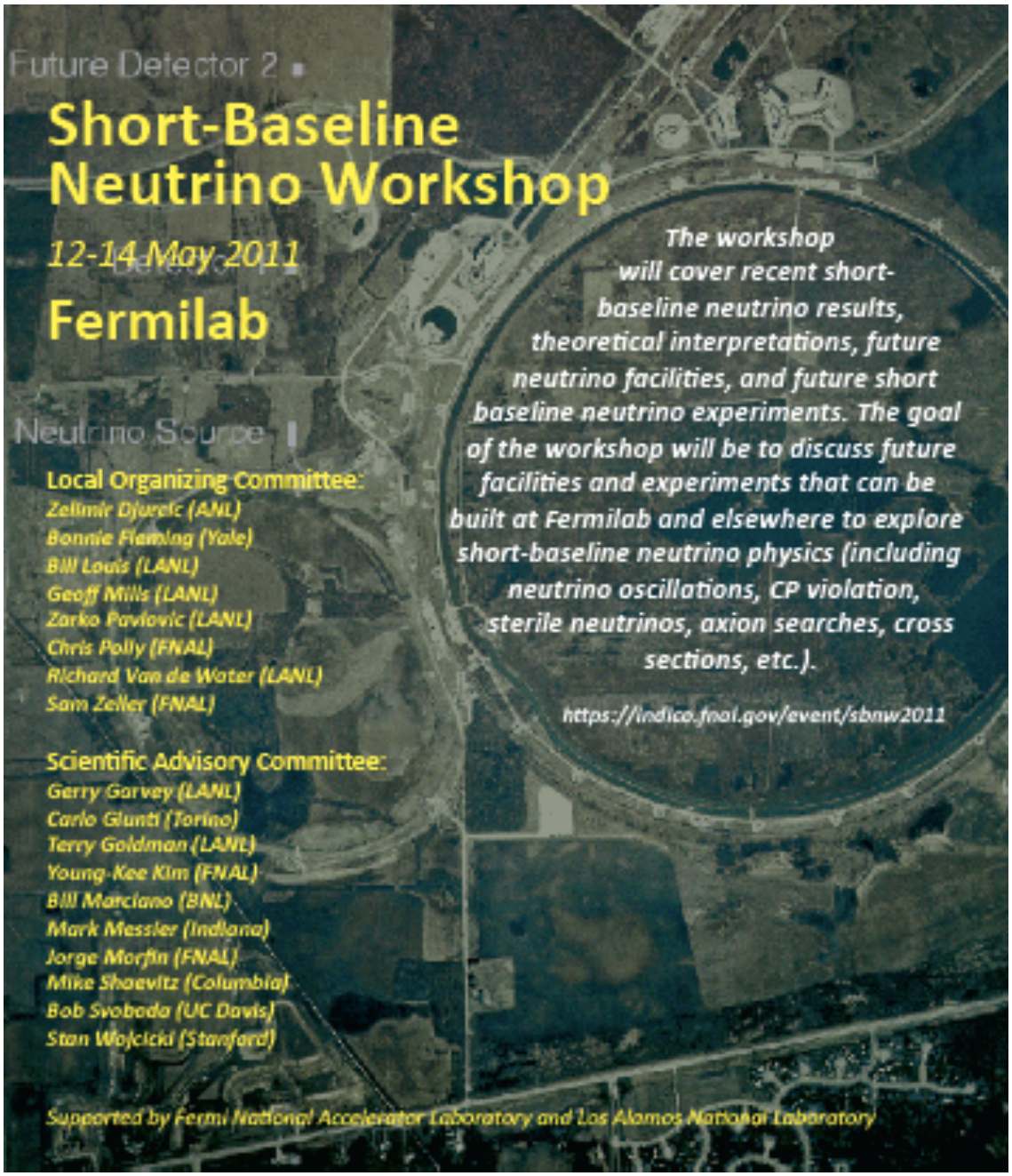
Future Short Baseline ν Physics at Fermilab

W.C. Louis, LANL, August 3, 2011

- Tantalizing Results from Short Baseline ν Experiments
- Theoretical Interpretations of Existing Data
- Future Proposed Experiments at Fermilab



109 Registrants
44 Institutions

Talks are on Web Page:
https://indico.fnal.gov/event/sbnw11

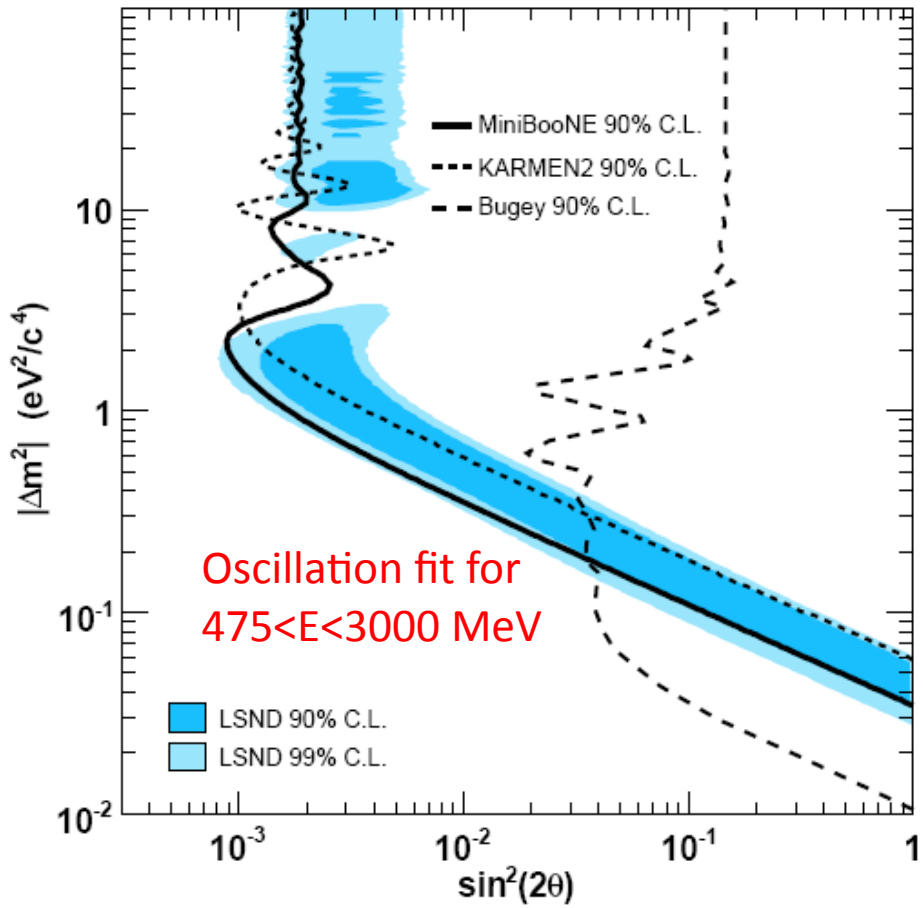
Motivation for Short Baseline

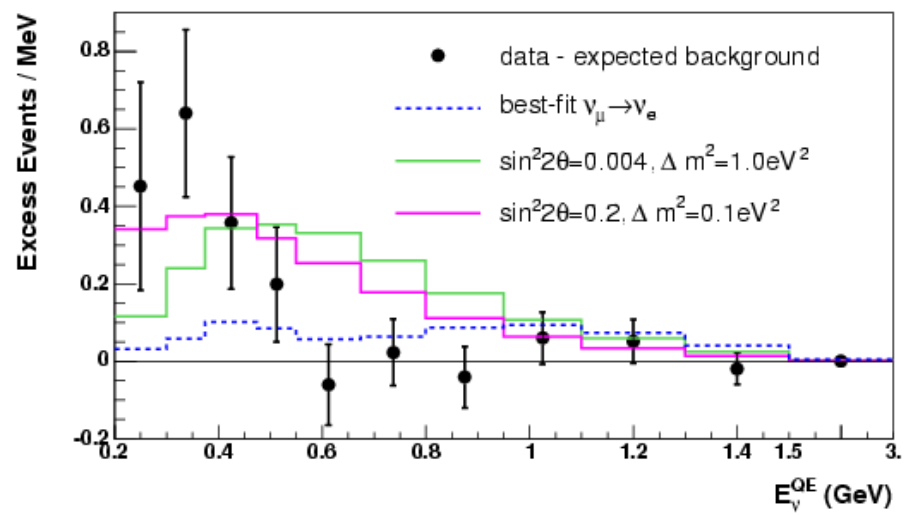
- Tantalizing results from short (& long) baseline experiments (LSND, MiniBooNE, MINOS, Reactor Antineutrinos, Radioactive Neutrino Sources, etc.) may possibly have a profound impact on our understanding of particle & nuclear physics.

- Neutrino cross sections are very interesting: nuclear effects, short-range correlations, pion exchange currents, pion absorption, initial state interactions, & final state interactions make this a rich and compelling area of study. Nuclear effects can affect neutrinos and antineutrinos differently and affect CP violation interpretations.

MiniBooNE Neutrino Results

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



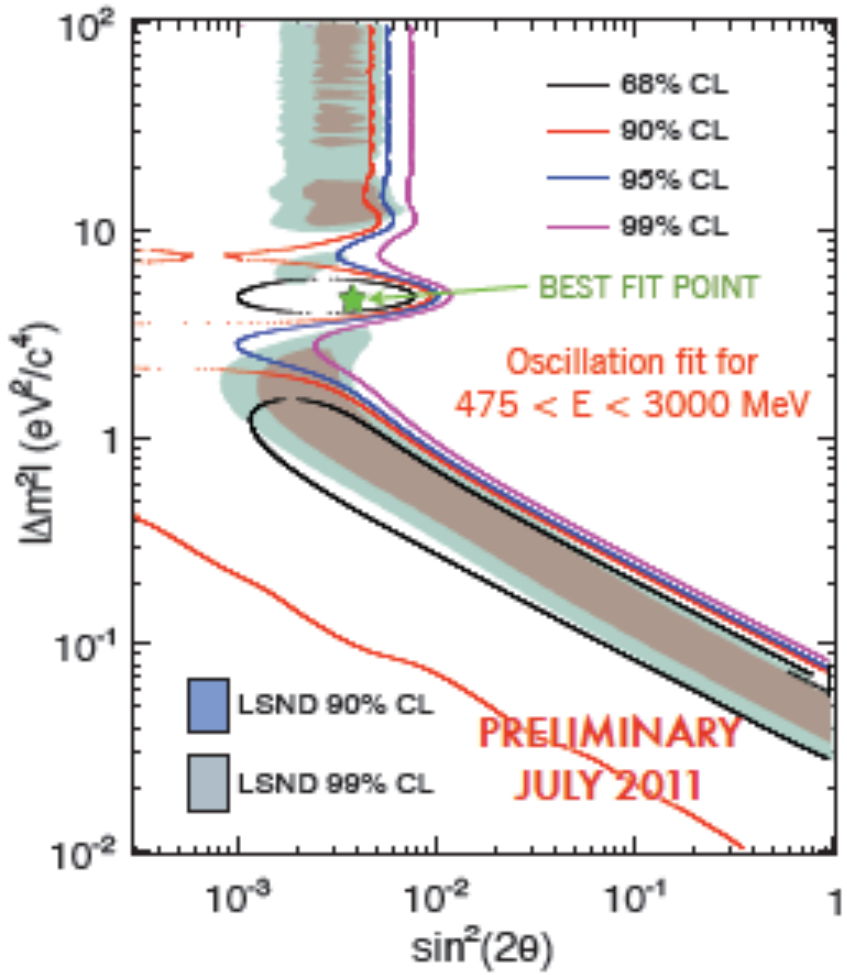


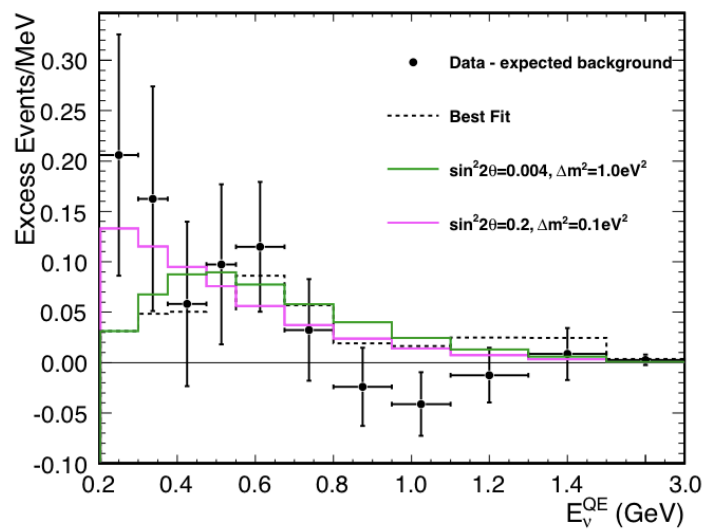
However, nuclear effects can affect the determination of E_ν^{QE}! (See WG2 talks by Nieves & Martini.) Will try to account for these effects & refit the data.

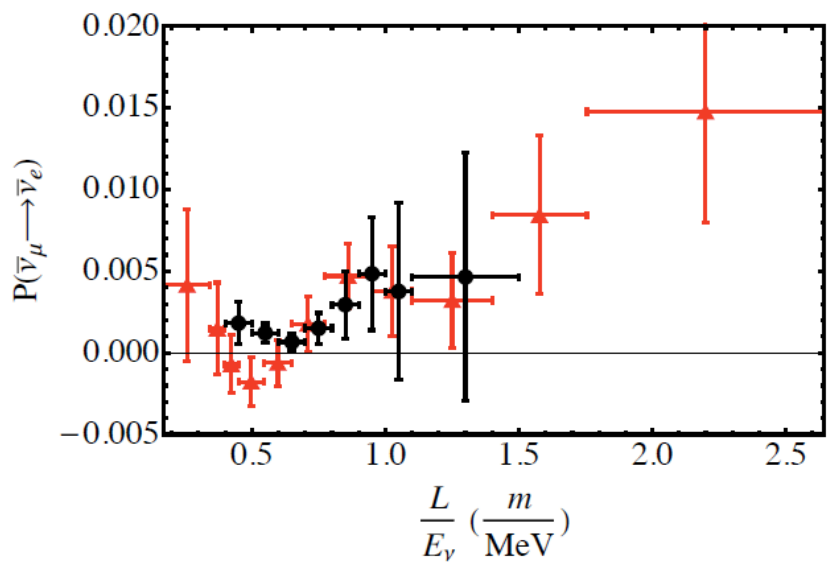
LSND & MiniBooNE Antineutrino Results

(see talk by Zelimir Djurcic in WG1.)

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







LSND & MiniBooNE Antineutrino Results

(See talk by Zelimir Djurcic in WG1.)

