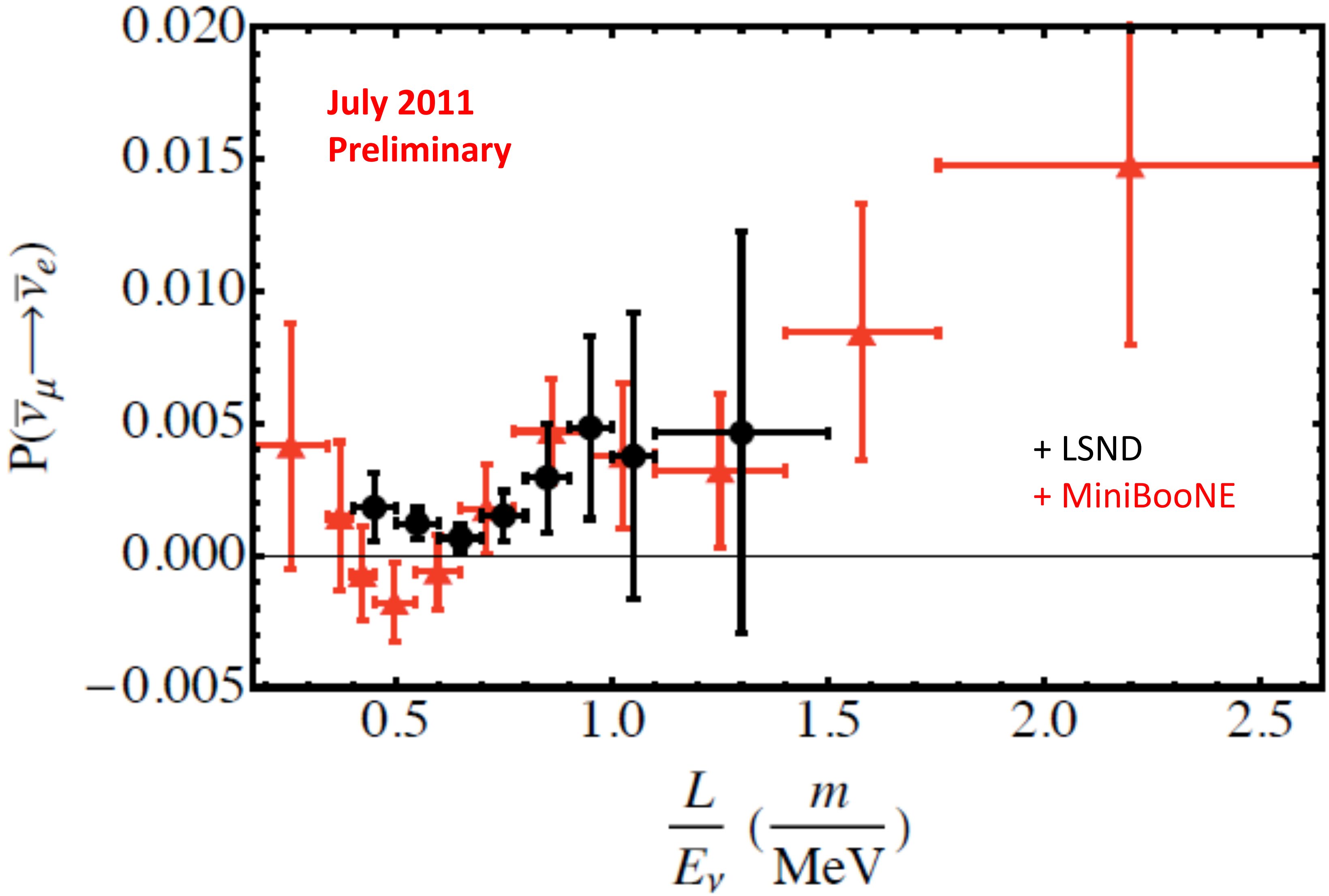






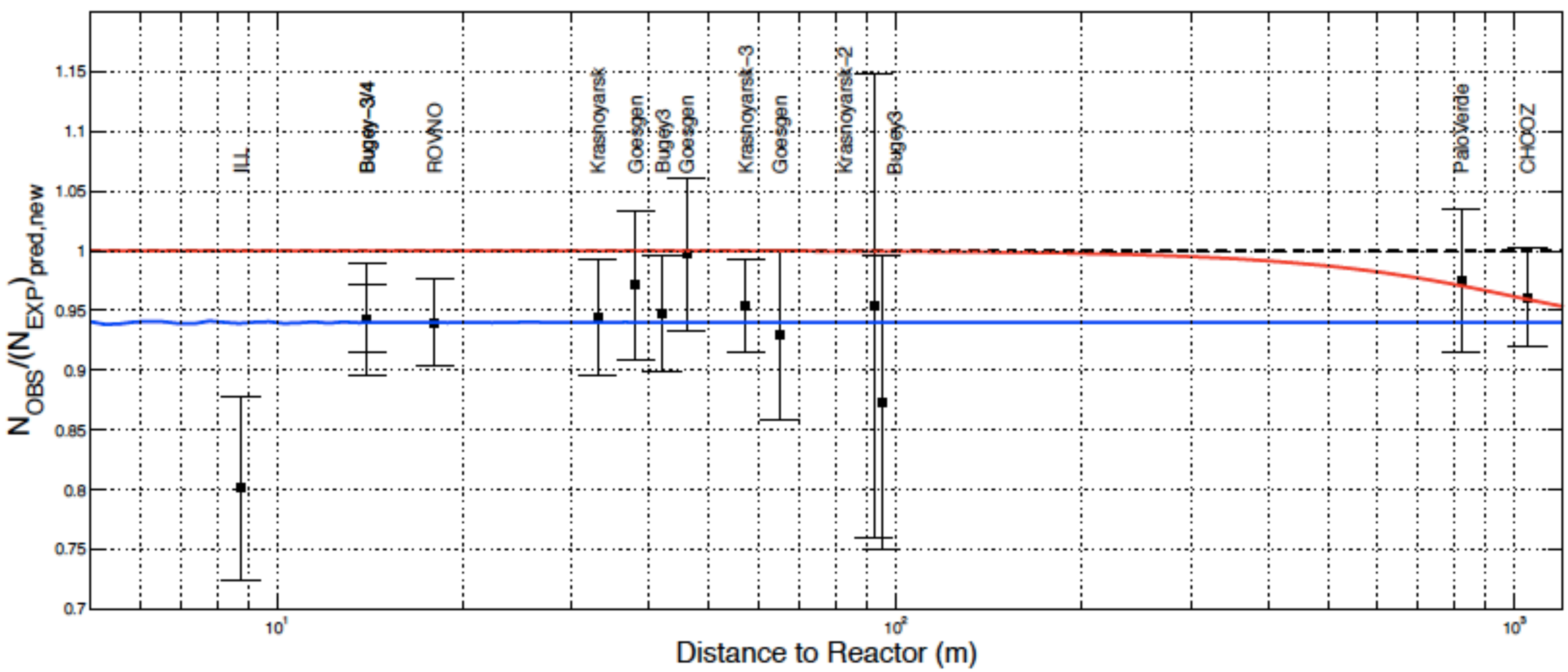
LSND vs MiniBooNE Antineutrino Results

