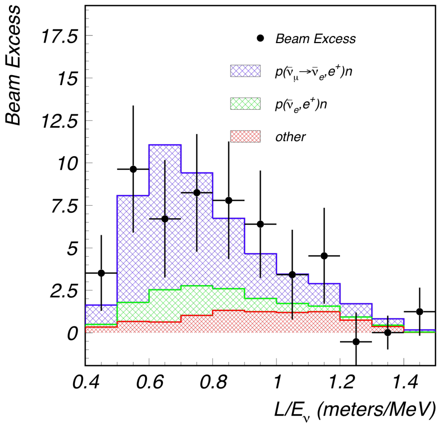
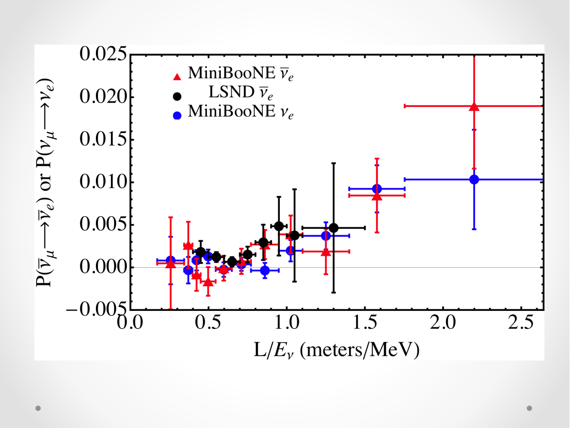
Sterile Neutrino Implications from Short-Baseline Neutrino Experiments

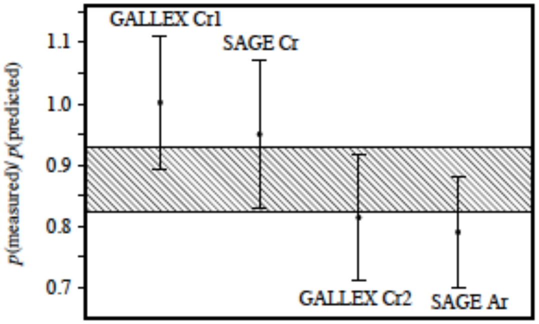
W.C. Louis, November 4, 2014

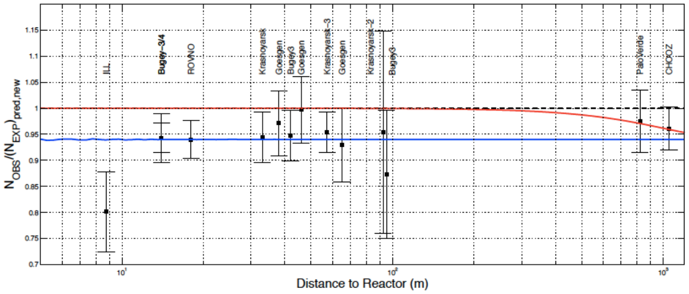
- Short-Baseline Anomalies from ν_e Appearance Experiments
- Short-Baseline Anomalies from ν_e Disappearance Experiments
- Searches for ν_μ Disappearance
- 3+N Sterile Neutrino Oscillation Models
- Future Short-Baseline Neutrino Experiments
- Conclusions

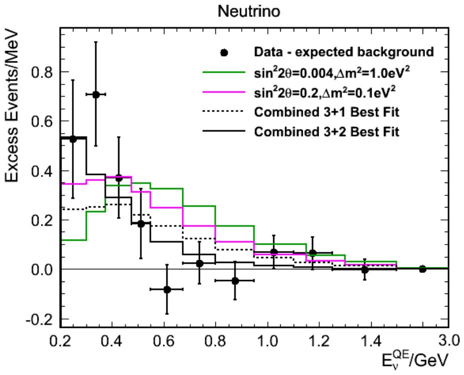
Short-Baseline Neutrino Anomalies

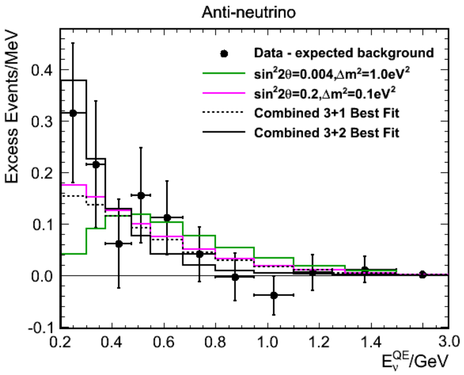


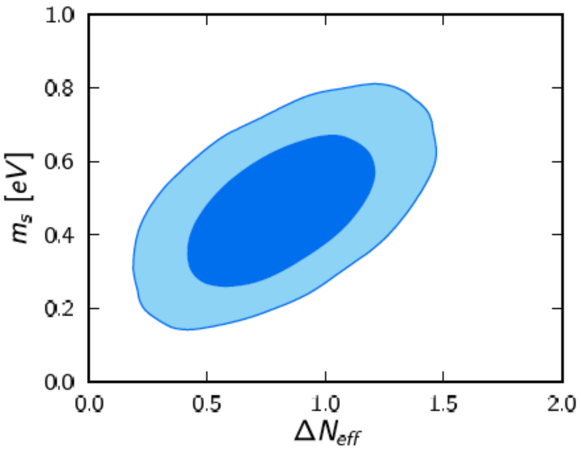












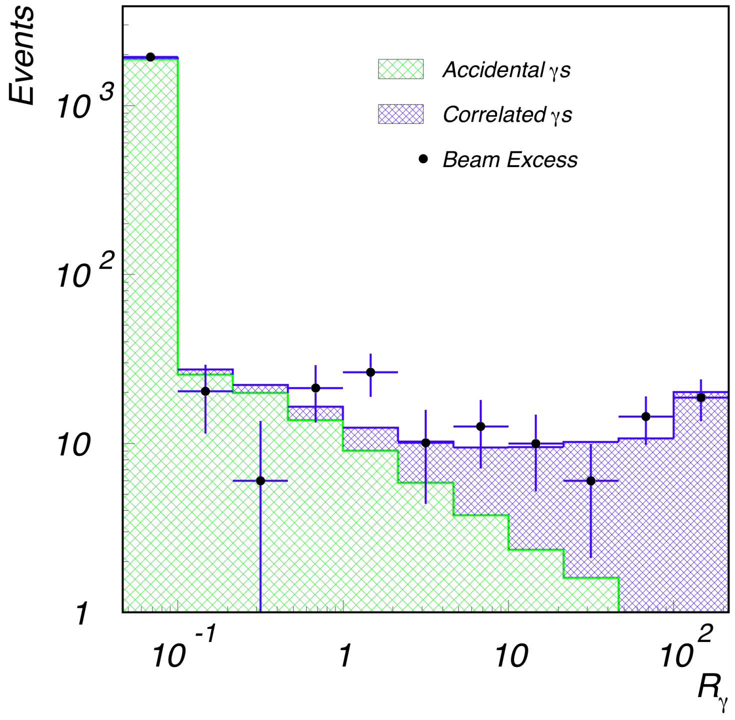
Short-Baseline Anomalies from ν_e Appearance Experiments