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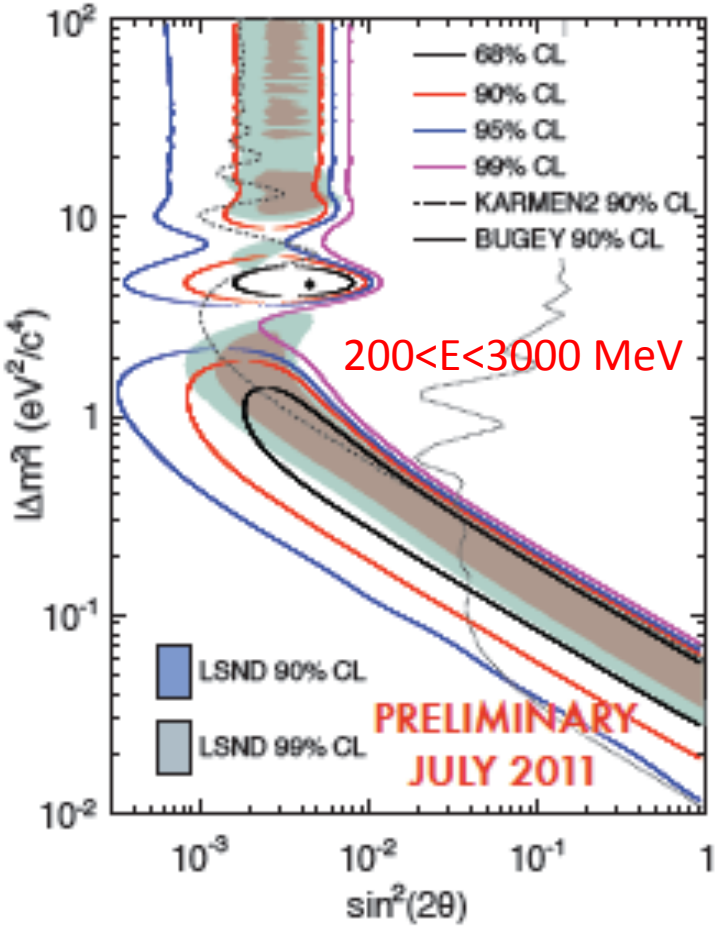
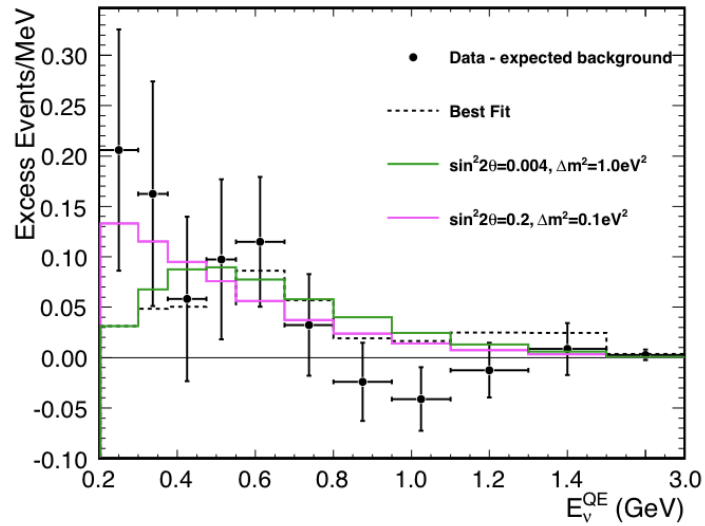
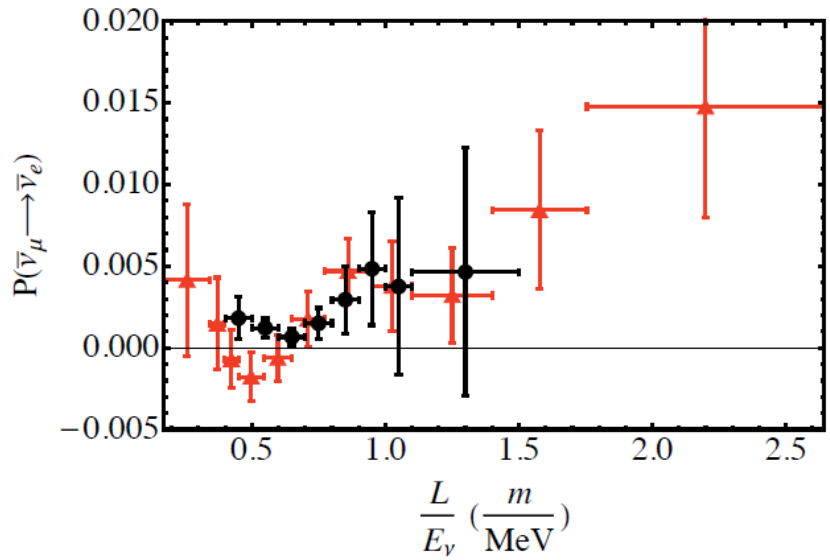
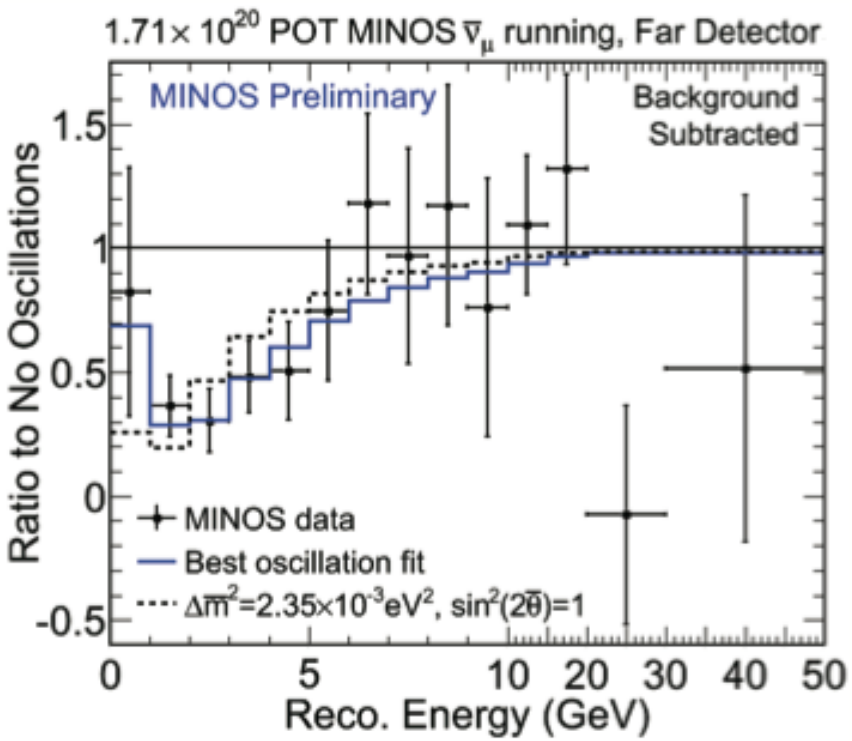


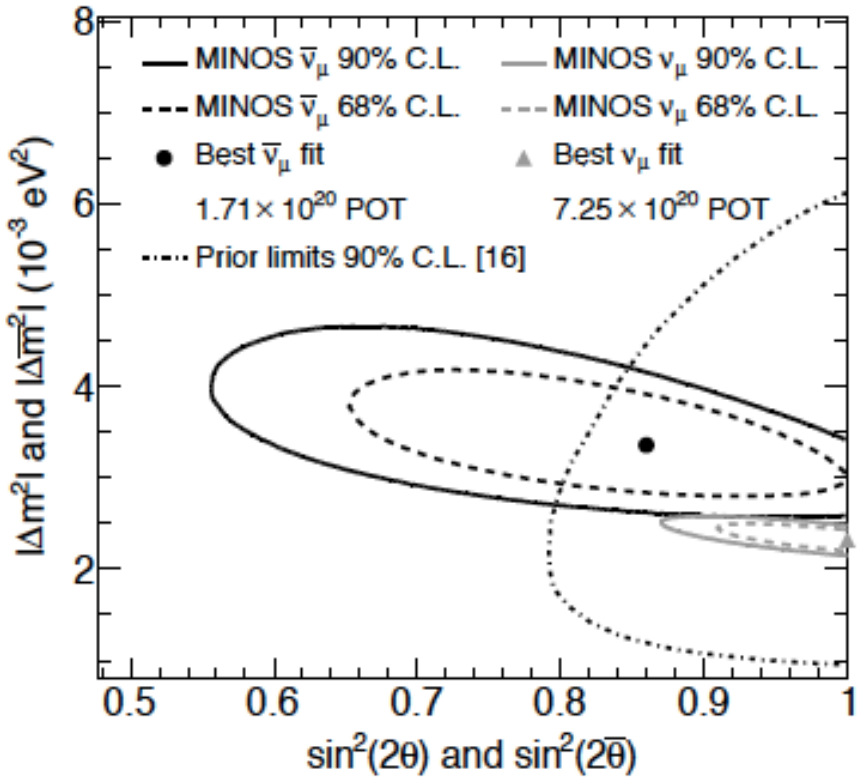




Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in $\bar{\nu}$ Mode

(See talk by Jeff Hartnell)



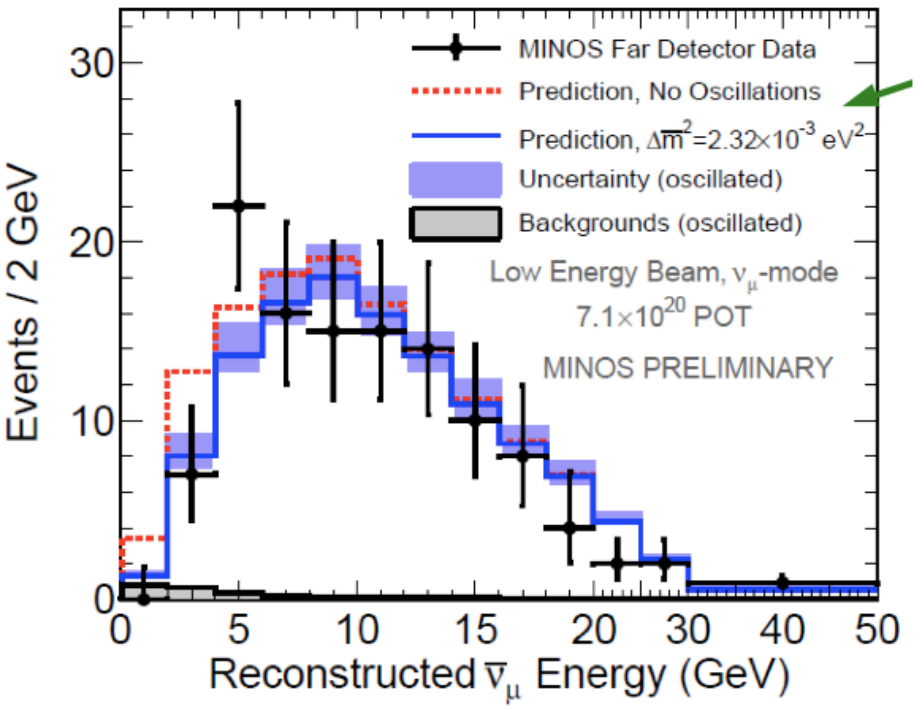


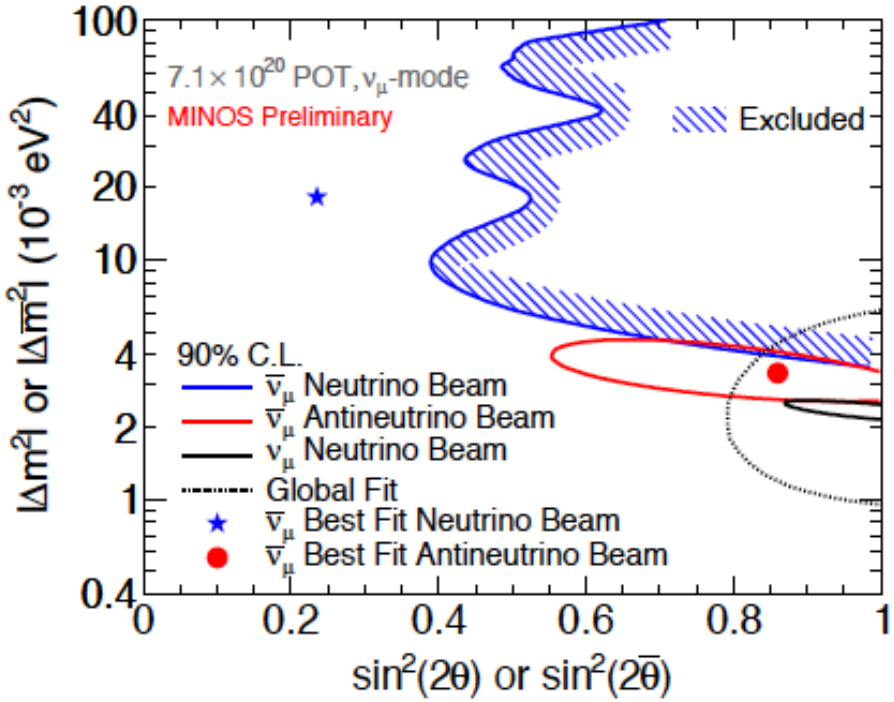
Expect $\bar{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.

"The probability that the underlying ν_μ and $\bar{\nu}_\mu$ parameters are identical is 2.0%." (arXiv:1104.0344)

Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in ν Mode

(See talk by Jeff Hartnell)



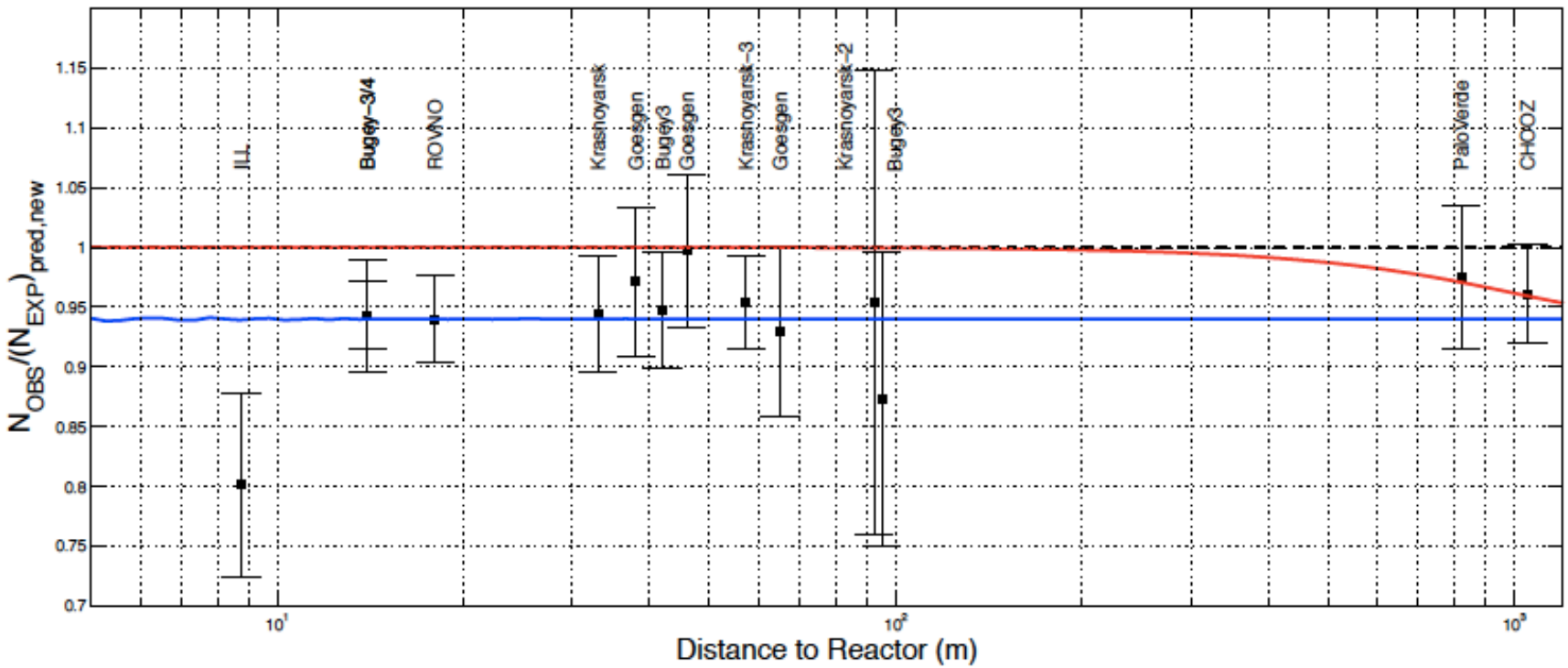


Expect $\bar{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.

Reactor Antineutrino Anomaly

(See talk by Guillaume Mention.)