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



Reactor Antineutrino Anomaly

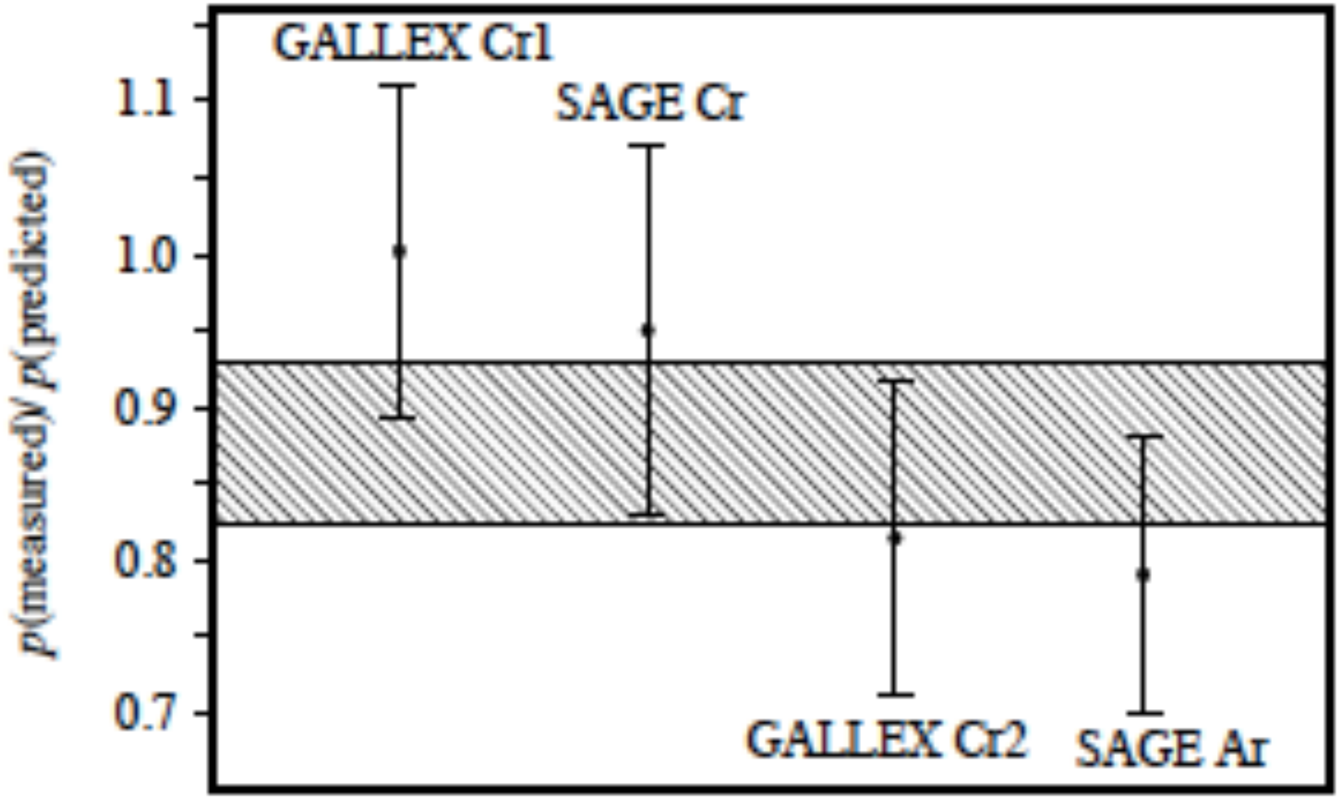
G. Mention et al., Phys.Rev.D83:073006,2011