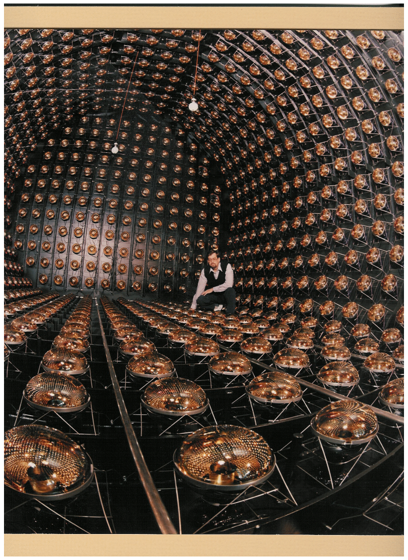
LSND Event Excess

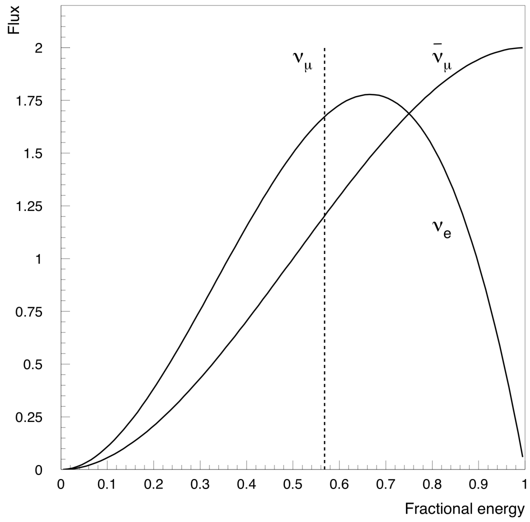
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)

Correlated γ = 117.9+-22.4 events

Excess = 87.9+-22.4+-6.0 events





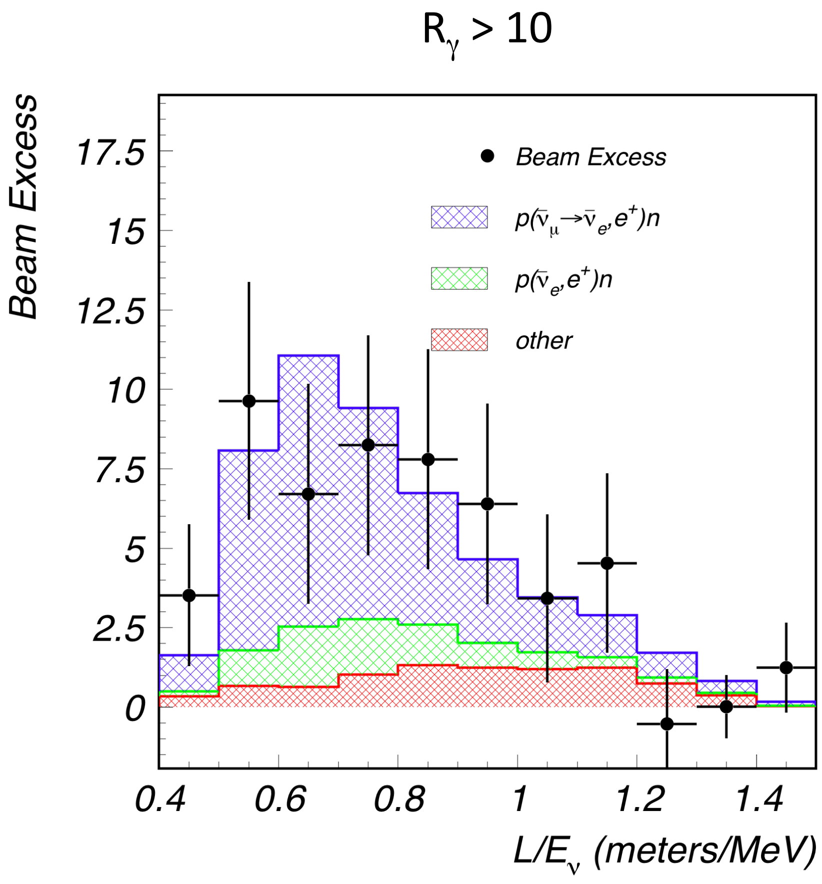


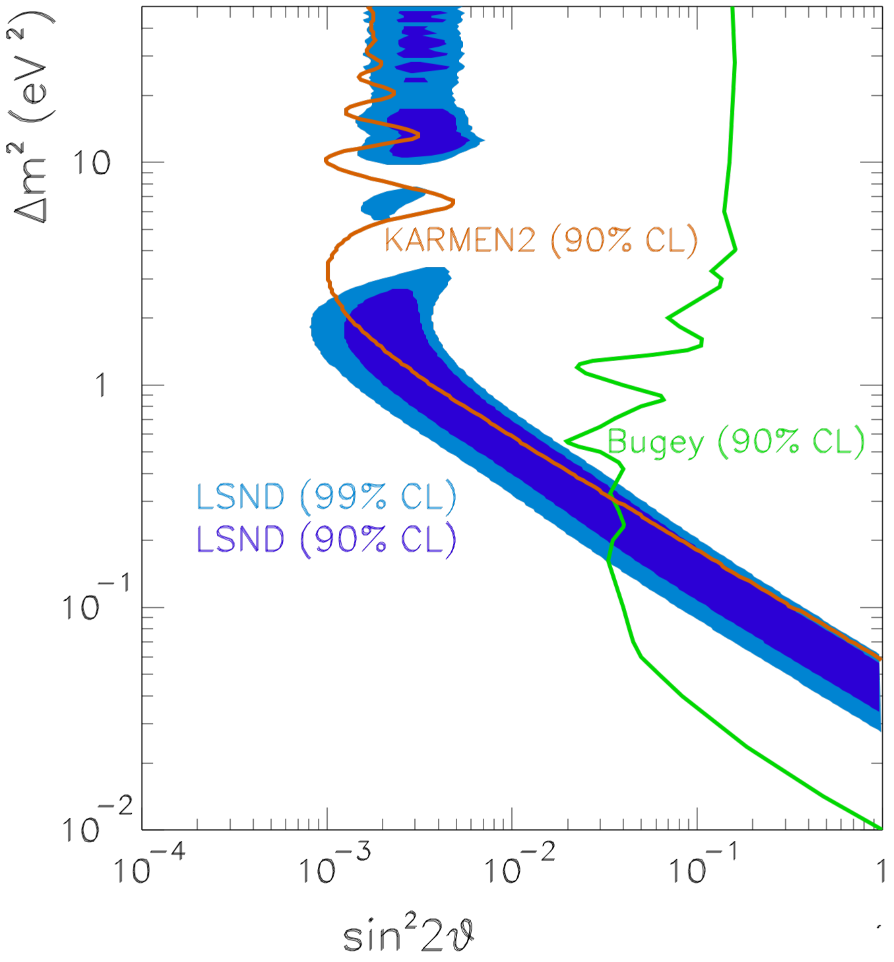
$\bar{\nu}_e$ p -> e^+ n, n p -> d γ(2.2 MeV)