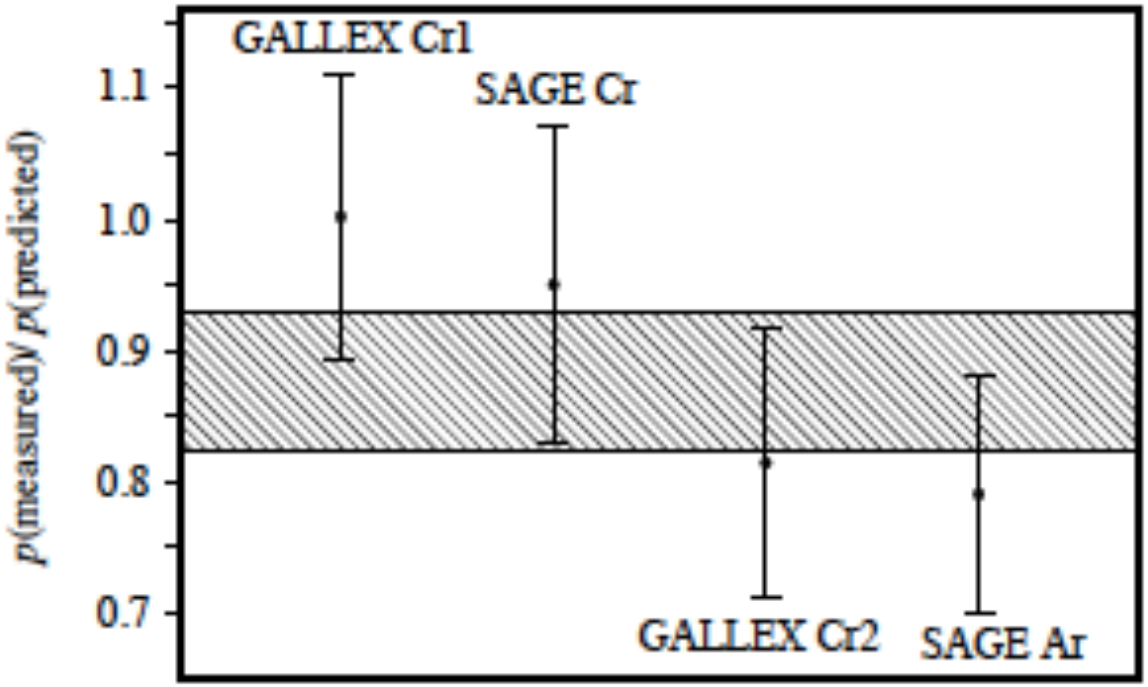
arXiv: 1101.2755



R=0.937+-0.027

Radioactive Neutrino Source Anomaly

SAGE, PRC 73 (2006) 045805
arXiv:nucl-ex/0512041

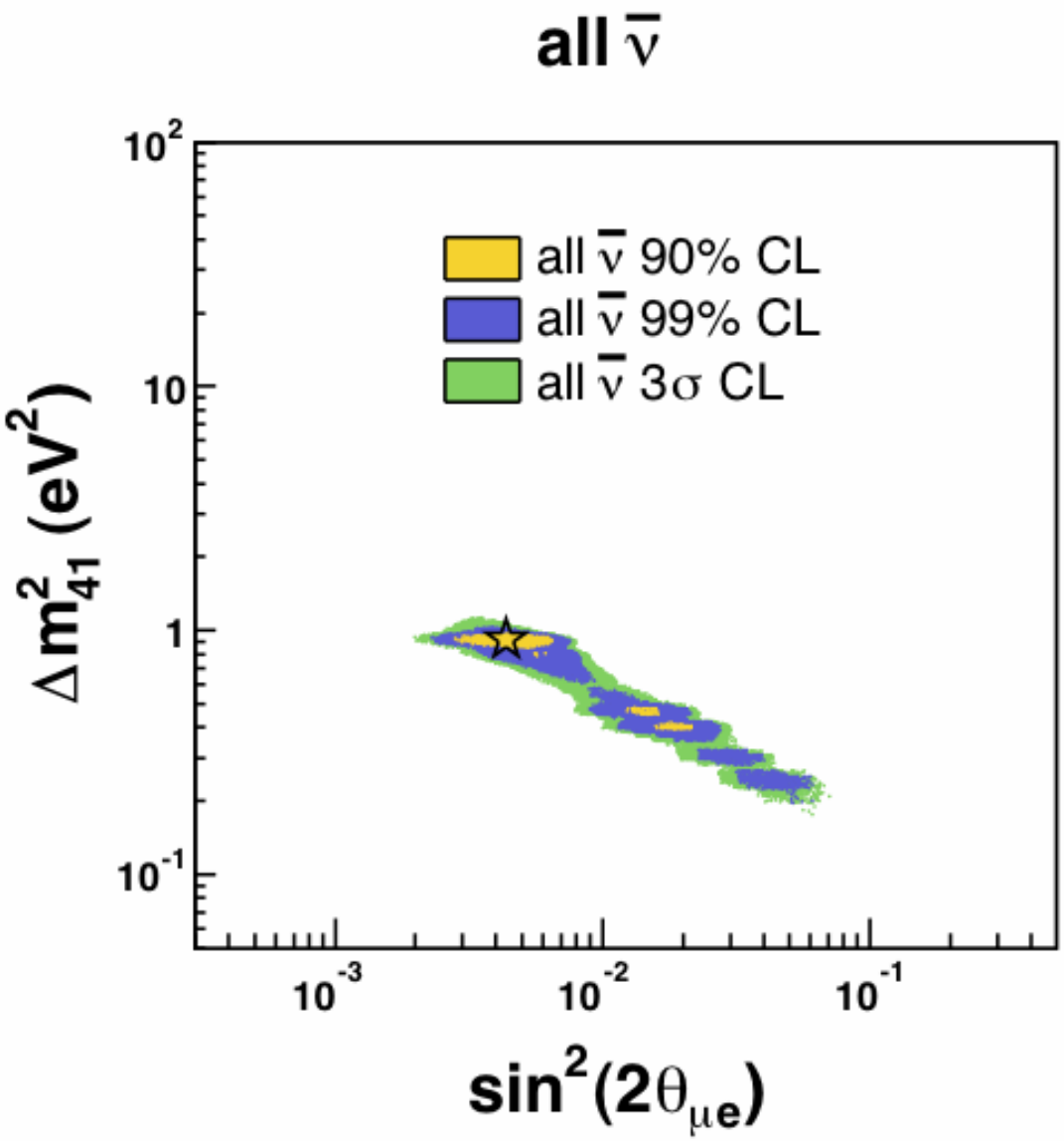


R=0.87+-0.05

Theoretical Interpretations

- Sterile Neutrinos (3+N Models with CP violation)
- Non-Standard Interactions
- Sterile ν Decay
- Lorentz Violation & CPT Violation

3+1 Global Fit to World Antineutrino Data (with new reactor ν normalization)



Updated from G. Karagiorgi et al., PRD80, 073001 (2009)

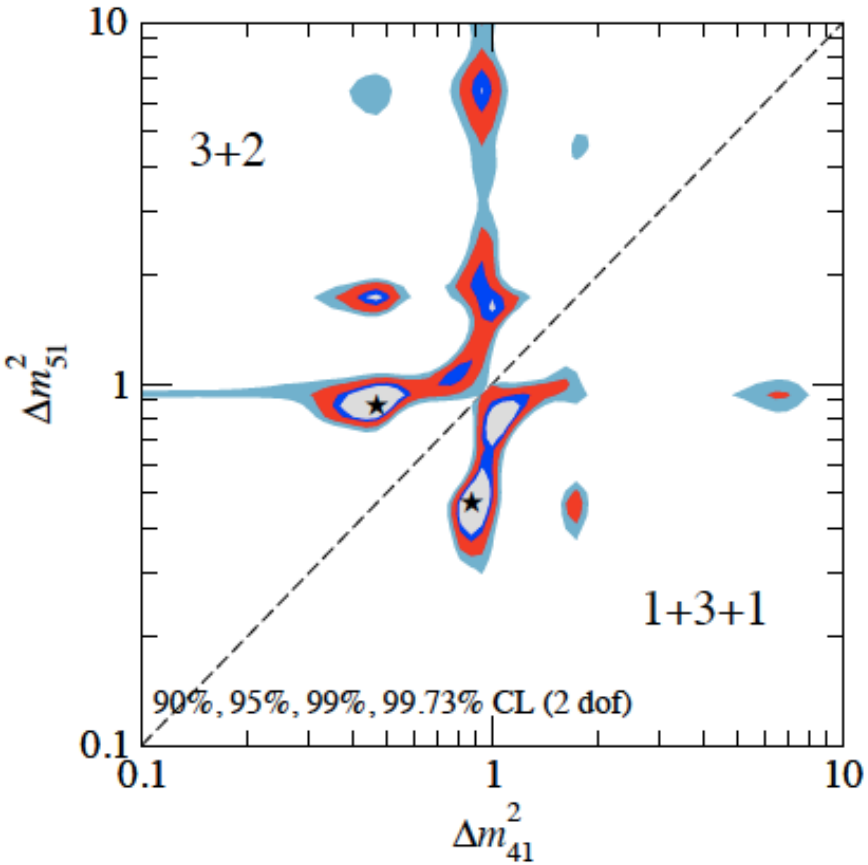
Best 3+1 Fit:
Δm_{41}^2 = 0.92 eV^2
$\sin^2 2\theta_{\mu e}$ = 0.45%
Prob. = 92%

Predicts $\overline{\nu_\mu}$ & $\overline{\nu_e}$ disappearance of $\sin^2 2\theta_{\mu\mu}$ ~ 24% and $\sin^2 2\theta_{ee}$ ~ 6.7%

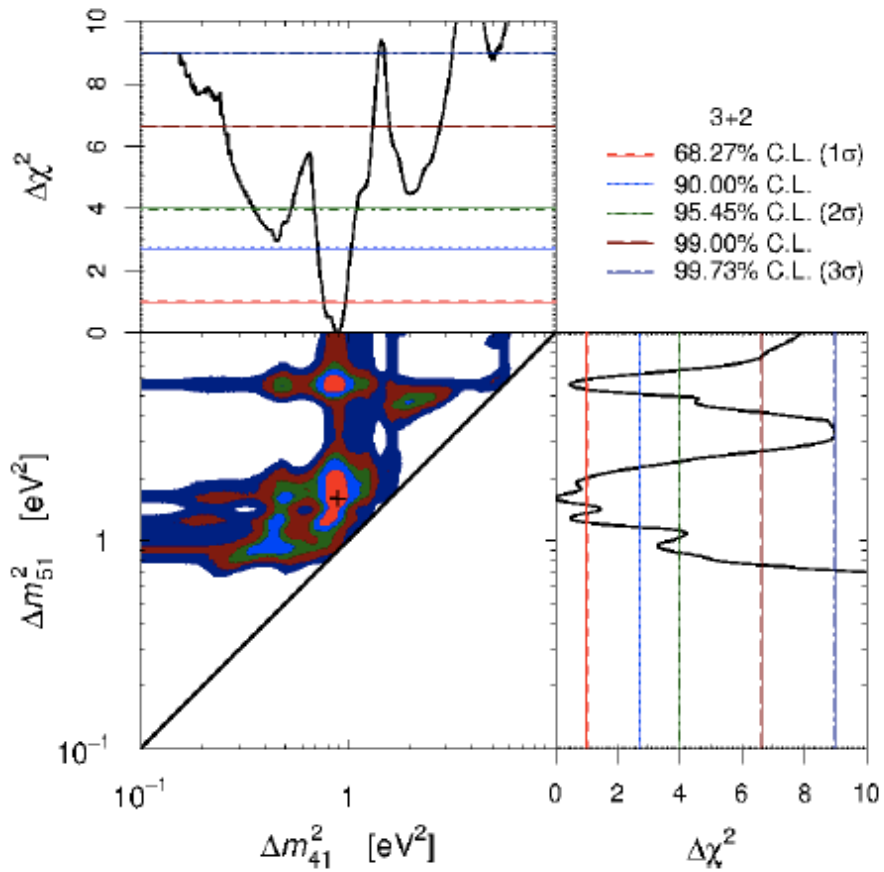
Global 3+2 Fit to World Neutrino & Antineutrino Data

(However, in 3+2 models there is some tension between neutrino and antineutrino data)

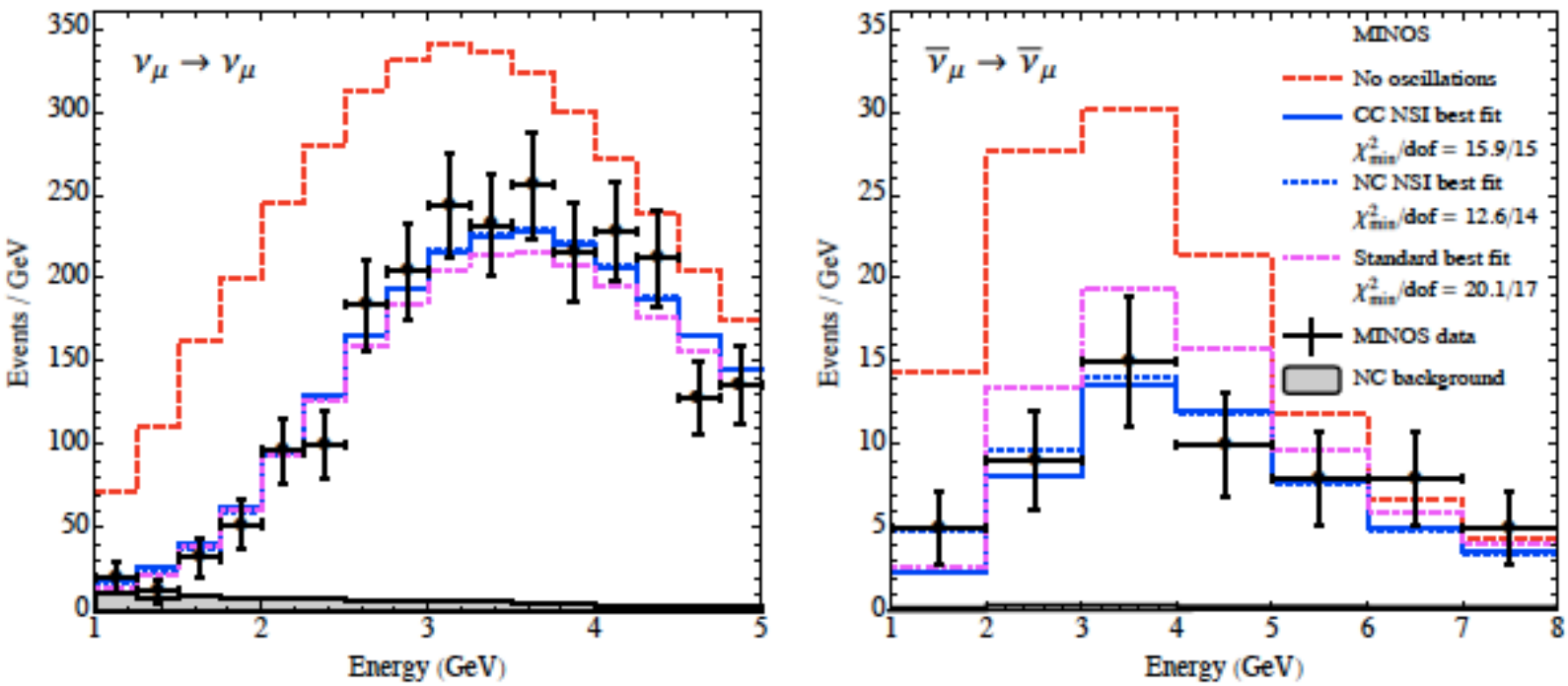
Kopp, Maltoni, & Schwetz, arXiv:1103.4570



Giunti & Laveder, arXiv:1107.1452



NSI



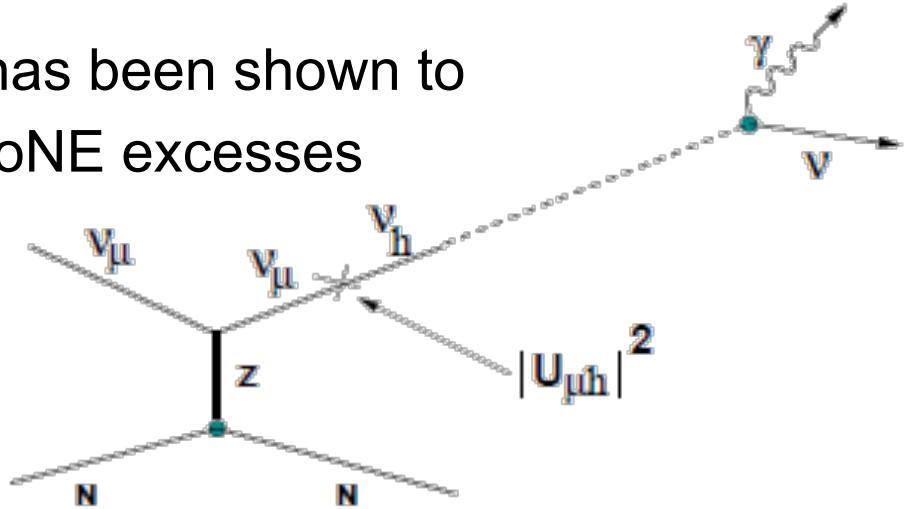
JK Machado Parke arXiv:1009.0014

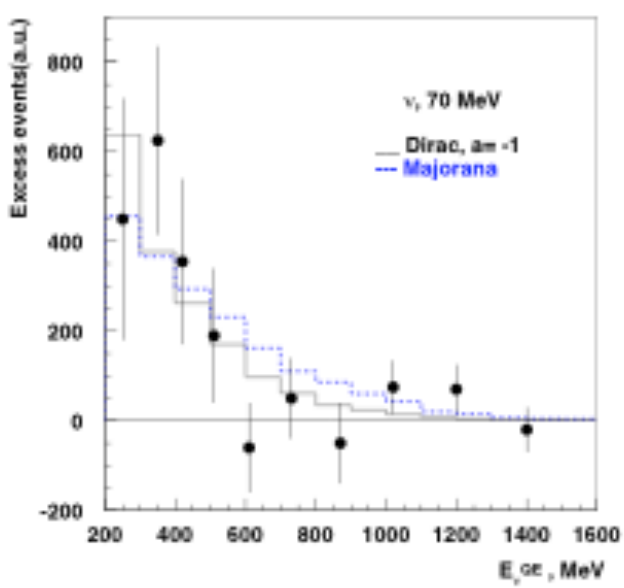
Sterile ν Decay?