R=0.937+-0.027

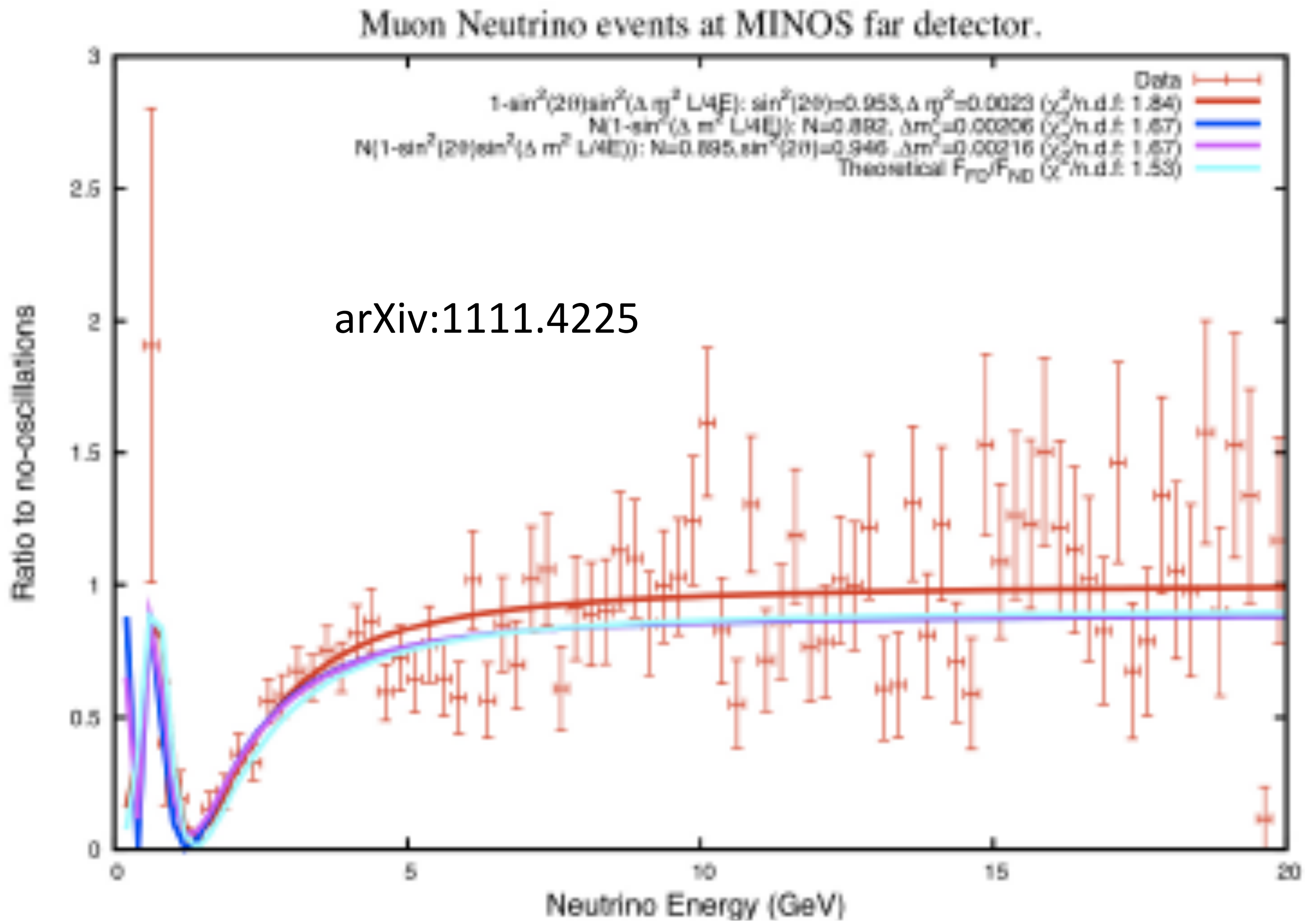
Radioactive Neutrino Source Anomaly

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



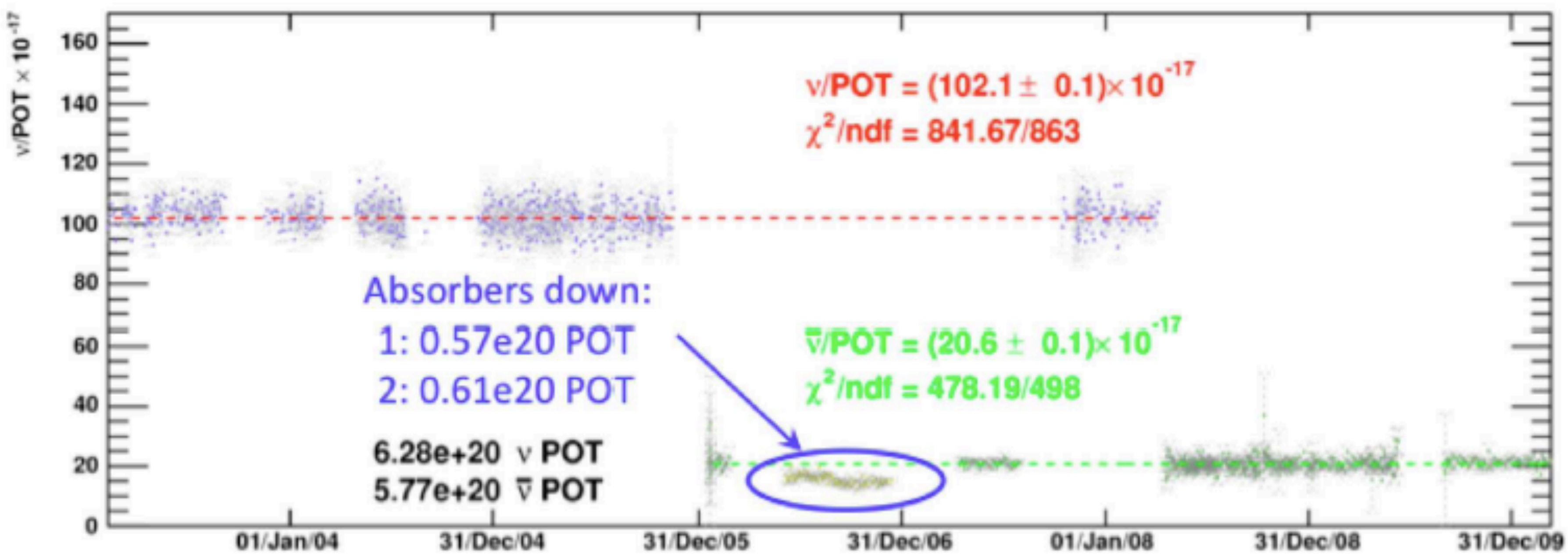
R=0.86+-0.05

Fitting MINOS data for ν_μ Disappearance

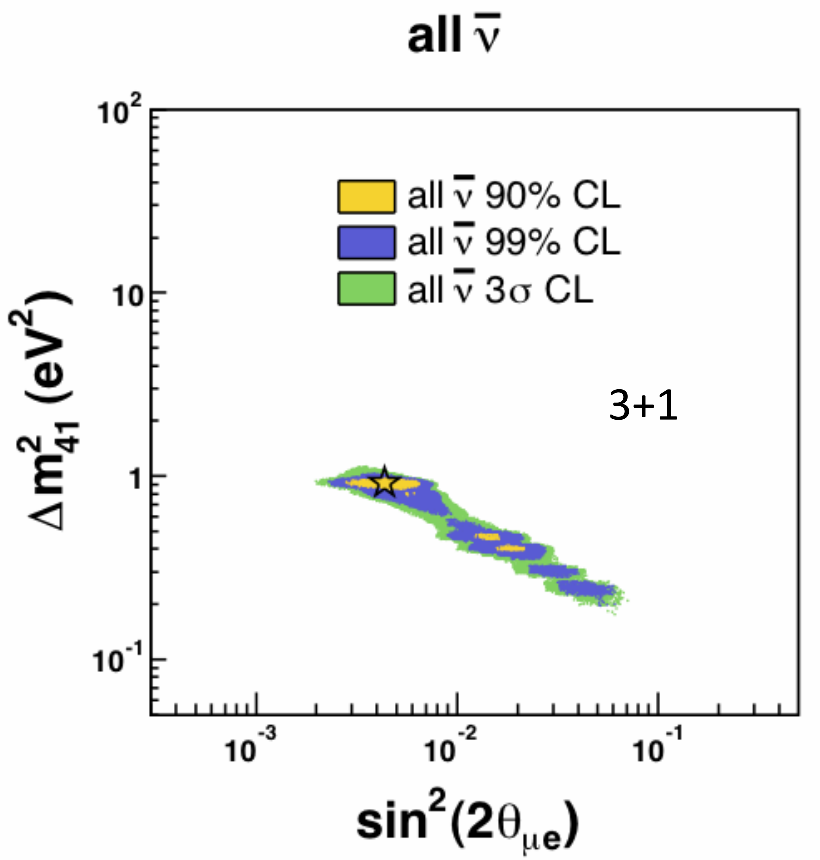


Case	$\Delta m^2(10^{-3}\text{eV}^2)$	$\sin^2 2\vartheta_\mu$	$\mathcal{N}_\mu$	χ^2/n.d.f