LSND collected 28,896 C on target and observed a 3.8 σ excess of events consistent with $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillations, corresponding to P_{osc} = (0.264+-0.067+-0.045)%

LSND Event Excess

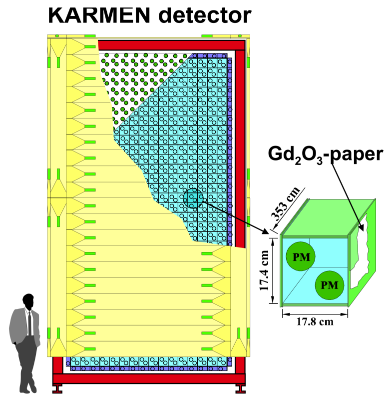
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)





Joint LSND/KARMEN Analysis

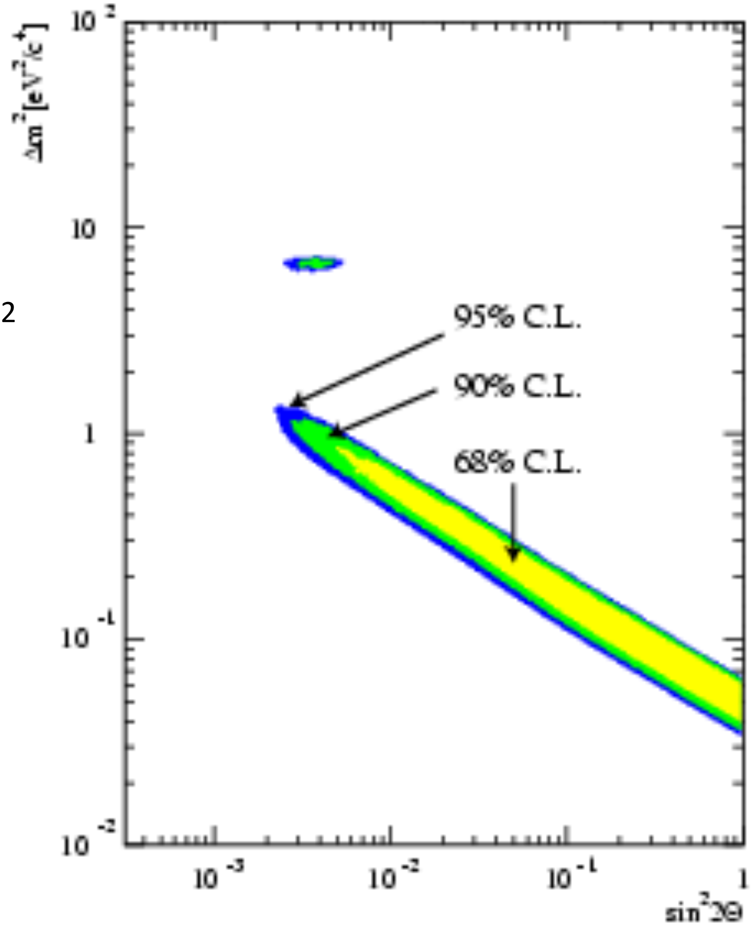
E. D. Church, K. Eitel, G. B. Mills, and M. Steidl, Phys. Rev. D66, 013001, (2002)