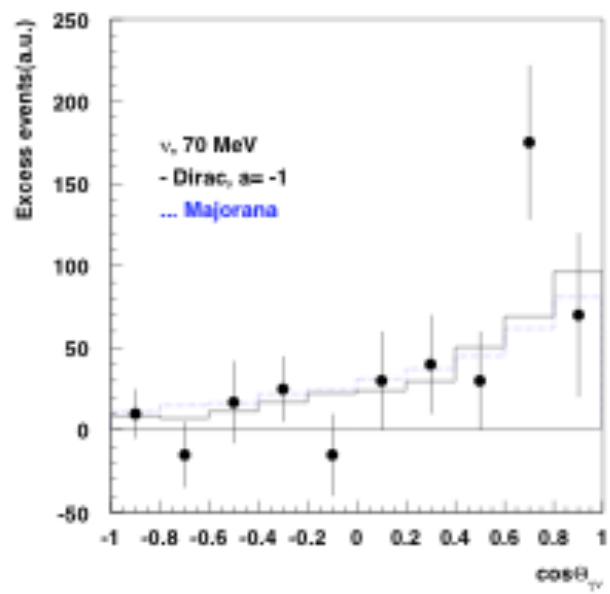
(See talk by Sergei Gninenko)

- 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?

A simple Lorentz-violating texture for neutrino mixing

Jorge S. Díaz and V. Alan Kostelecký

Physics Department, Indiana University, Bloomington, IN 47405, U.S.A.

(Dated: IUHET 552, December 2010)

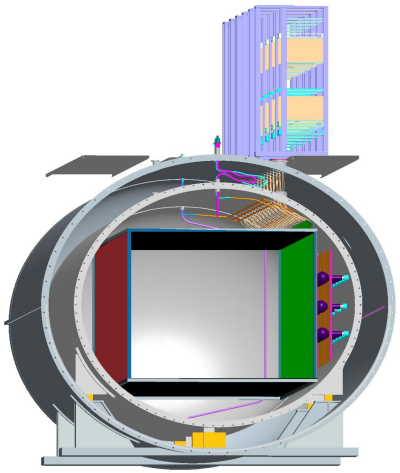
Abstract

A three-parameter model of neutrino oscillations based on a simple Lorentz- and CPT-violating texture is presented. The model is consistent with established data and naturally generates low-energy and neutrino-antineutrino anomalies of the MiniBooNE type. Texture enhancements accommodate the LSND signal and the MINOS anomaly.

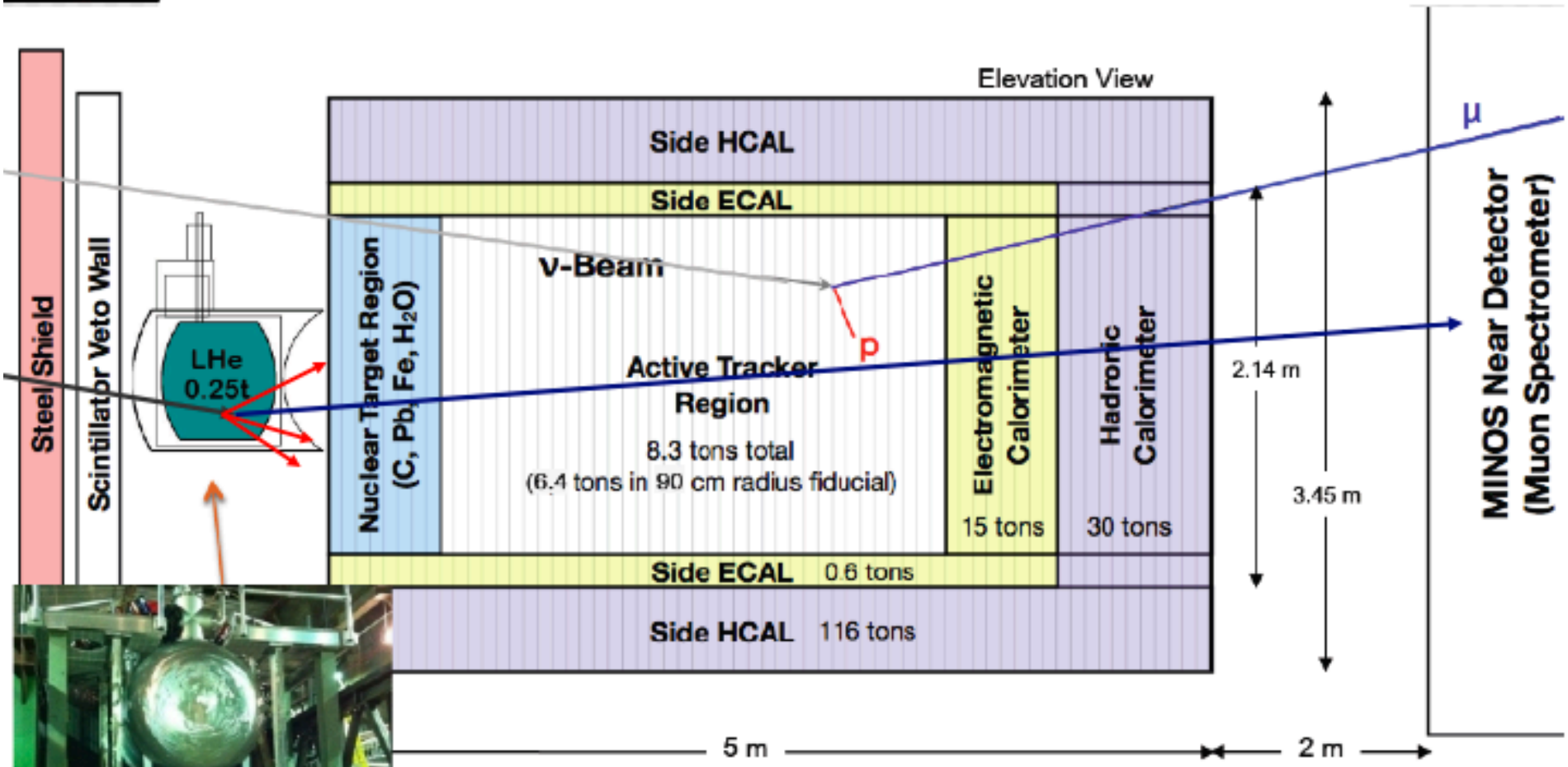
arxiv: 1012.5985

Future ν Experiments at Fermilab

- More MiniBooNE $\bar{\nu}$ Data (15E20 POT)
- MINERvA with H2/D2 targets
- More MINOS data (MINOS+)
  - Take data with higher energy beam
- MicroBooNE
  - Address MB low energy excess
- BooNE: a 2nd Mineral Oil or LAr detector
  (LOI arXiv:0910.2698)
- NOvA with 2 near detectors
- NOvA with nearby cyclotron
- Muon Storage Ring
- Project X

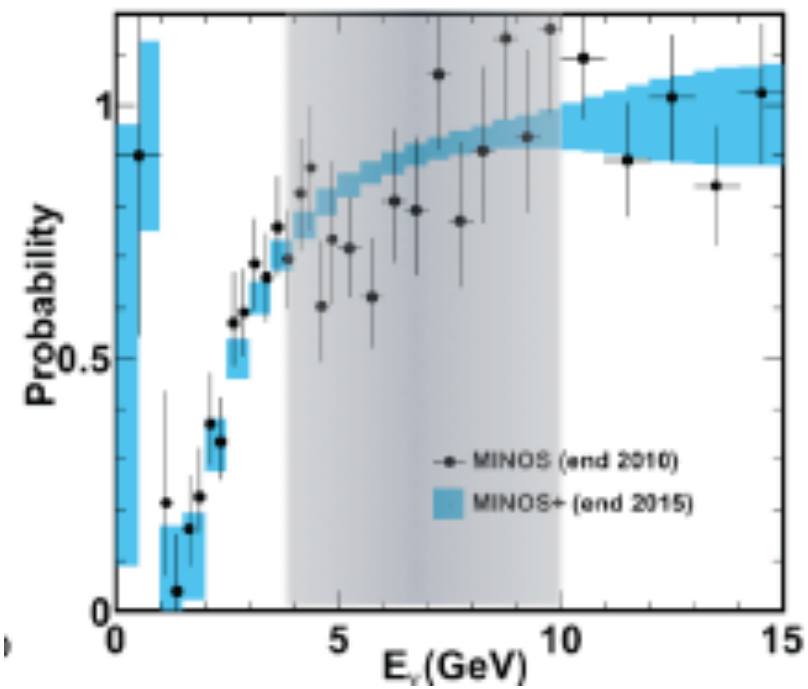


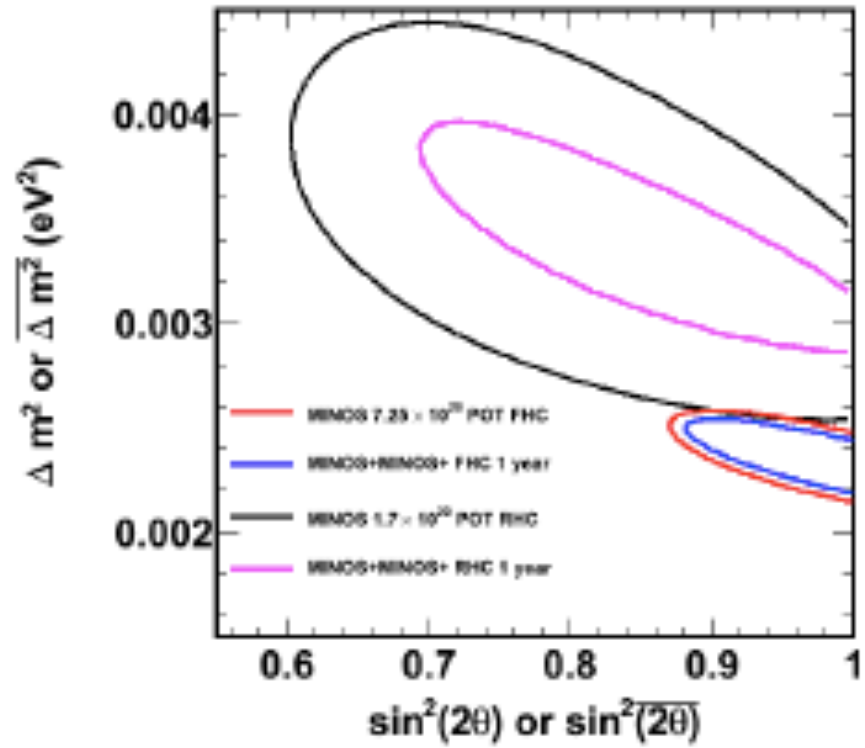
MINERνA Cryogenic Target



MINERνA Targets: carbon, lead, iron, …, and helium.
And also hydrogen and deuterium?

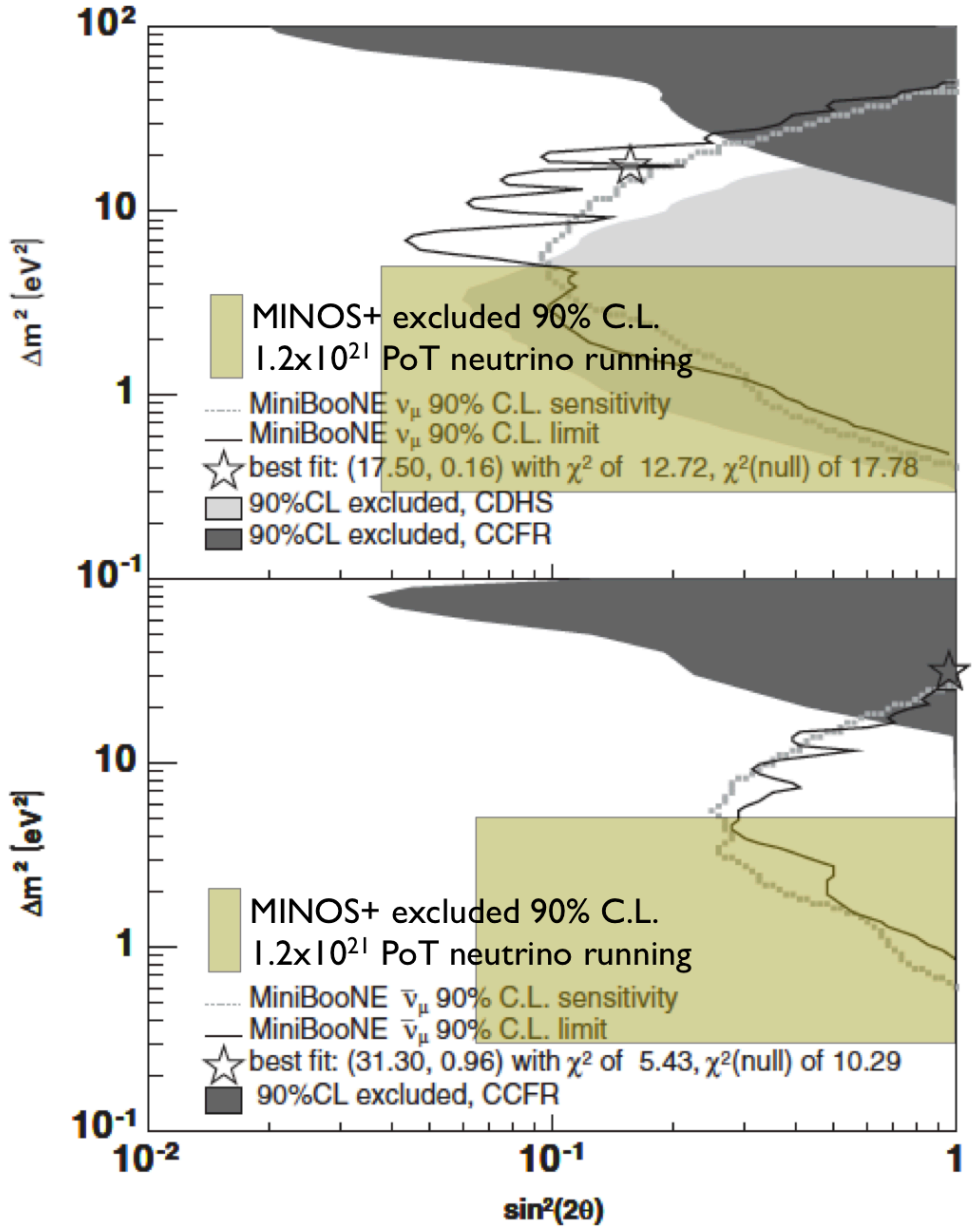
MINOS+





Use higher energy NOvA beam (peaked at 7 GeV) to improve oscillation measurements.