I	2.31 ± 0.10	0.953 ± 0.04	$1^\dagger$	1.65
II	2.07 ± 0.09	$1^\dagger$	0.895 ± 0.03	1.48
III	2.17 ± 0.13	0.946 ± 0.048	0.897 ± 0.03	1.48
$\mathcal{R}_{\mu\mu}$	–	–	–	1.53

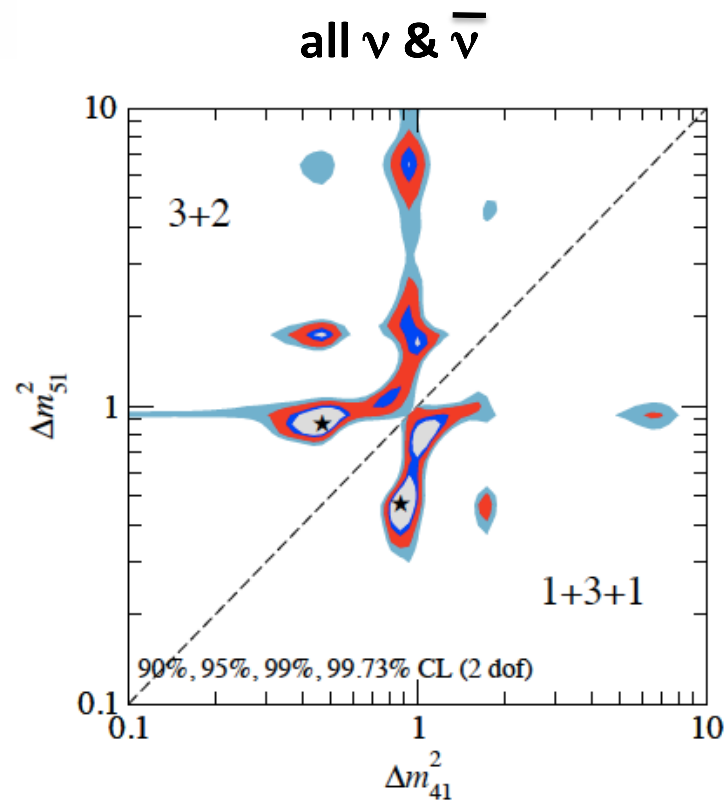
MiniBooNE Event Rate/POT Has Been Very Stable Over the Life of the Experiment