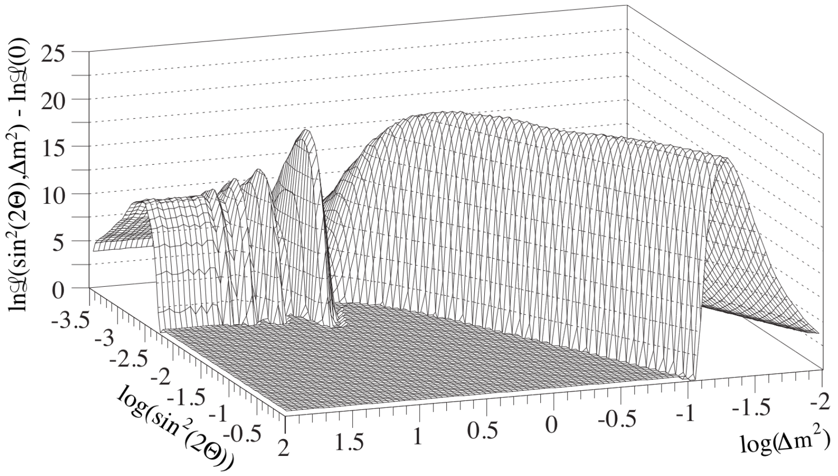


96% active volume of ^{12}C and p

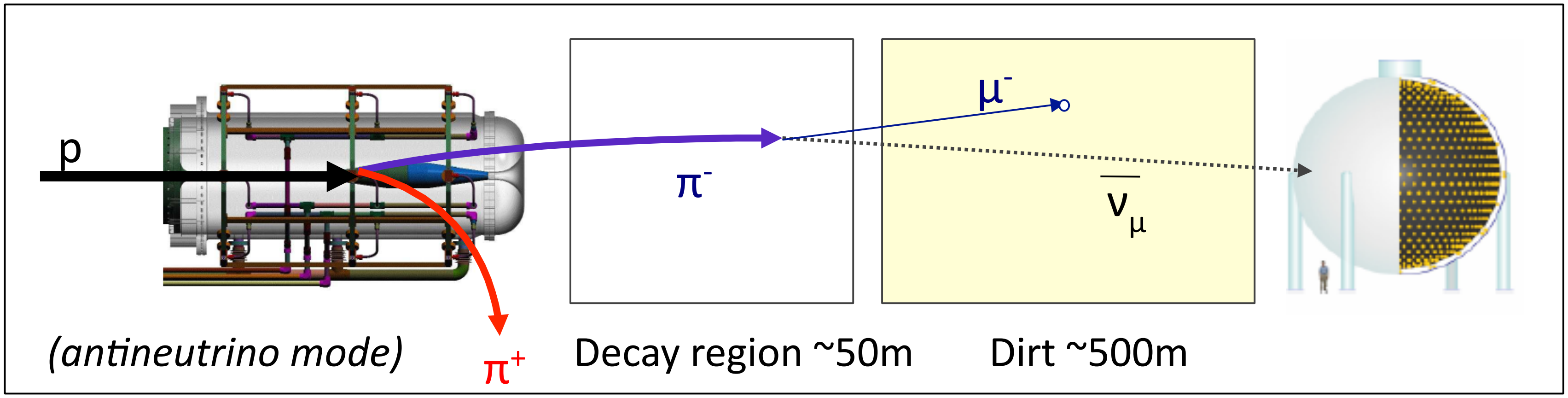
$E \quad \frac{11.5\%}{\sqrt{E[MeV]}} \qquad t_{ISIS} \quad 2ns$

KARMEN observed no event excess; however, a joint analysis of KARMEN (17.7m) & LSND (30m) reveals a favored region of $\Delta m^2 < 1$ eV^2





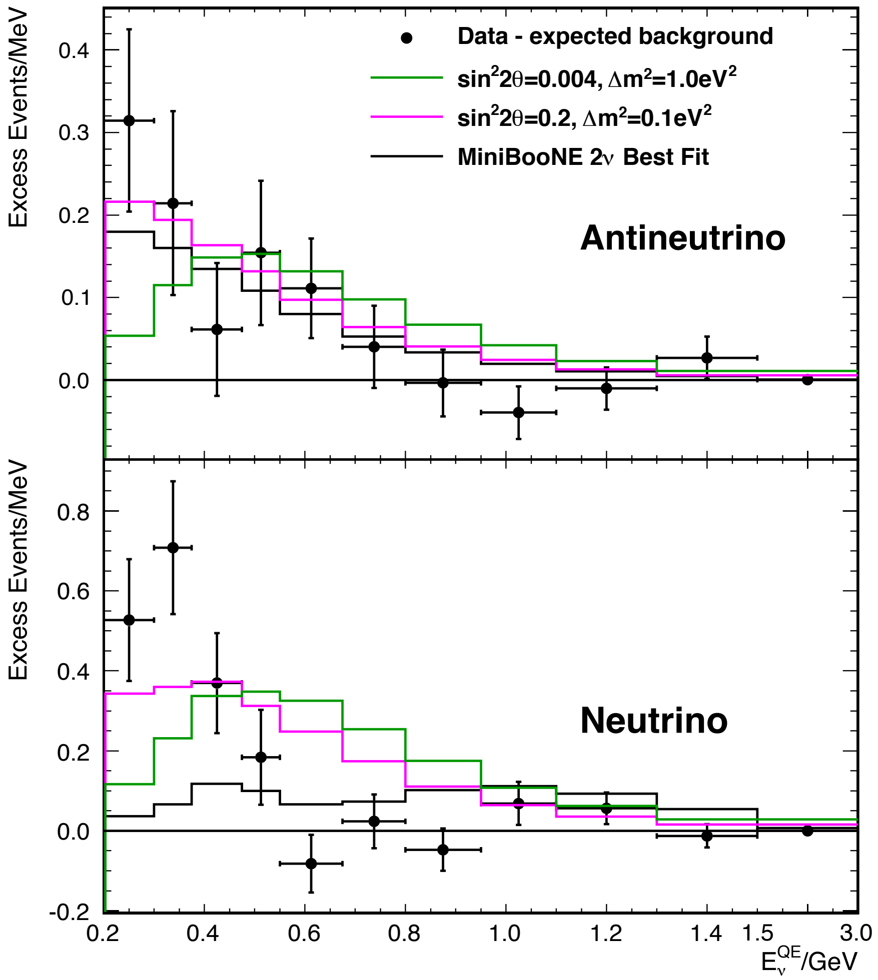
MiniBooNE Experiment



- Similar L/E as LSND for $\bar{\nu}_\mu \to \bar{\nu}_e$ & $\nu_\mu \to \nu_e$ oscillations
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)



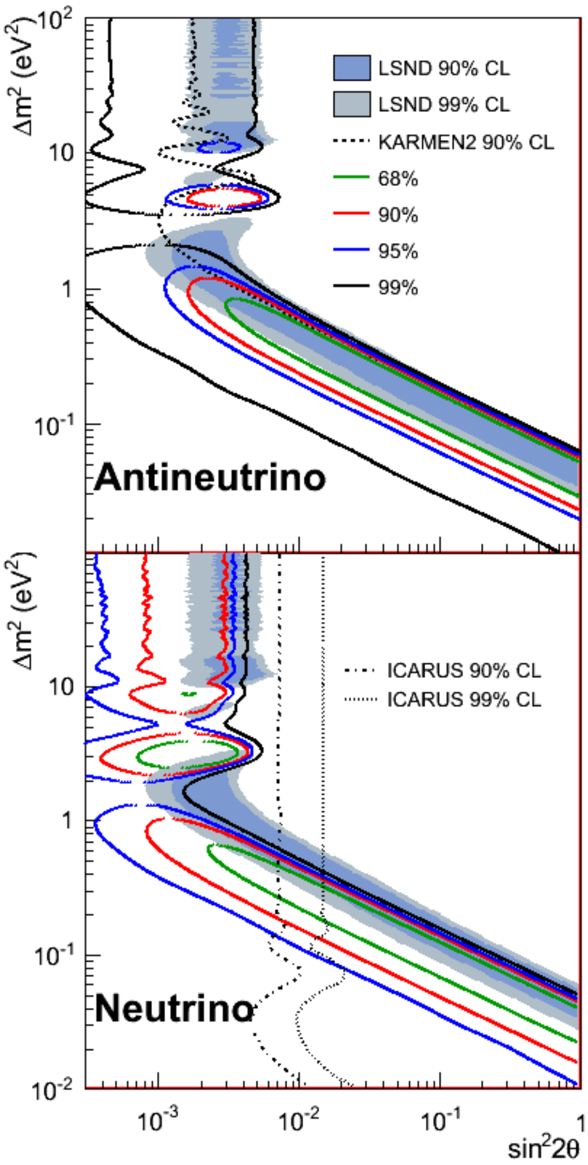
Antineutrino Event Excess from 200-1250 MeV = 78.4+-20.0+-20.3 (2.8σ)