High Δm^2 Disappearance with MINOS+

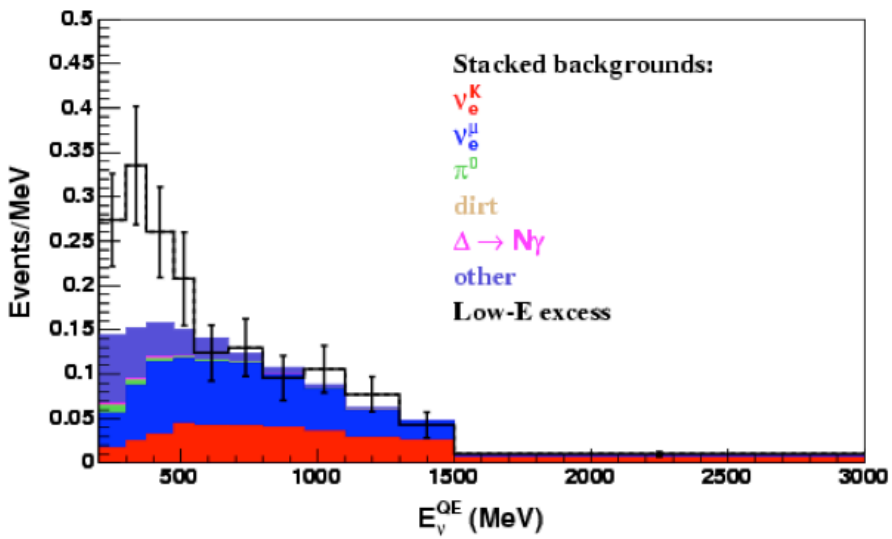


MicroBooNE LArTPC

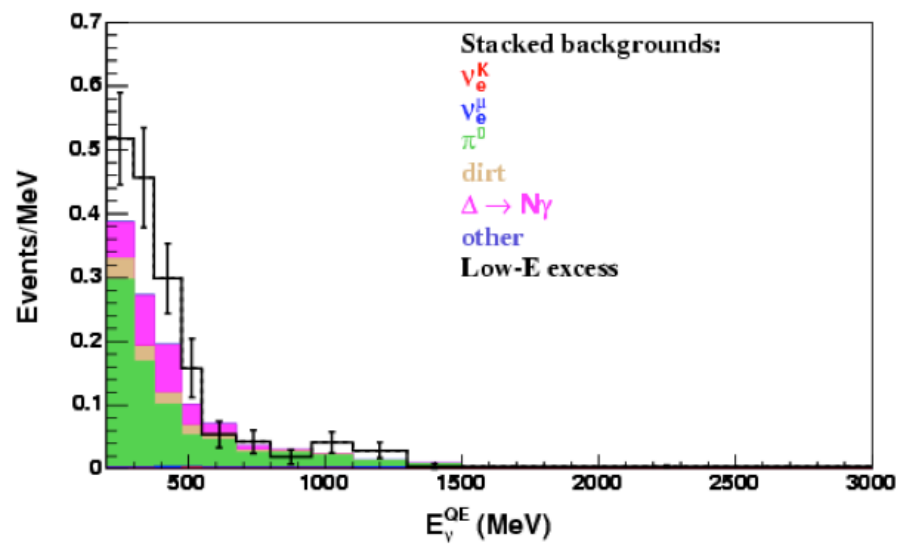
- e/γ separation capability removes ν_μ induced single γ backgrounds
- electron neutrino efficiency: ~x2 better than MiniBooNE
- sensitivity at low energies (down to tens of MeV compared to 200 MeV on MiniBooNE)

As a counting experiment: translates to 5σ sensitivity if excess is ν_e, 4σ if excess is γ

Low energy excess above background if excess is electrons

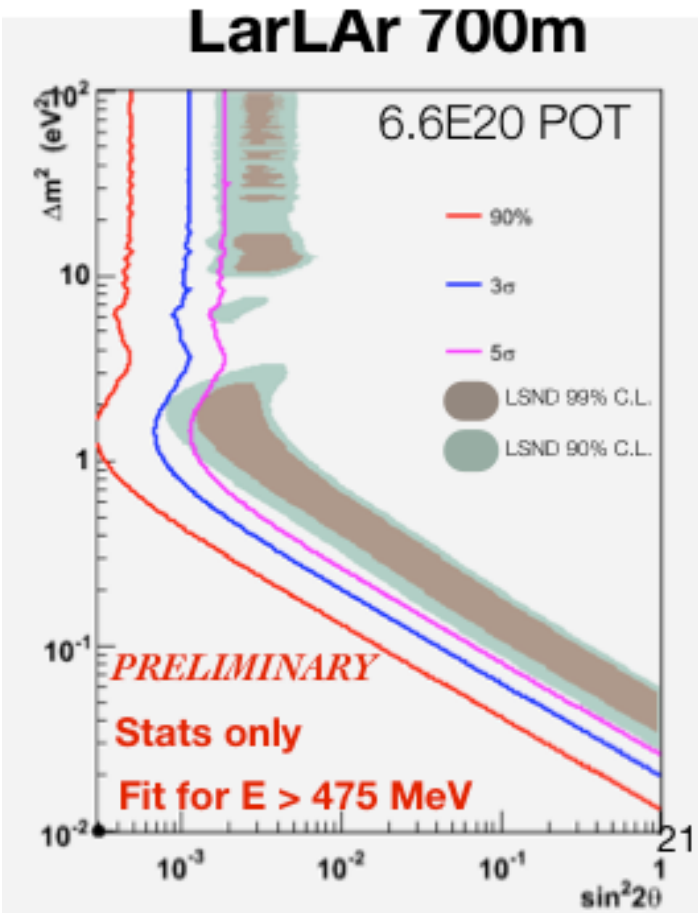


Low energy excess above background if excess is photons

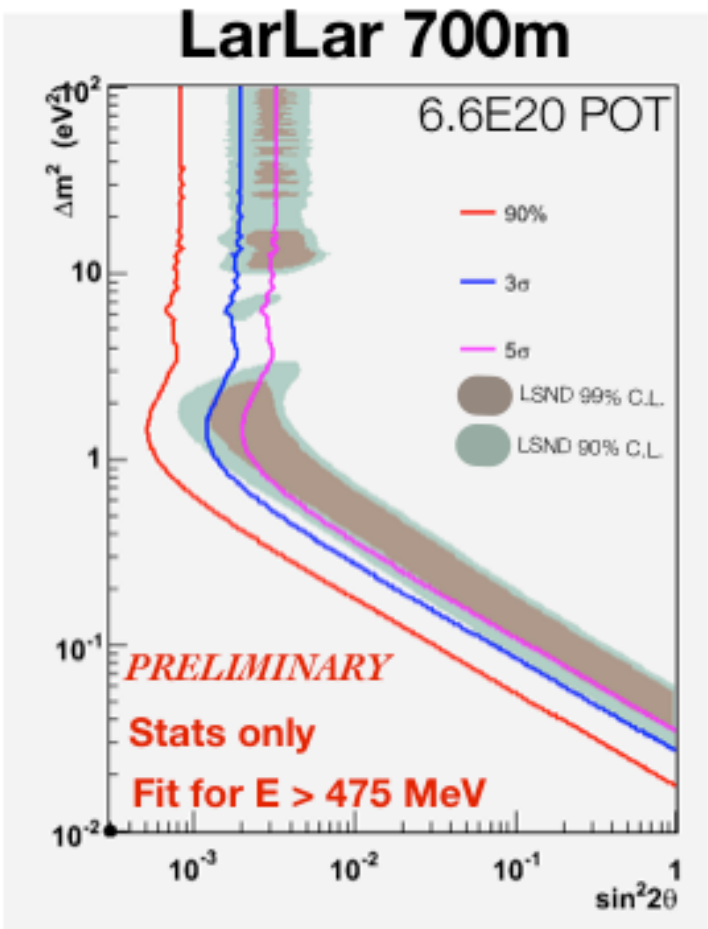


Sensitivities for μBooNE II (200 m) & LarLAr (700 m)

Neutrino Mode



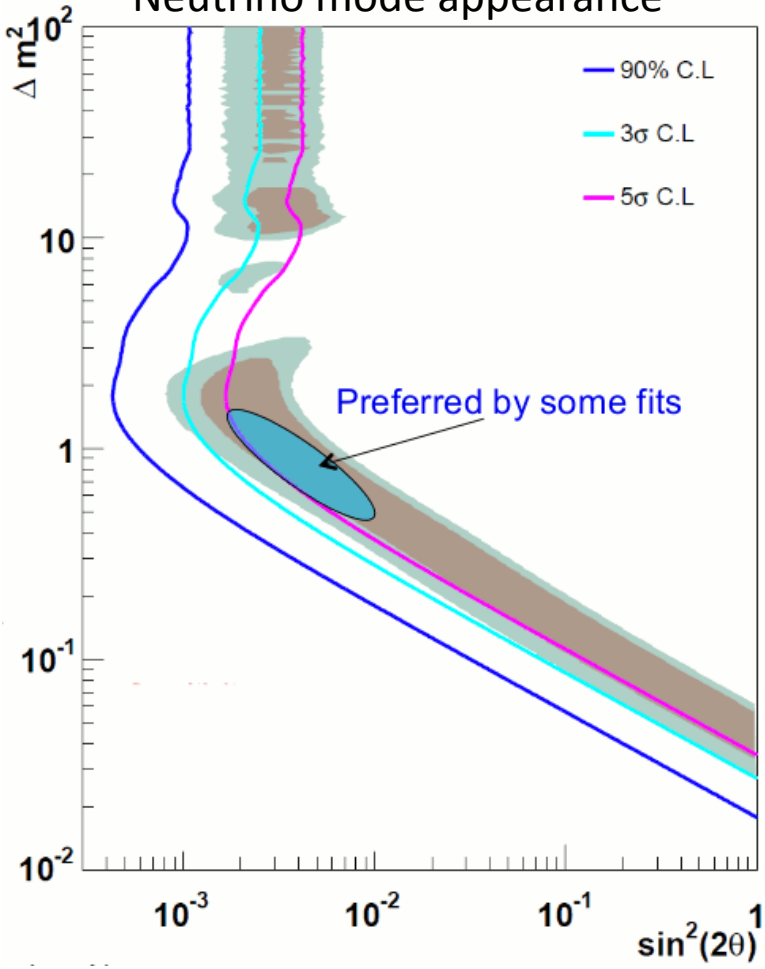
Antineutrino Mode



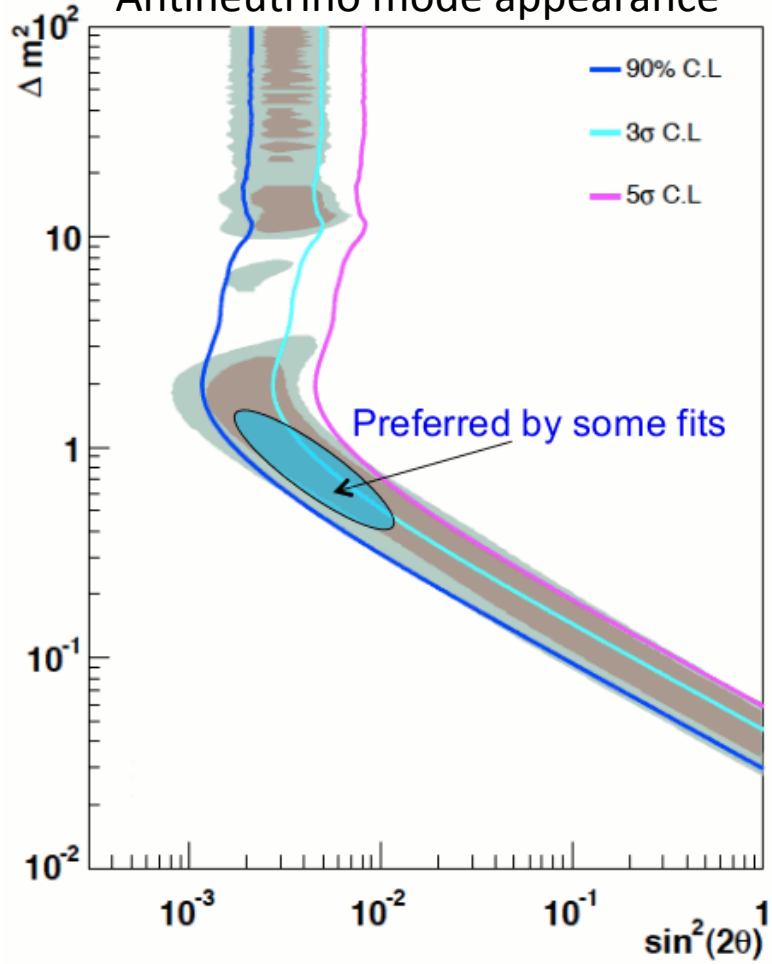
BooNE: Near Detector at ~200 m

BooNE Appearance Sensitivity: 1E20 POT each mode (only 1 year running)

Neutrino mode appearance



Antineutrino mode appearance

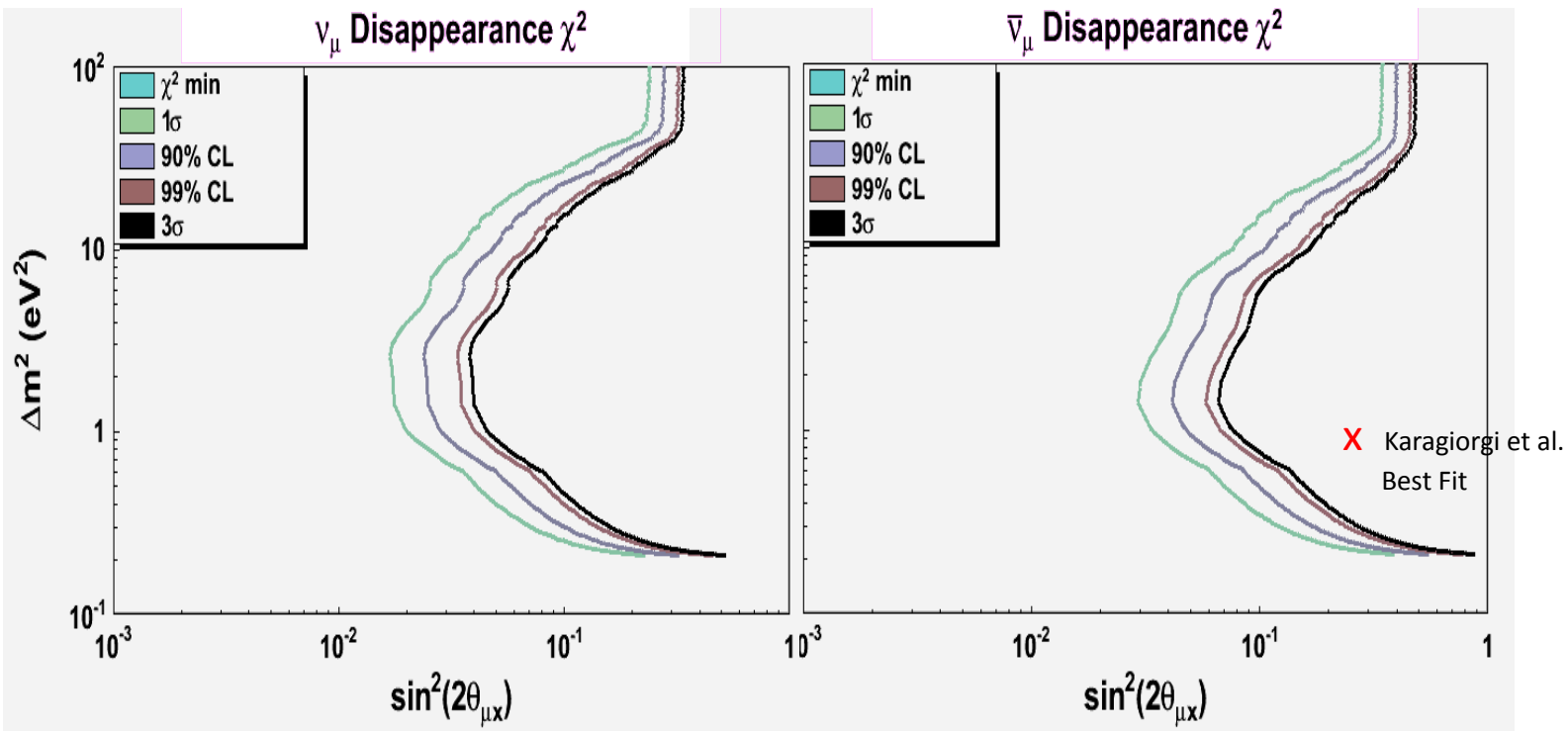


BooNE Disappearance Sensitivity

- Much better sensitivity for ν_μ & $\bar{\nu}_\mu$ disappearance
- Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