3+N Global Fits to World ν Data



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

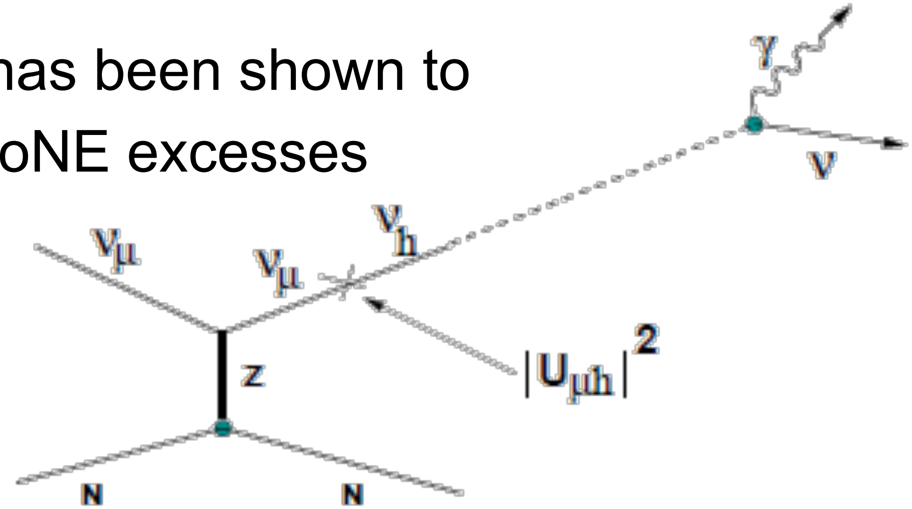


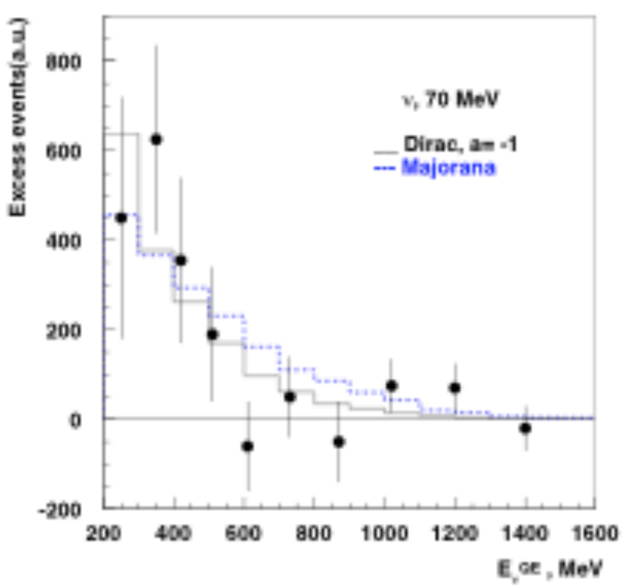
Kopp, Maltoni, & Schwetz,
Phys. Rev. Lett. 107, 091801 (2011)

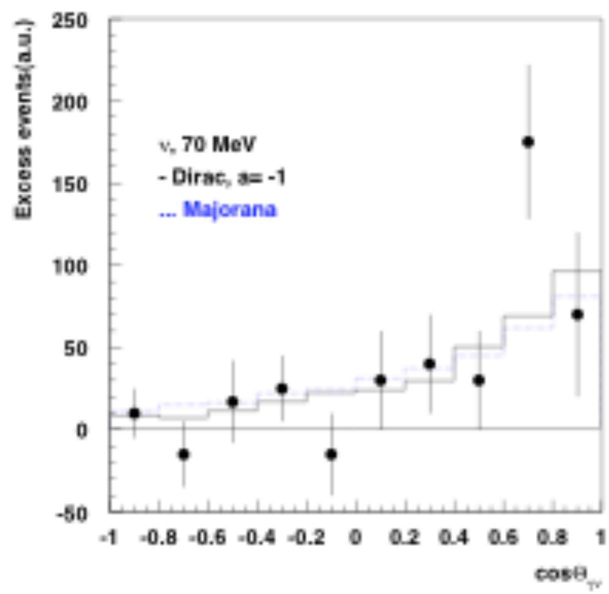
Sterile ν Decay

- 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

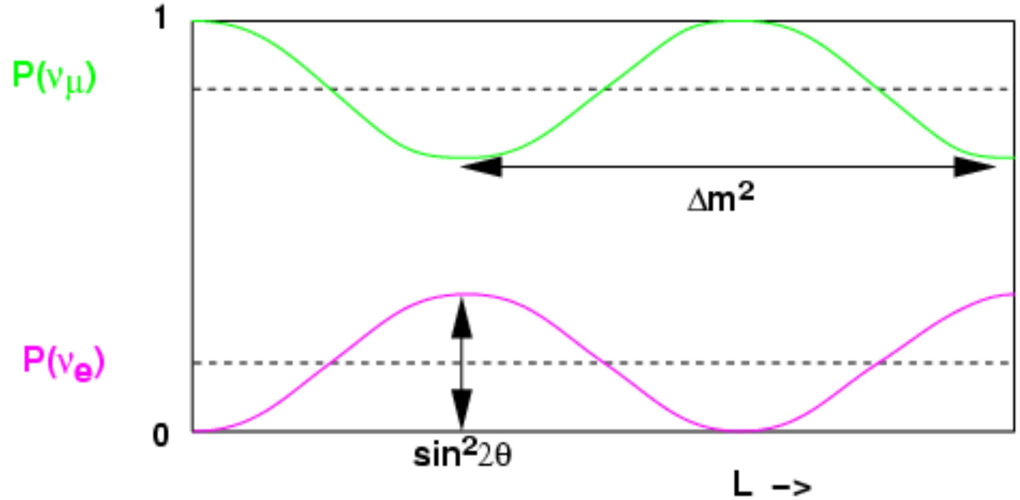
Jorge S. Díaz and V. Alan Kostelecký
Physics Department, Indiana University, Bloomington, IN 47405, U.S.A.
(Dated: IUHET 561, August 2011)

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

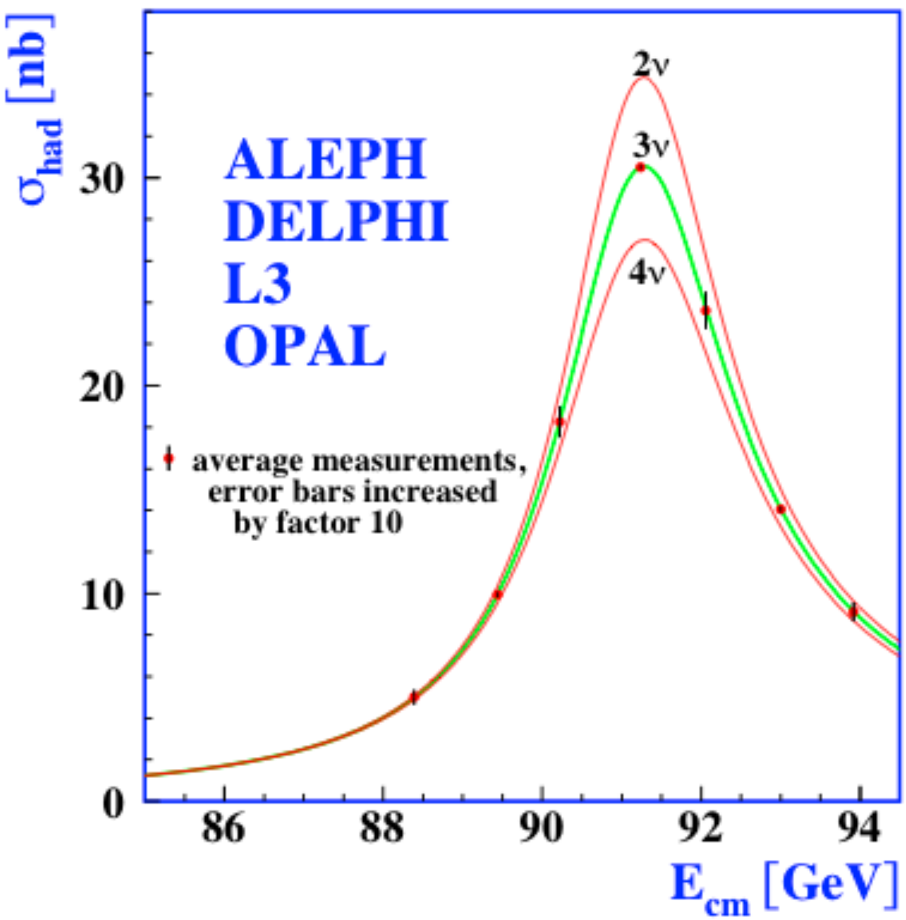
Weak Eigenstates		Eigenstates of Propagation
ν_μ	=	$\cos\Theta\,\nu_1 + \sin\Theta\,\nu_2$
ν_e	=	$-\sin\Theta\,\nu_1 + \cos\Theta\,\nu_2$