Neutrino Event Excess from 200-1250 MeV = 162.0+-28.1+-38.7 (3.4σ)

Combined Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)

2ν Fits to MiniBooNE ν Oscillation Data

Phys. Rev. Lett. 110, 161801 (2013)



Antineutrino

$P_{bf} = 66\%$, $P_{null} = 5.4\%$

P_{null} relative to $P_{bf} = 0.5\%$

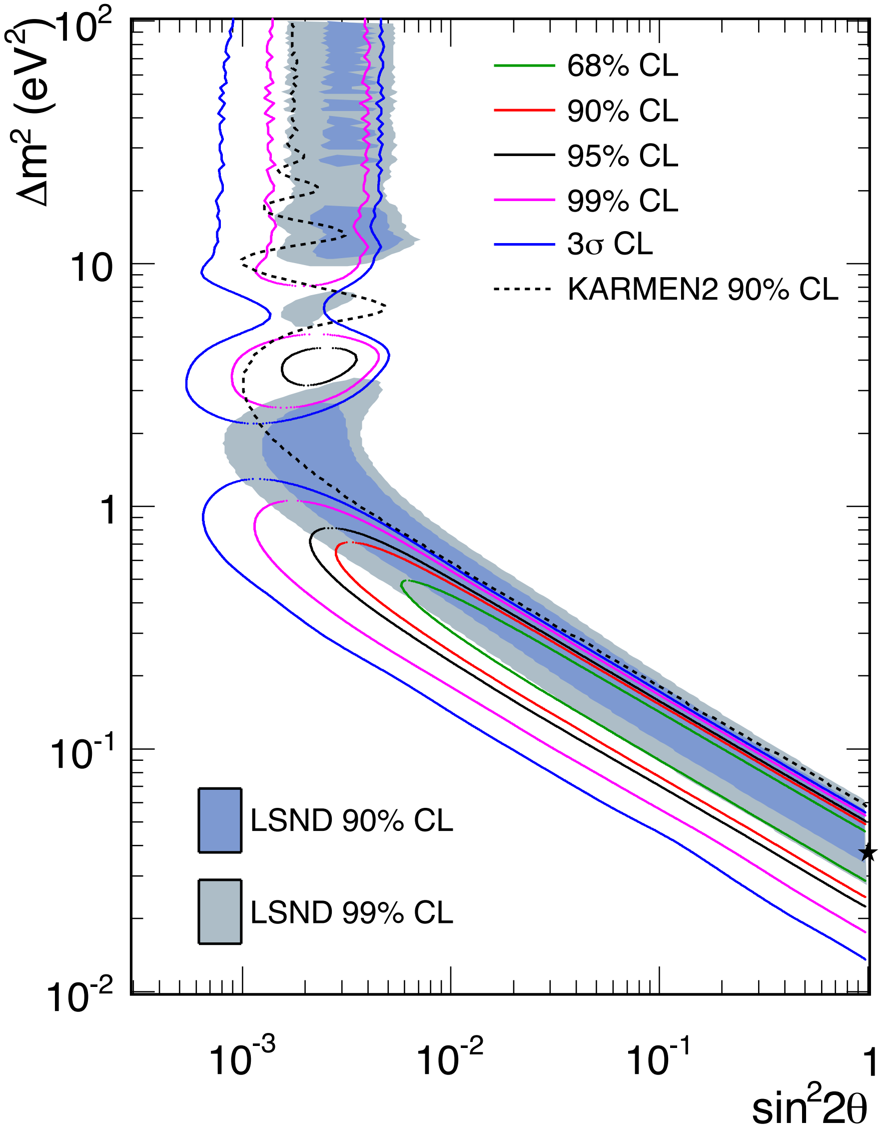
Neutrino

$P_{bf} = 6.1\%$, $P_{null} = 0.5\%$

P_{null} relative to $P_{bf} = 2.0\%$

Caveats Associated with MiniBooNE Combined Neutrino + Antineutrino 2ν Fit

arXiv:1207.4809



P_{bf} = 6.7%, P_{null} = 0.1%
P_{null} relative to P_{bf} = 0.03%

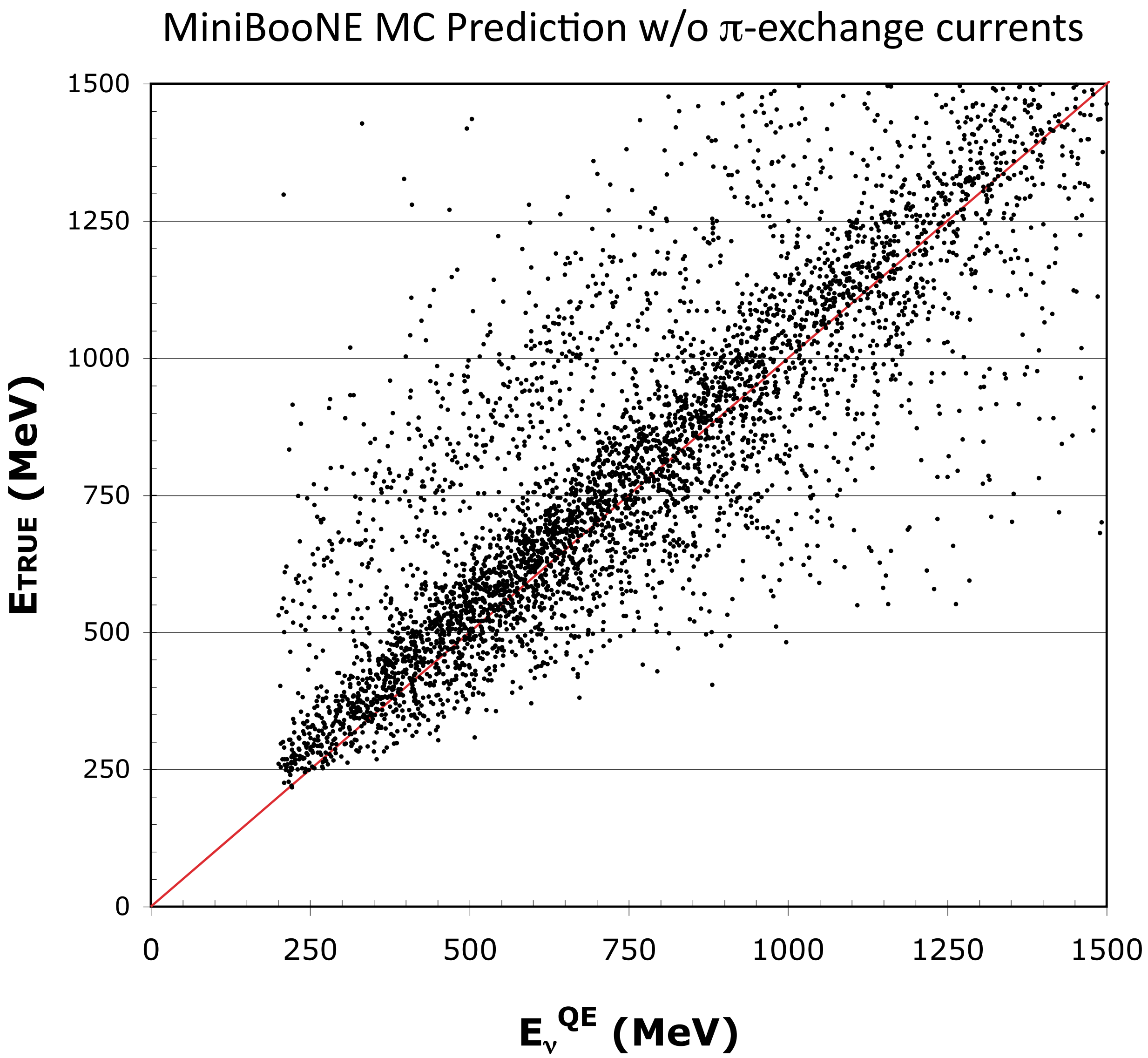
Caveats:

ν energy distortions can affect the oscillation fits:

- π exchange currents
- ν_e & ν_μ disappearance
- 3+N models with $\cancel{C}$P

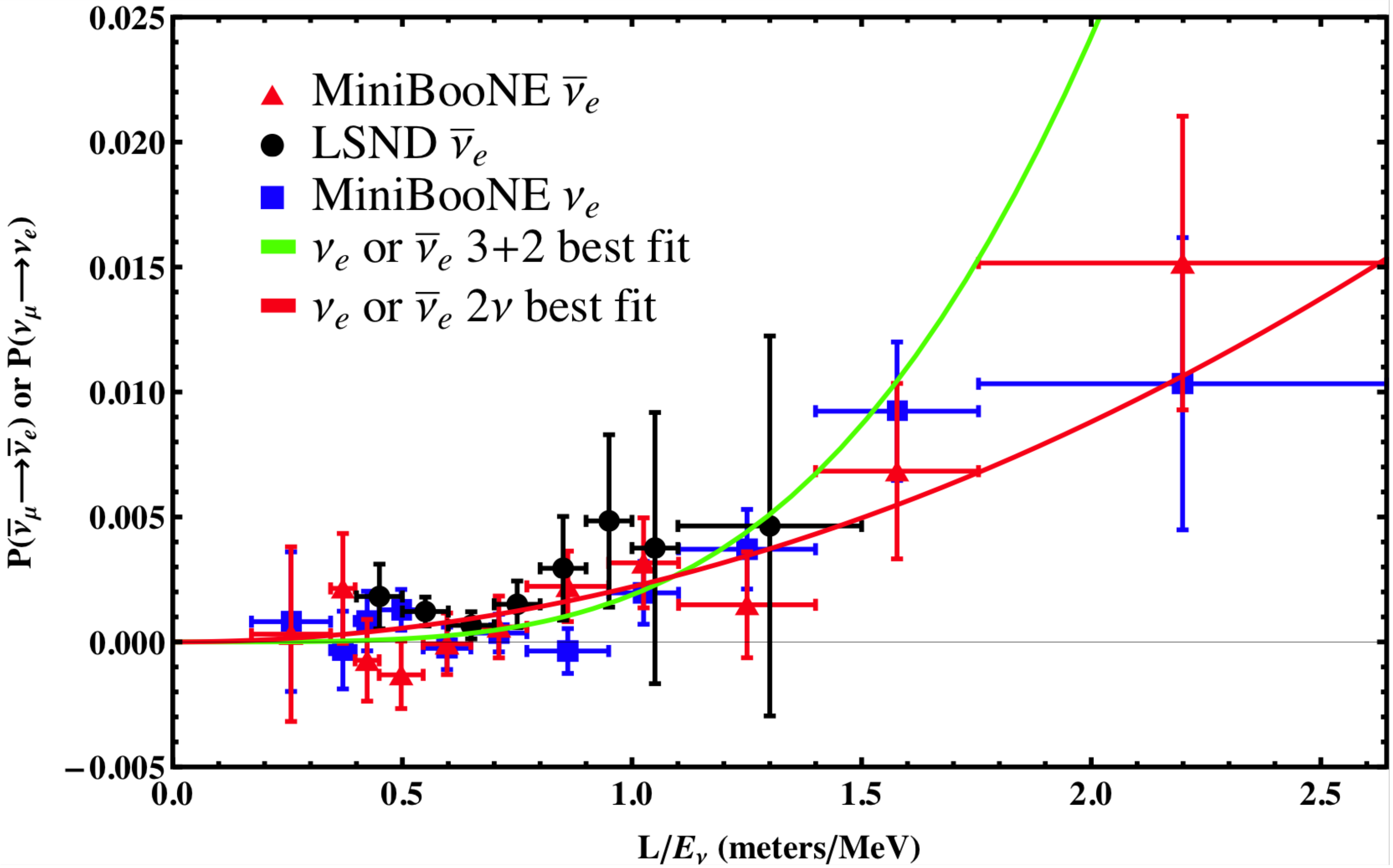
$\langle E_{true} \rangle > \langle E_{recon} \rangle$

(This Causes the Oscillation Probability to be Overestimated)