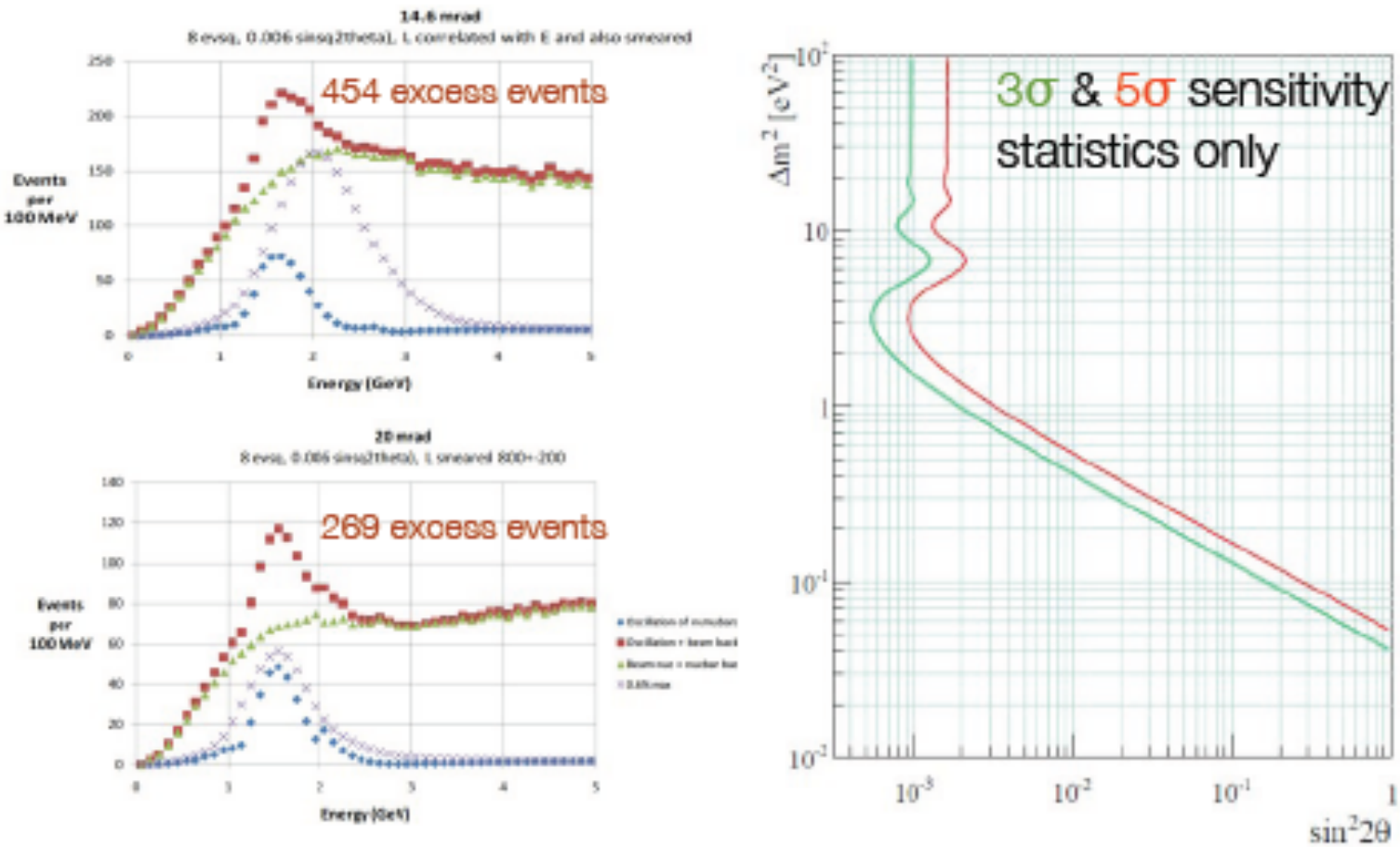
6.5e20 Far/1e20 Near POT

1e21 Far/1e20 Near POT

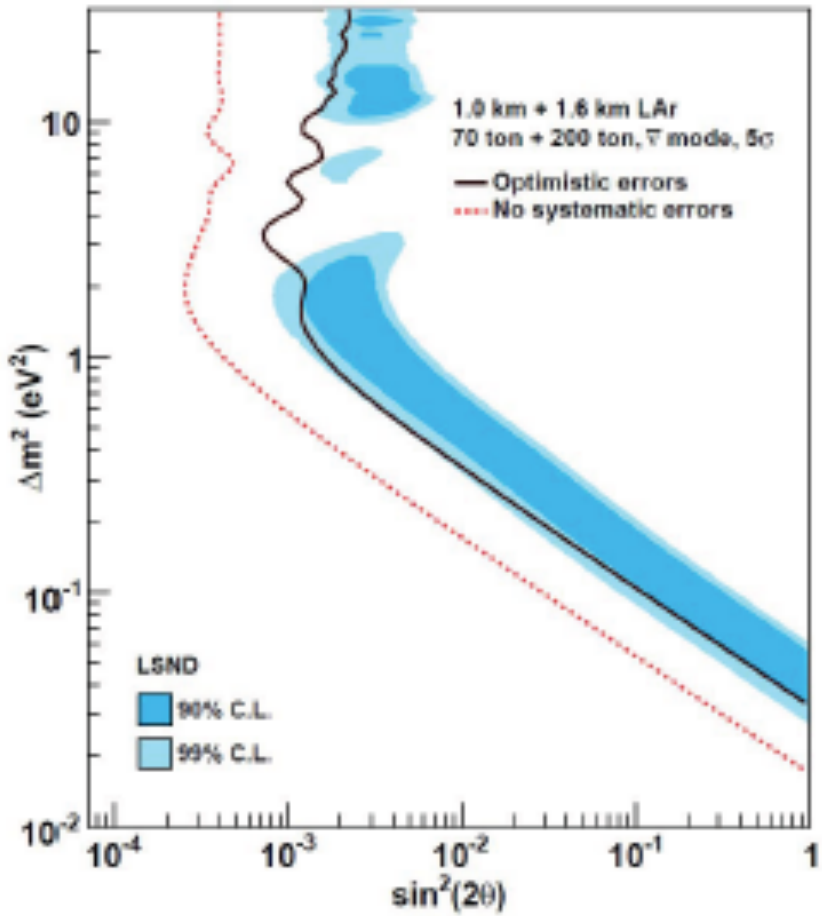


Two NOvA Near Detectors

Possible signals in a new cavern



Beyond NOvA



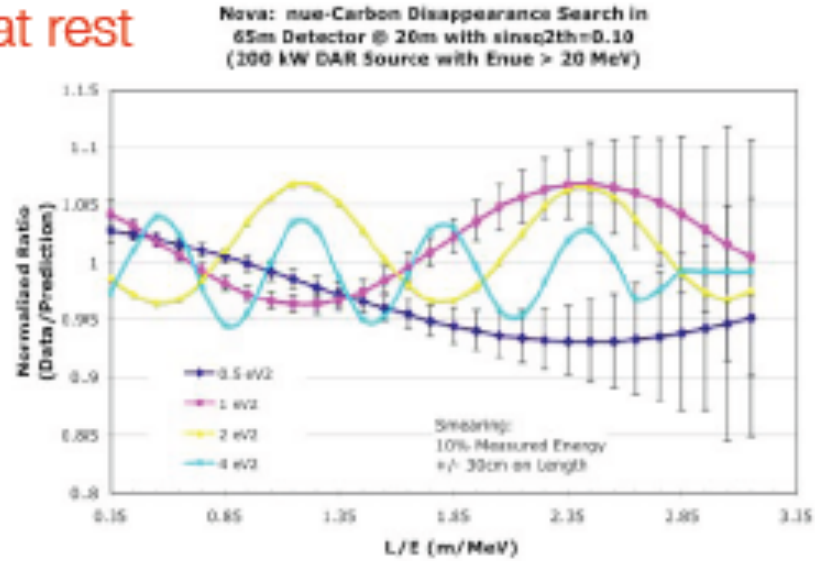
Beyong NOvA:

Using NuMI at 2 km to test LSND / MiniBooNE

Not part of NOvA, but a new idea for possible future use of NuMI. NuMI has several advantages over Booster beam: high power (700 kW vs 11 kW), relatively low wrong-sign contamination in antineutrino beam.

Cyclotron with NOvA

Locate a 100 kW cyclotron in assembly building to produce $\bar{\nu}_e$ from muon decay at rest



Short-baseline Neutrino Oscillation Waves in Ultra-large Liquid Scintillator Detectors

Sanjib Kumar Agarwalla[a], J.M. Conrad[b], M.H. Shaevitz[c]

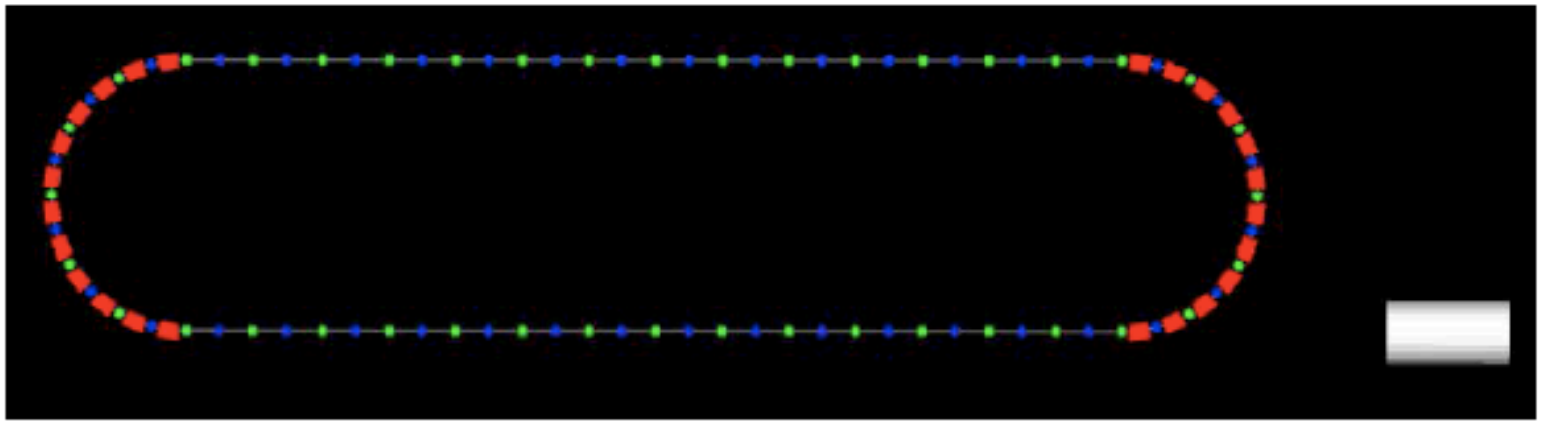
[a] *Instituto de Física Corpuscular, CSIC-Universitat de València, Apartado de Correos 22085, E-46071 Valencia, Spain*
[b] *Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[c] *Department of Physics, Columbia University, New York, New York 10027, USA*

See talk by Alan Bross in WG1.

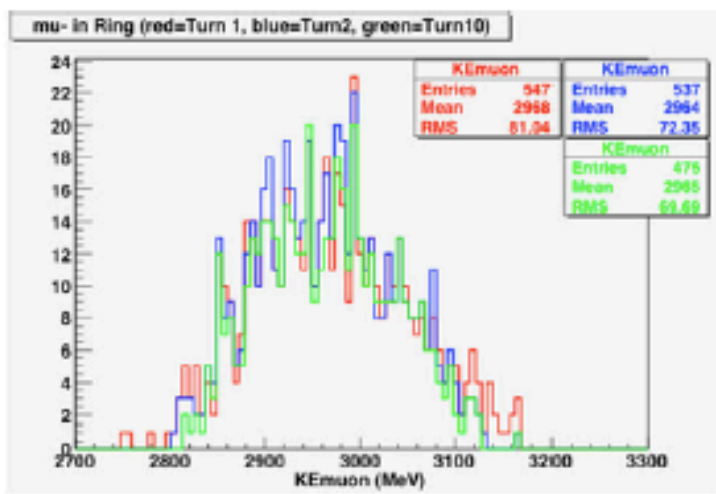
Basic concept

G4Beamline Simulation

Tom Roberts
Muons Inc.



- 8 GeV protons on 2 λ_I Be target
- 3 GeV Racetrack ring (M. Popovic)
  - For now, injection is perfect
    - Not defined
- Tuned for μ^- with KE = 3.000 GeV
  - $\delta p/p \approx 2\%$
- Detectors (scintillator)
  - Near: 200T @ 20 m
  - Far: 800T @ 600 m



Long Term Possibilities (>8 years) Make Precision measurements of new physics:

If smoking gun is found, then design/build a series of experiments with Project X to explore in detail the source of new physics:

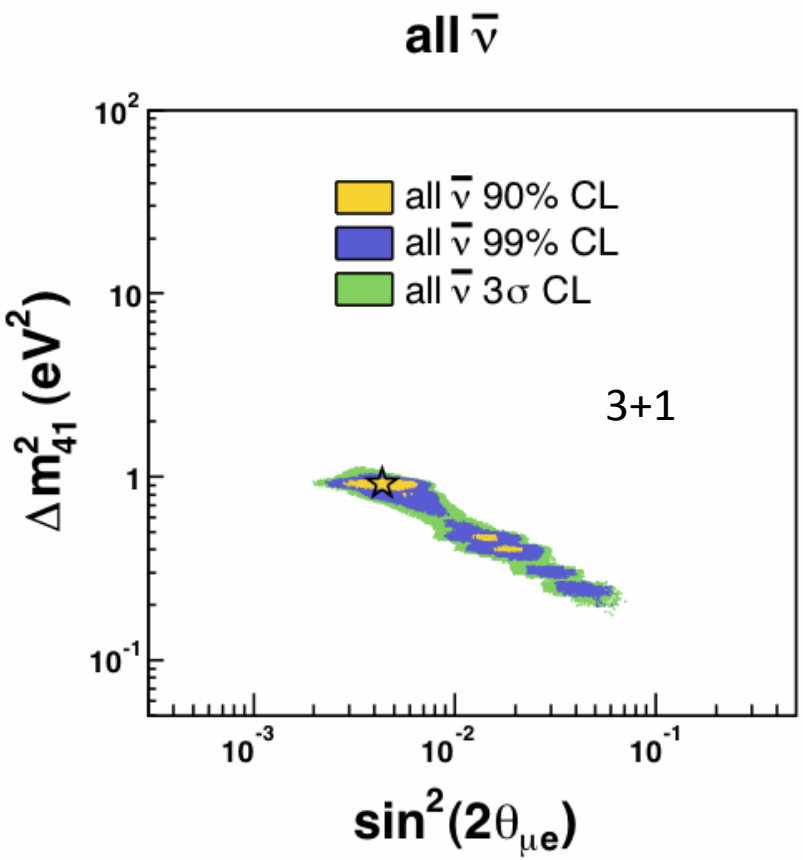
- DIF (300-600kW at 3GeV with a new accumulator)
  - 15-30 times more flux with reduced Kaon background.
- DIF (250-500kW at 8GeV with antiproton accumulator) directly into BNB.
- Sterile neutrinos
- Beam dump exotics - axions, paraphotons, etc.
- Cross sections

Conclusions

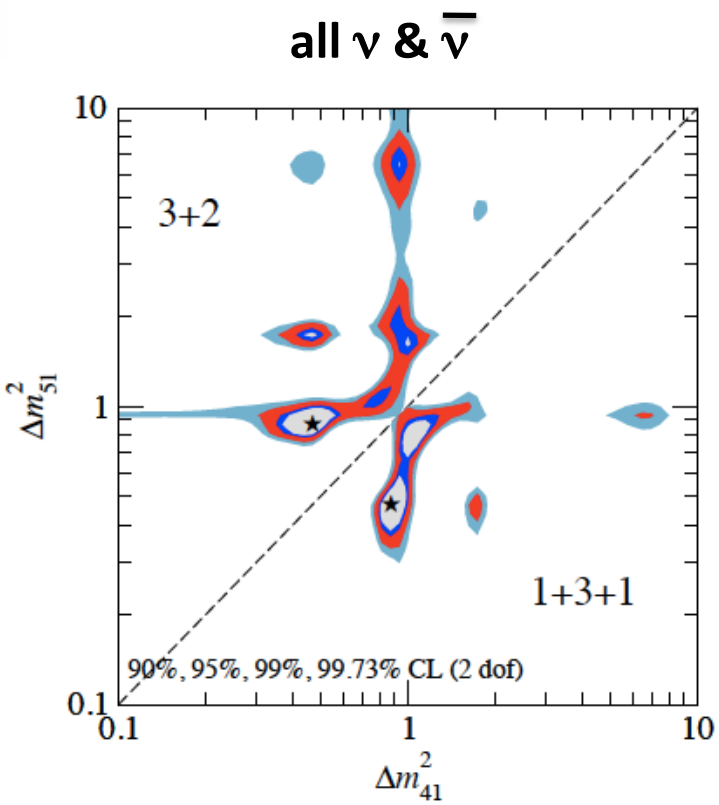
- World antineutrino data agree very well with a 3+1 model
- Key test of 3+1 is a search for $\bar{\nu}_\mu$ disappearance
- World neutrino + antineutrino data can be explained somewhat well by a 3+2 model with CP violation, although there is tension between appearance and disappearance experiments
- Other models are possible besides 3+N: NSI, sterile neutrino decay, Lorentz violation, CPT violation, etc.
- MINERvA, MINOS+, NOvA (two detectors), BooNE at FNAL (two oil Detectors or two LAr detectors), μ Storage Ring, ICARUS at CERN, OscSNS at ORNL, or new reactor and radioactive source experiments could measure cross sections and neutrino oscillations with high significance (>5σ) and prove whether sterile neutrinos, NSI, Lorentz Violation, or CPT Violation occur in the lepton sector.
- Project X could make precision measurements of new physics!