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

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

LEP Experiments at CERN: 3 Active Neutrinos!

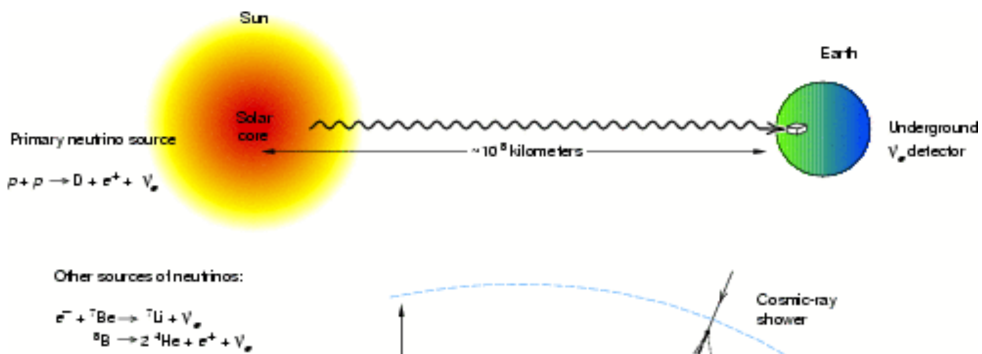


arXiv:hep-ex/0509008v3

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

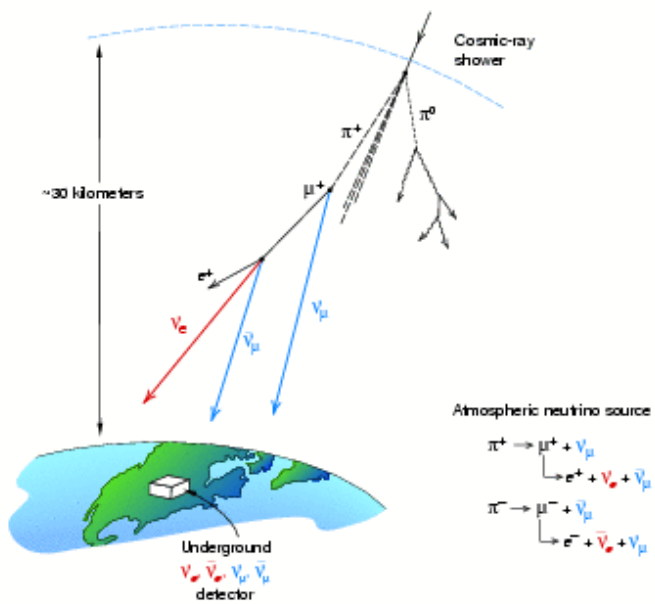
Sterile neutrinos would interact by Gravity but not by the Strong, Electromagnetic, or Weak Interactions.

Evidence/Observation of ν Oscillations



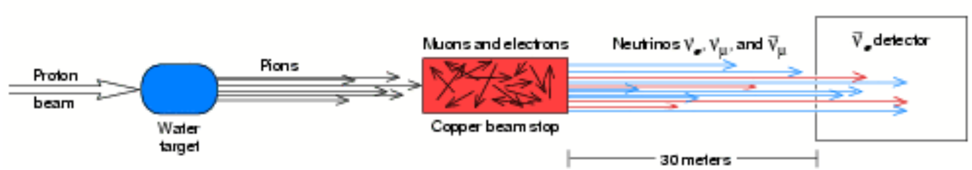
SuperK, SNO, KamLAND, BOREXINO

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



SuperK, K2K, MINOS, OPERA, T2K, Double Chooz, Daya Bay

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



LSND, MiniBooNE, Reactor ν, Radioactive Source

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

A Proposal to Build a MiniBooNE Near Detector:BooNE

October 12, 2011

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University of Alabama, Tuscaloosa, AL 35487

Z. Djurcic
Argonne National Laboratory, Argonne, IL 60439

D. Smith
Embry-Riddle Aeronautical University, Prescott, AZ 86301

R. Ford, T. Kobilarcik, W. Marsh, C. D. Moore, & G. P. Zeller
Fermi National Accelerator Laboratory, Batavia, IL 60510

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Probability of Neutrino Oscillations