MiniBooNE L/E Distributions

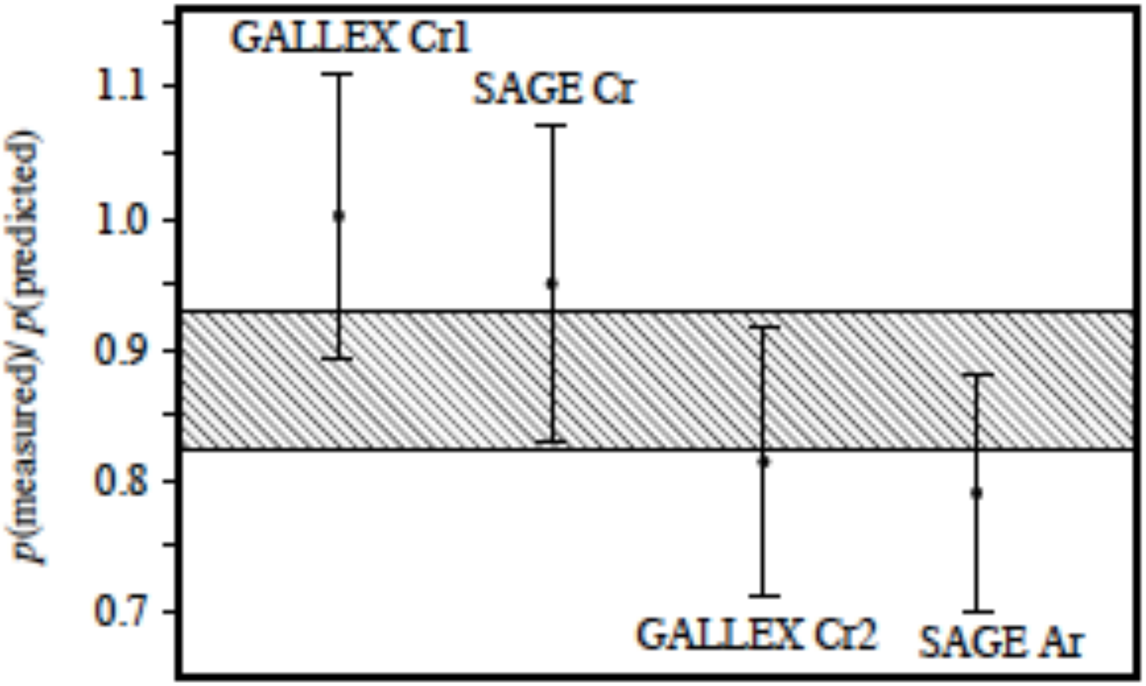
arXiv:1207.4809



Short-Baseline Anomalies from ν_e Disappearance Experiments

Gallium Anomaly

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



R=0.86+-0.05

GALLEX & SAGE observe fewer events than expected from their calibration measurements, consistent with ν_e disappearance to sterile neutrinos.

Gallium Anomaly

Giunti et al.; arXiv:1210.5715

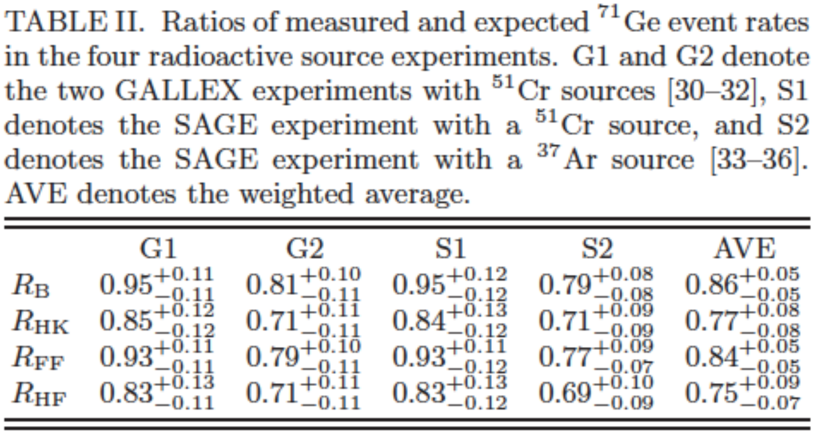
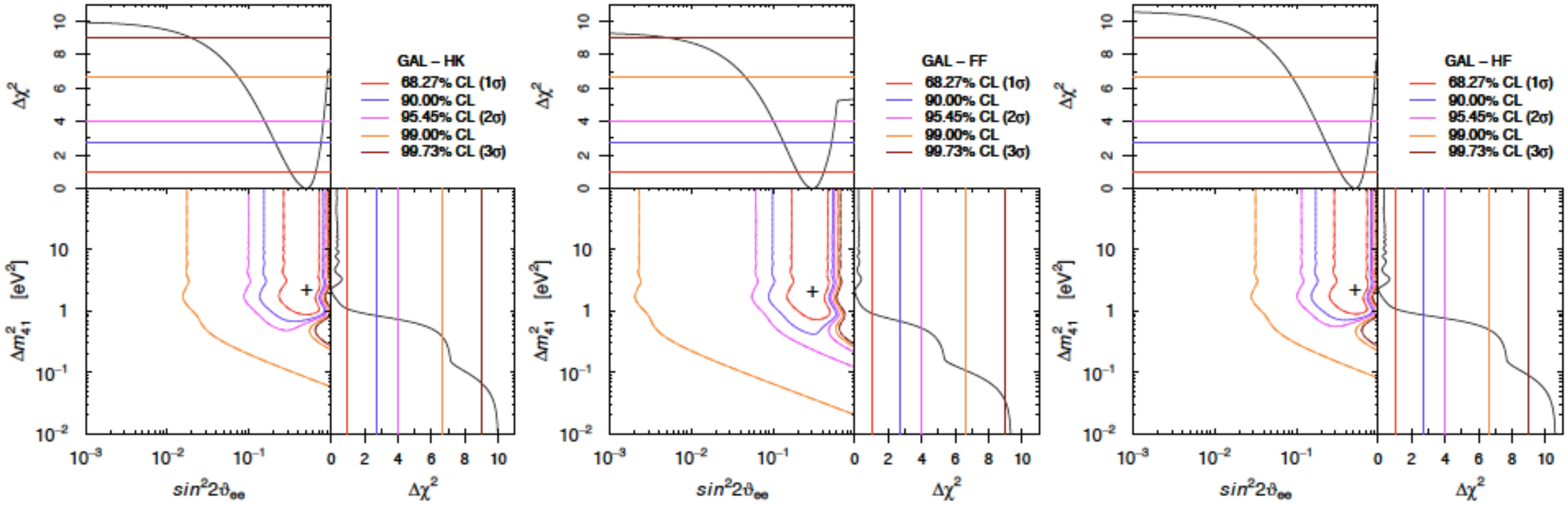