Backup

Global Fits to World ν Data



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

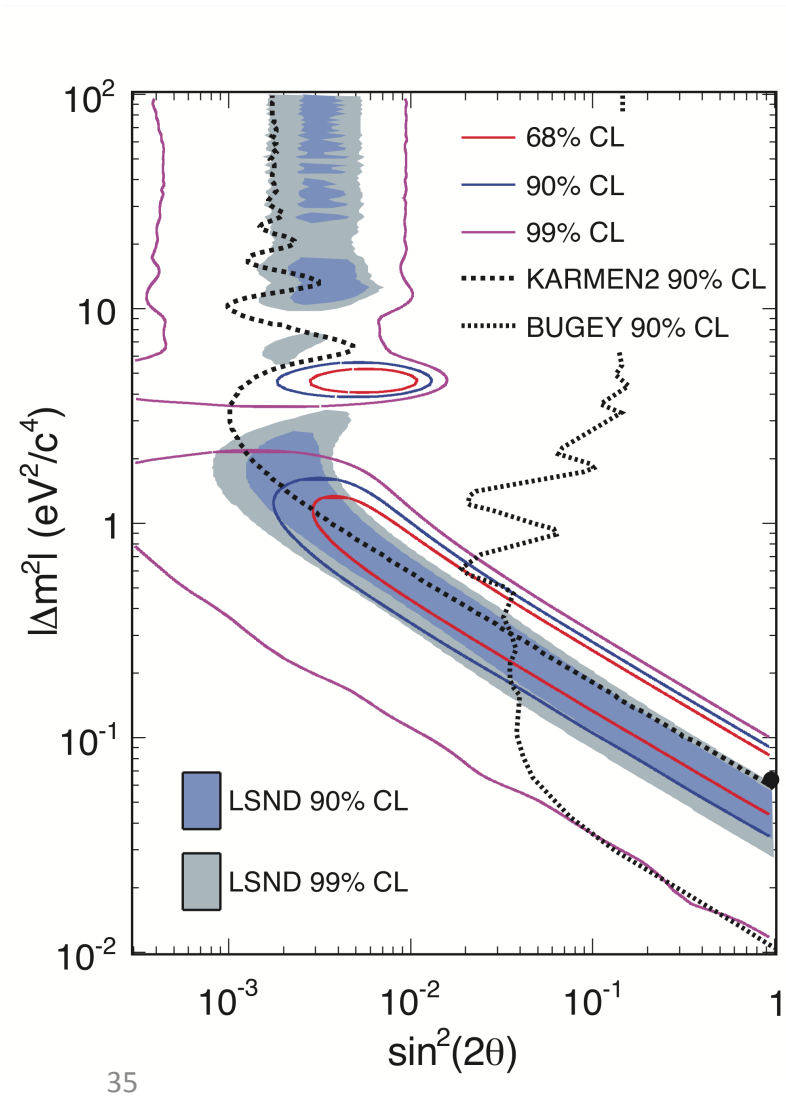


Kopp, Maltoni, & Schwetz, arXiv:1103.4570

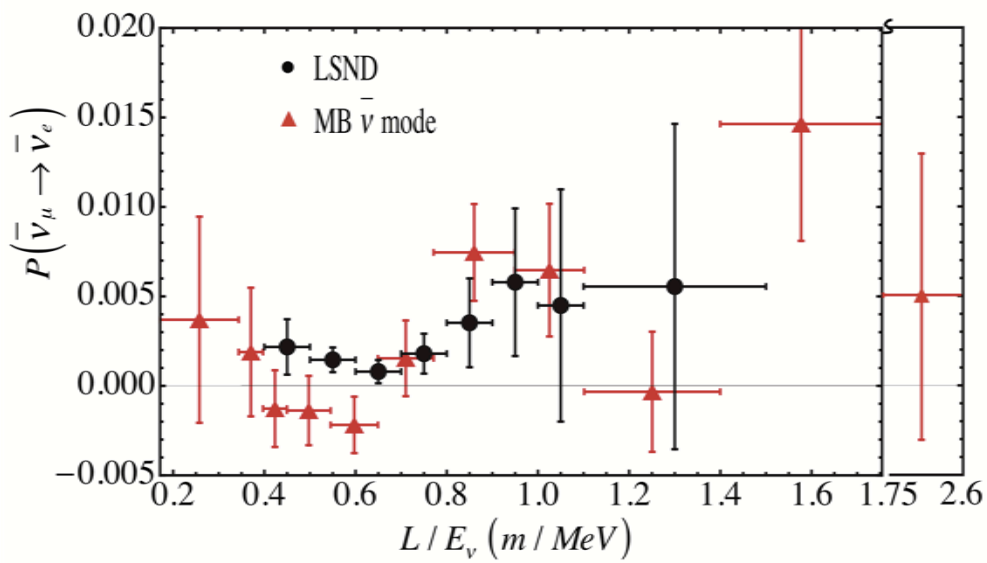
What is Short Baseline?

- "Short" refers to L_ν/E_ν and not just L_ν
- Note that L_ν/E_ν is proportional to the ν lifetime in its CM frame
- Our definition of "Short" is L_ν/E_ν ~ 1 (km/GeV or m/MeV)
- This definition includes radioactive ν source experiments (~1 m/1 MeV), reactor ν experiments (~5 m/5 MeV), accelerator ν experiments (~1 km/1 GeV), & IceCube atmospheric ν (~1000 km/1 TeV)

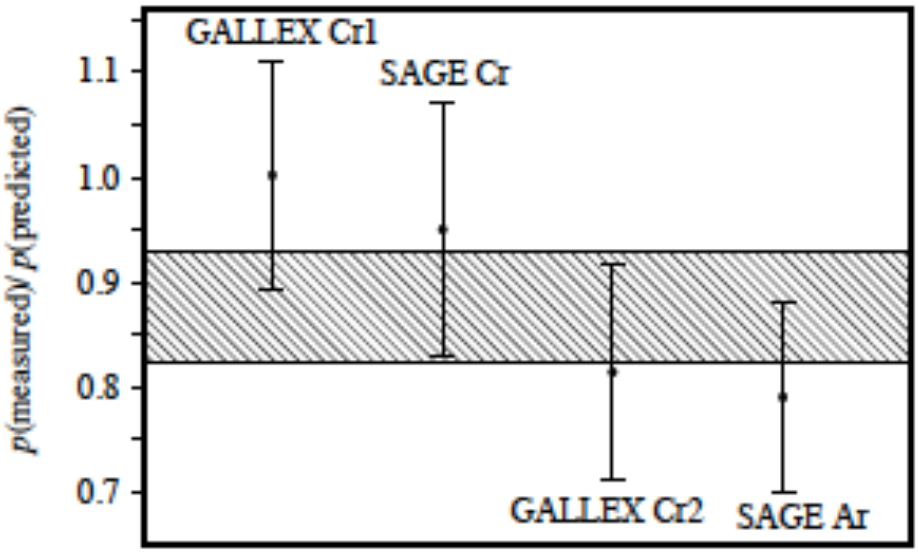
LSND & MiniBooNE Antineutrino Results



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

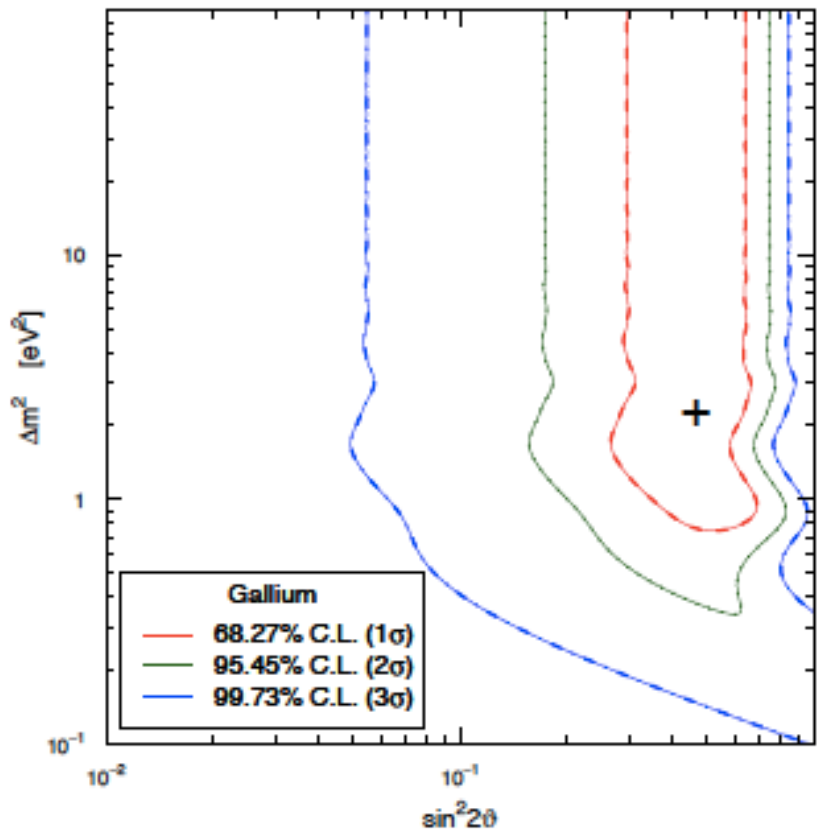


Radioactive Neutrino Sources



R=0.86+-0.05

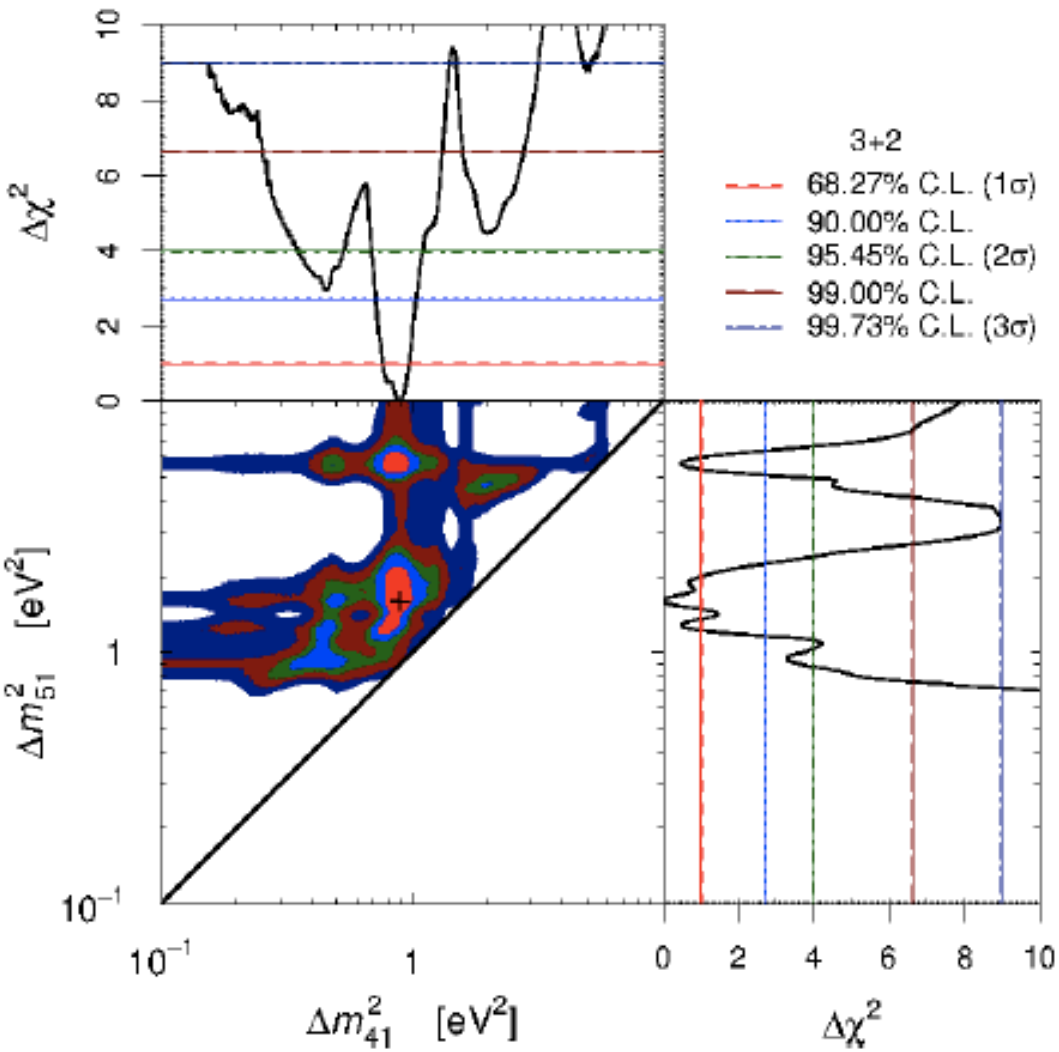
SAGE, PRC 73 (2006) 045805
arXiv:nucl-ex/0512041



Giunti & Laveder, arXiv:1006.3244

Global 3+2 Fit to World Neutrino & Antineutrino Data

Giunti & Laveder, arXiv:1107.1452



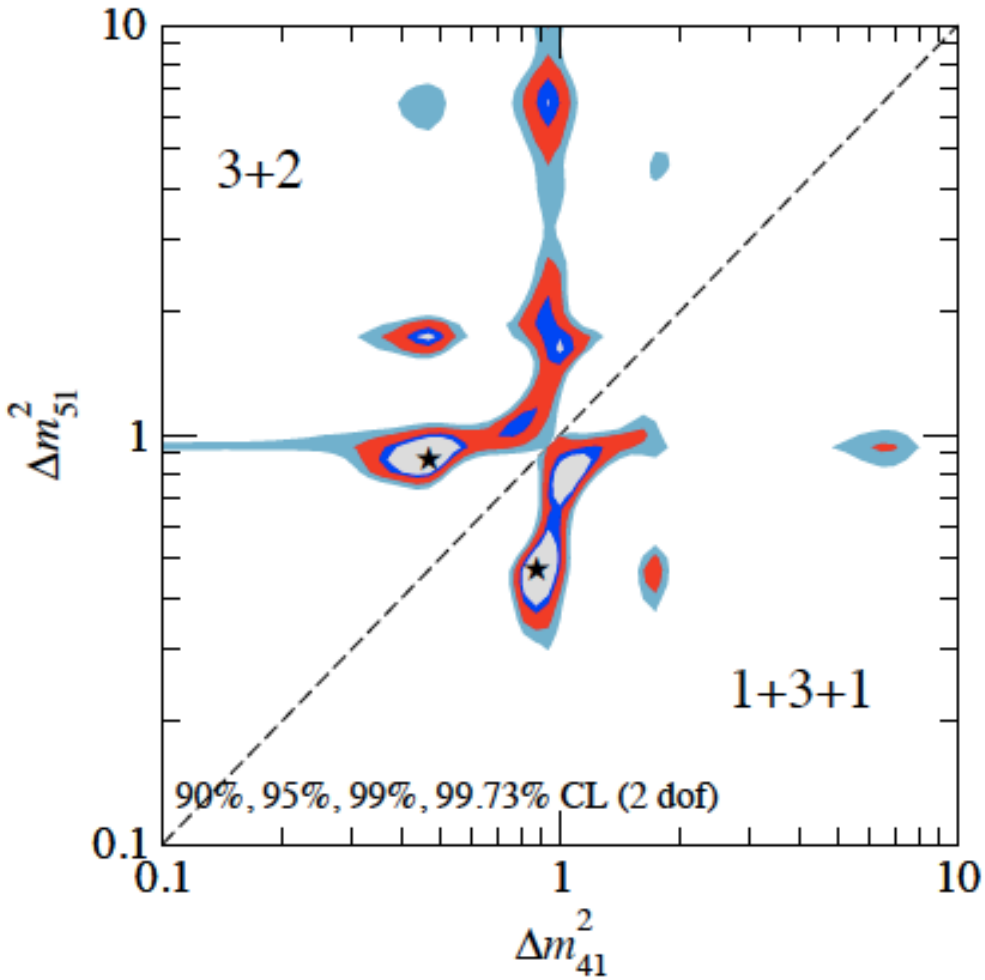
	3+1	3+2
$\chi^2_{\rm min}$	100.2	91.6
NDF	104	100
GoF	59%	71%
Δm^2_{41} [eV^2]	0.89	0.90
$\lvert U_{e4}\rvert^2$	0.025	0.017
$\lvert U_{\mu 4}\rvert^2$	0.023	0.018
Δm^2_{51} [eV^2]		1.60
$\lvert U_{e5}\rvert^2$		0.017
$\lvert U_{\mu 5}\rvert^2$		0.0064
η		1.52π
$\Delta\chi^2_{\rm PG}$	24.1	22.2
$\rm NDF_{PG}$	2	5
PGoF	6×10^{-6}	5×10^{-4}

However, in 3+2 models there is some tension between neutrino & antineutrino data.