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

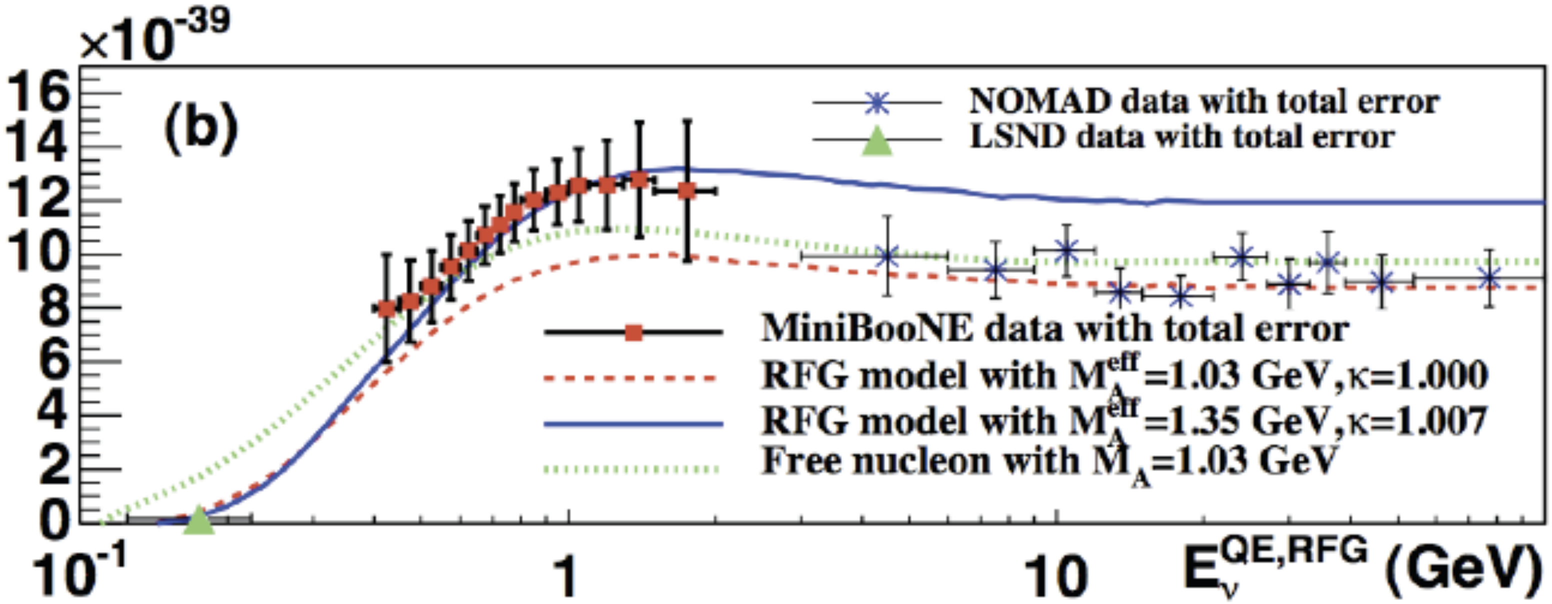
As N increases, the formalism gets rapidly more complicated!

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!

ν_μ CCQE Scattering

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

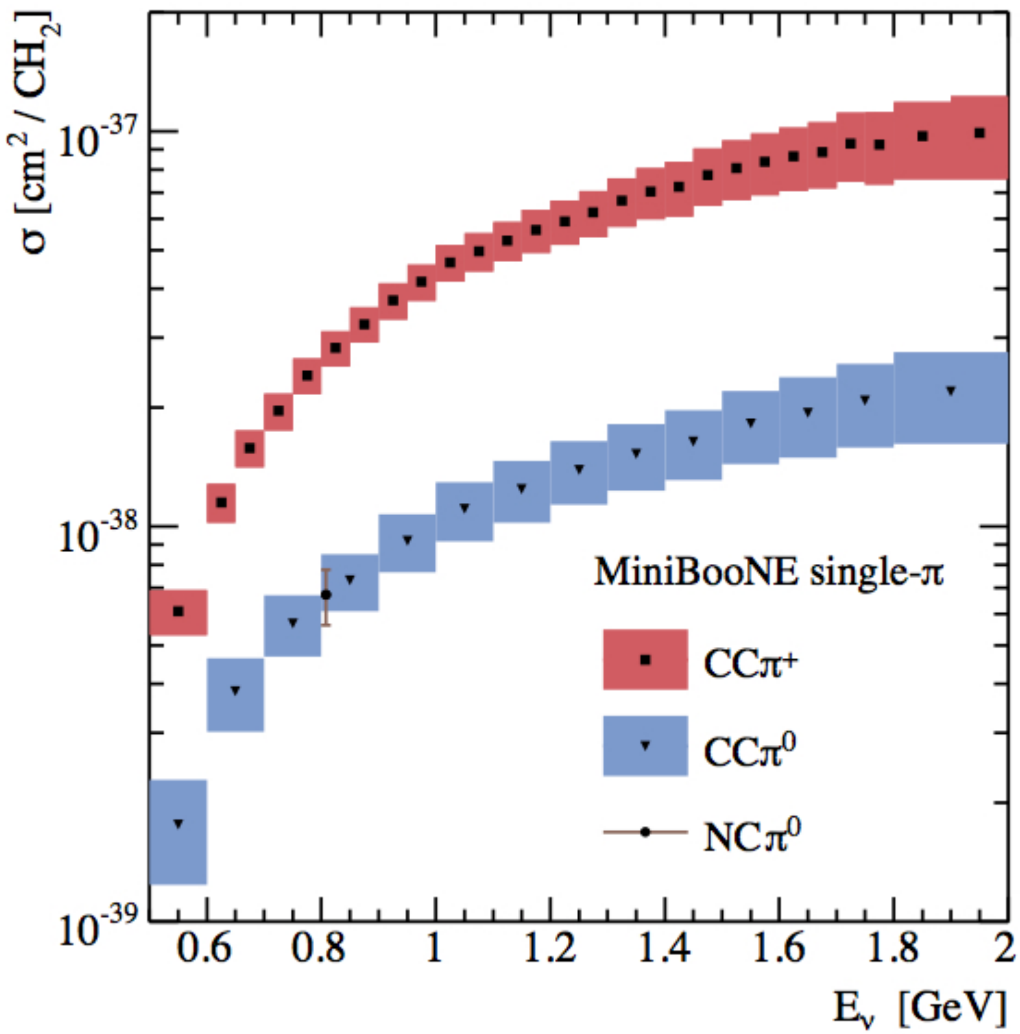


Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}C) > 6\ \sigma_{\nu\mu}(n)$

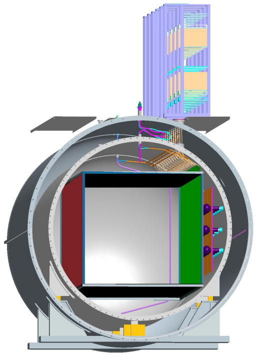
How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

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).

Single Pion Cross Sections



(R. Nelson, NuInt11)



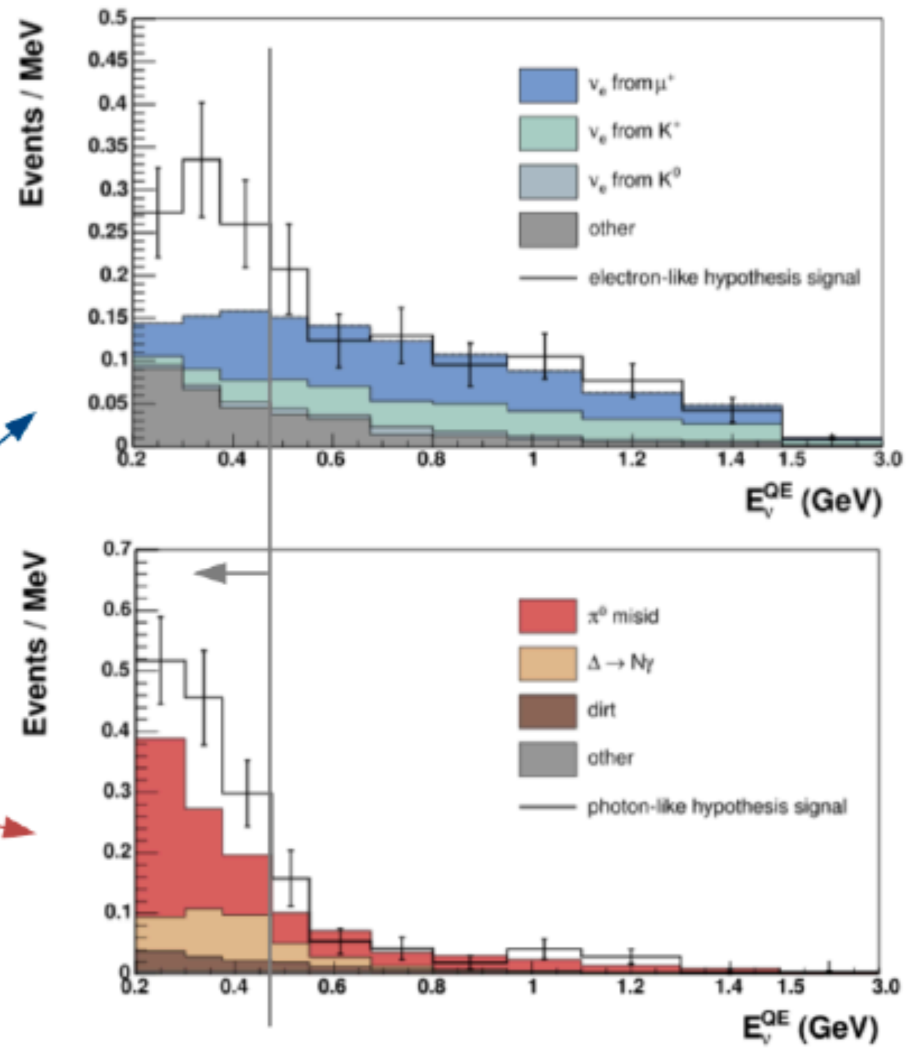
MicroBooNE at FNAL

MicroBooNE sensitivity to low energy excess:

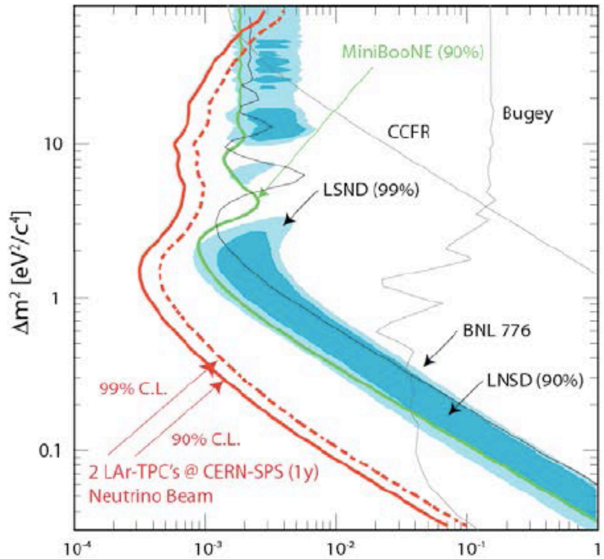
(neutrino running,
- 70 ton fiducial volume,
- x2 higher PID efficiency than MiniBooNE,
- 3% mis-ID,
- 6.0e20 POT)

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 SPS (arXiv:1203.3432)



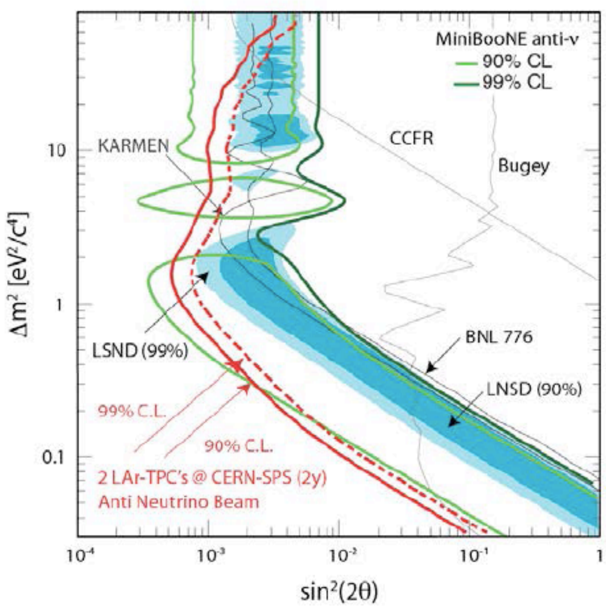


Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

600 ton ICARUS at ~1600 m

150 ton LAr at ~330 m