Global 3+2 Fit to World Neutrino & Antineutrino Data

Kopp, Maltoni, & Schwetz, arXiv:1103.4570

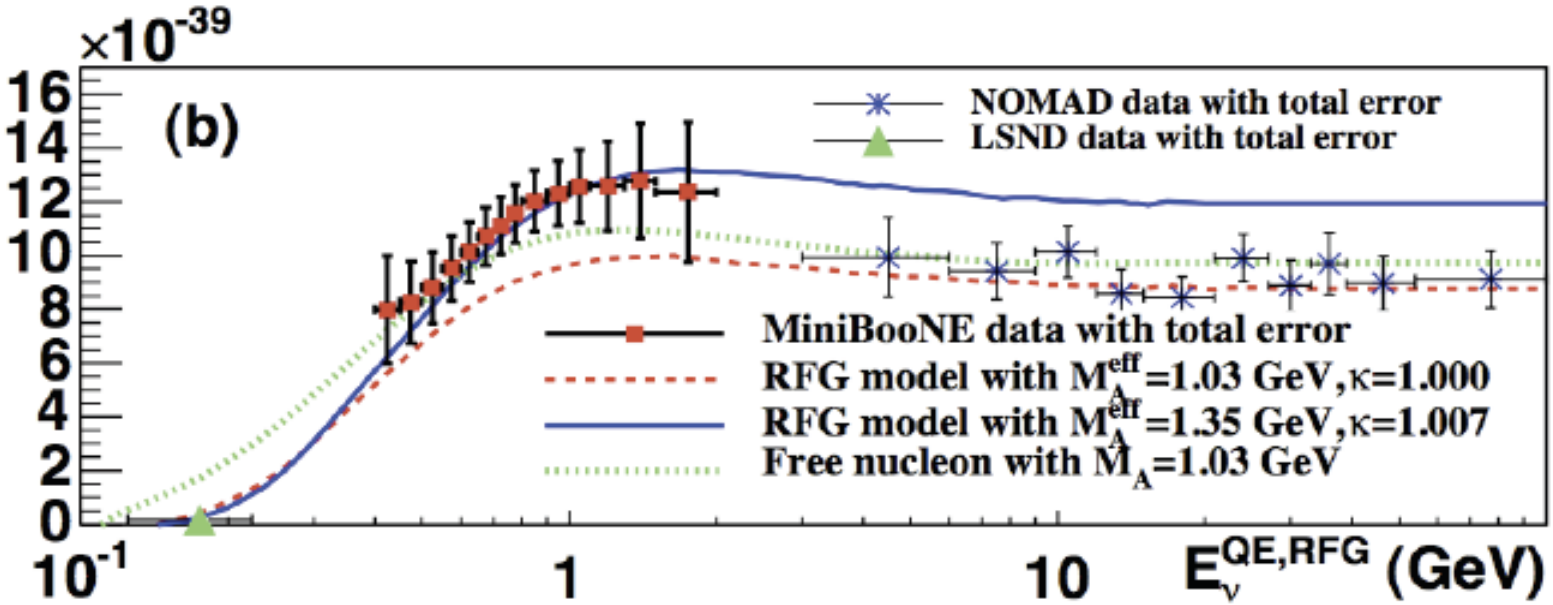
	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130



However, in 3+2 models there is some tension between neutrino & antineutrino data.

ν_μ CCQE Scattering

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

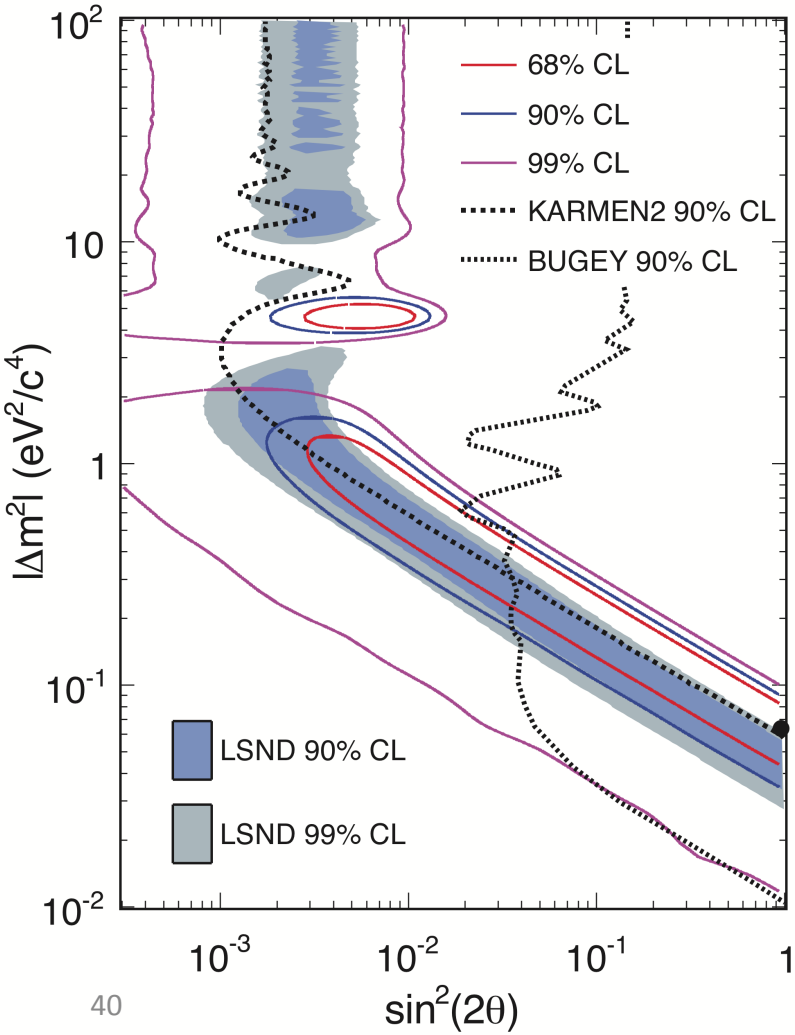


Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}C)>6\ \sigma_{\nu\mu}(n)$

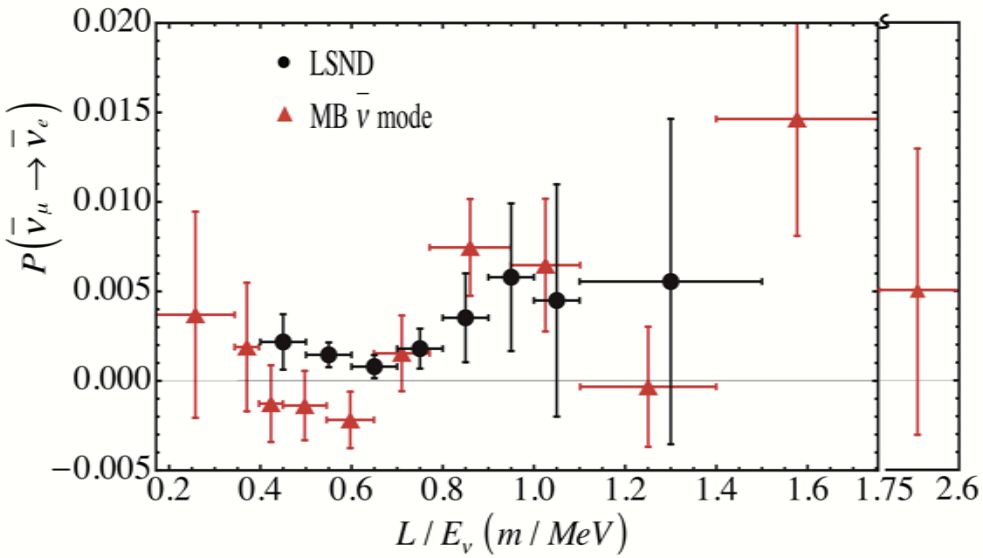
How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys.Rev.**C65,** 024002 (2002) & Gerry Garvey. These nuclear effects could have a big effect on searches for CP Violation.

LSND & MiniBooNE Antineutrino Results

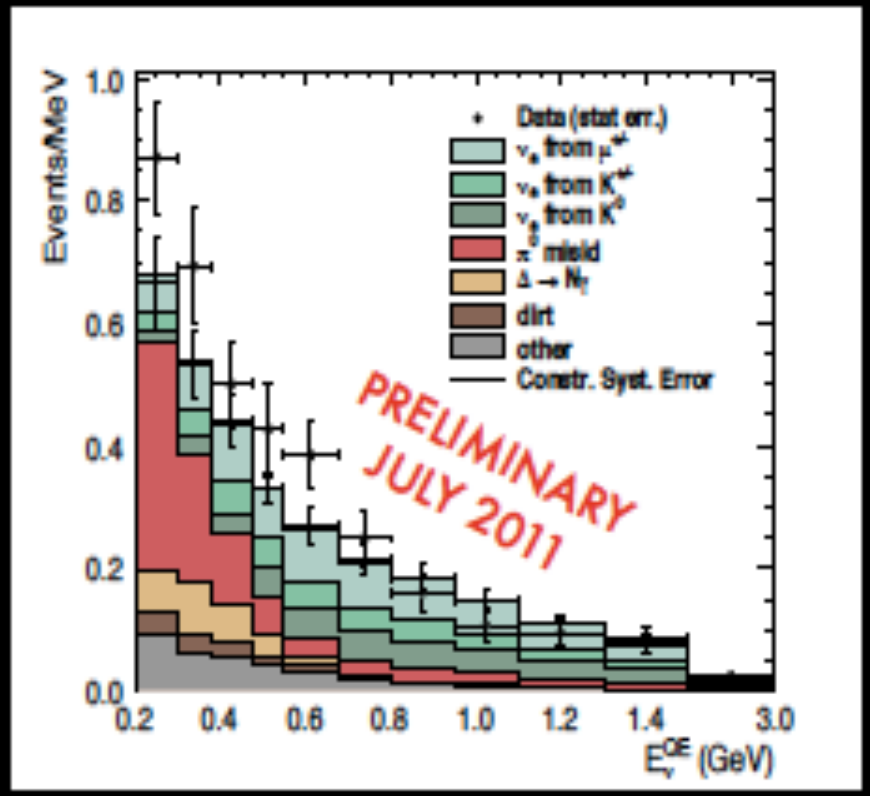


A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 105, 181801 (2010)



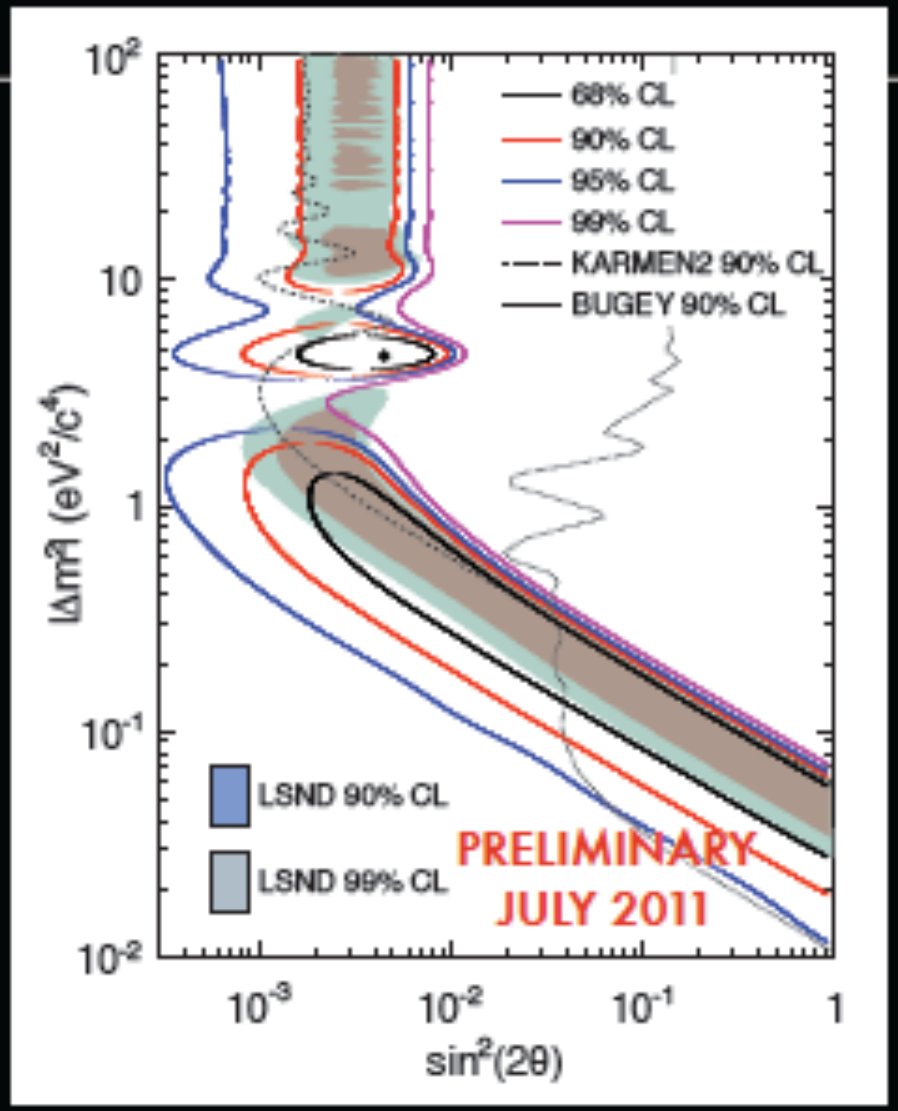
The full energy range

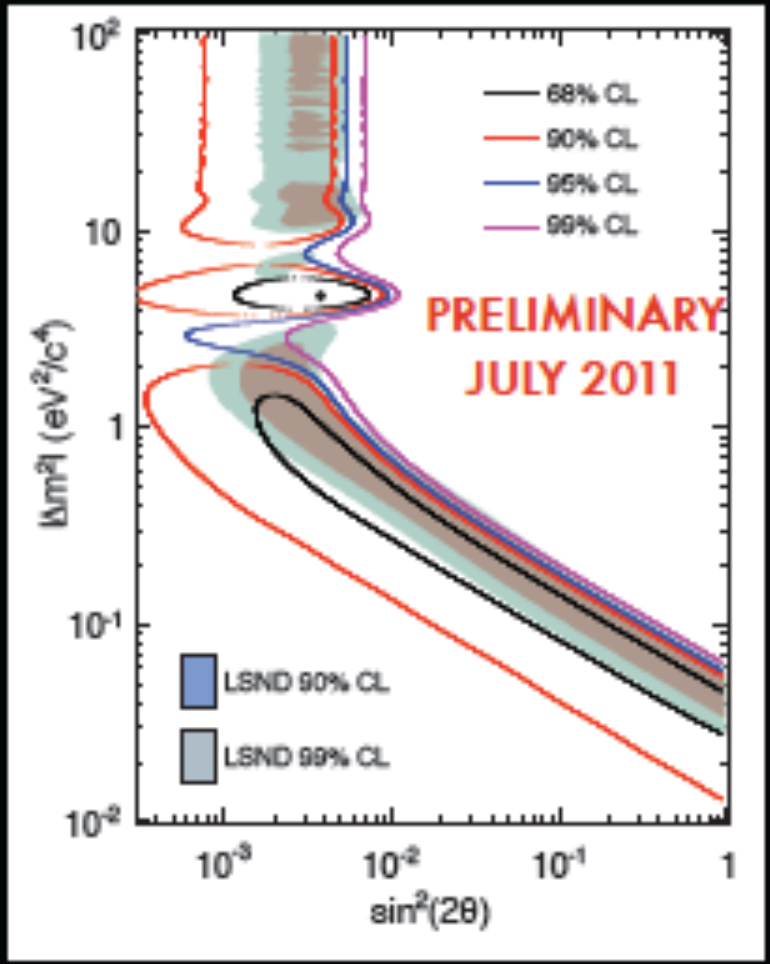
- Low-energy excess is now more prominent; excess above background in 200<E<475 MeV is 38.6±18.5 events.
- Full energy range: excess is 57.7±28.5



Oscillation fits: full energy range

- Results for **8.58E20 POT**
- Maximum likelihood fit for *simple two-neutrino model*
- Oscillation hypothesis preferred to background-only at 97.6% confidence level.
- Fit over all bins:
  - P_{χ^2}(null)= 10.1%
  - P_{χ^2}(best fit)= 50.7%
- This is not our primary test of LSND, due to known low-energy excess



Another way to fit: subtract low-E excess expected from neutrinos

- In principle, we are trying to fit for $\bar{\nu}$ oscillations only, with expected contributions from ν subtracted as background
- However, neutrino contribution to low-energy excess isn't in background simulation since its explanation is unknown
- We can assume it scales with total neutrino-induced event rate in each bin, and subtract it out when fitting for antineutrino oscillations.
- Oscillation hypothesis preferred to background-only at 94.2% confidence level.
- Fit over all bins: P_{χ^2}(null)=28.3%; P_{χ^2}(best fit)=76.5%