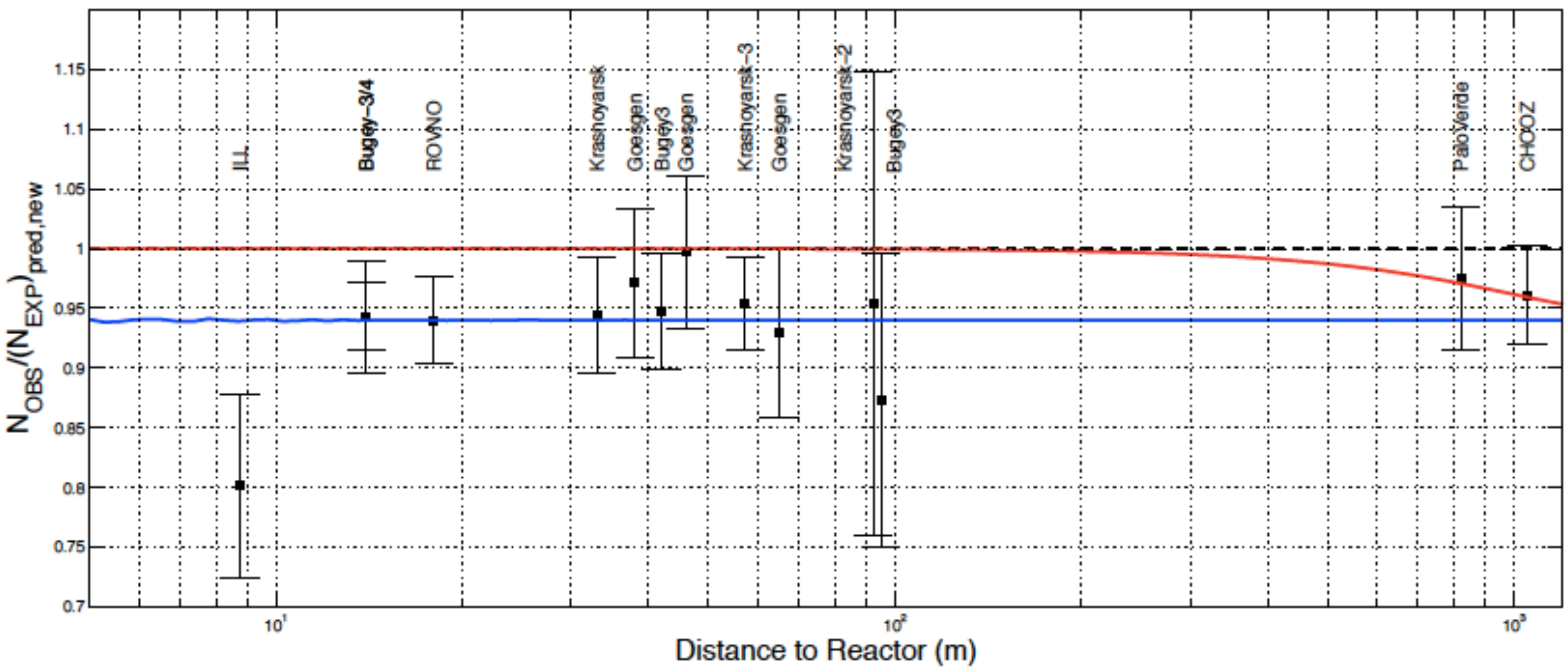
TABLE II. Ratios of measured and expected ^{71}Ge event rates in the four radioactive source experiments. G1 and G2 denote the two GALLEX experiments with ^{51}Cr sources [30–32], S1 denotes the SAGE experiment with a ^{51}Cr source, and S2 denotes the SAGE experiment with a ^{37}Ar source [33–36]. AVE denotes the weighted average.

	G1	G2	S1	S2	AVE
R_{B}	$0.95^{+0.11}_{-0.11}$	$0.81^{+0.10}_{-0.11}$	$0.95^{+0.12}_{-0.12}$	$0.79^{+0.08}_{-0.08}$	$0.86^{+0.05}_{-0.05}$
R_{HK}	$0.85^{+0.12}_{-0.12}$	$0.71^{+0.11}_{-0.11}$	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.09}_{-0.09}$	$0.77^{+0.08}_{-0.08}$
R_{FF}	$0.93^{+0.11}_{-0.11}$	$0.79^{+0.10}_{-0.11}$	$0.93^{+0.11}_{-0.12}$	$0.77^{+0.09}_{-0.07}$	$0.84^{+0.05}_{-0.05}$
R_{HF}	$0.83^{+0.13}_{-0.11}$	$0.71^{+0.11}_{-0.11}$	$0.83^{+0.13}_{-0.12}$	$0.69^{+0.10}_{-0.09}$	$0.75^{+0.09}_{-0.07}$



Reactor Neutrino Anomaly

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



R=0.937+-0.027

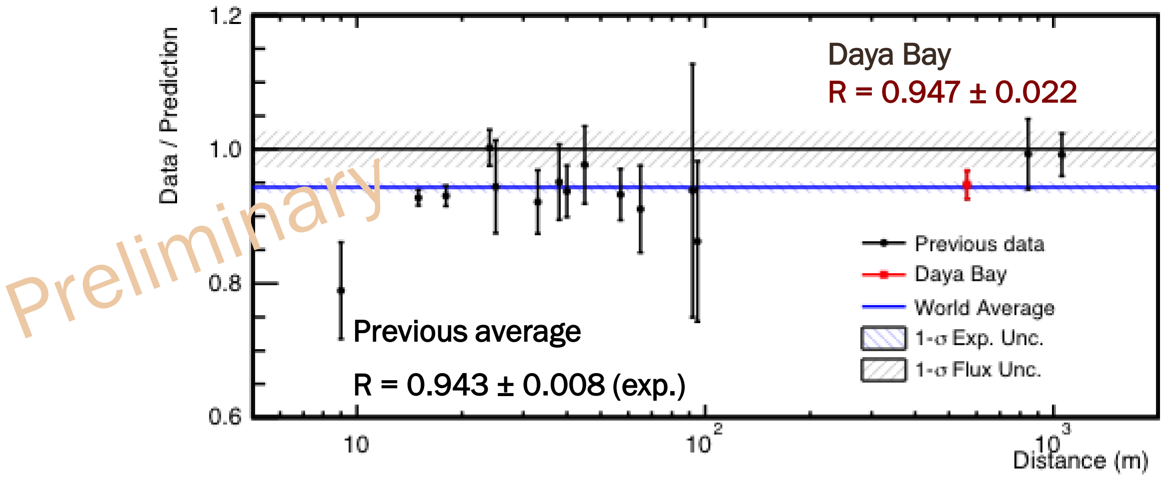
Reactor Neutrino experiments observe fewer events than expected, consistent with $\bar{\nu}_e$ disappearance to sterile neutrinos. However, the systematic errors are larger than assumed! (Hayes, Friar, Garvey, & Jonkmans, arXiv:1309.4146)

From WL Zhong Daya Bay presentation at ICHEP2014

ABSOLUTE REACTOR ANTINEUTRINO FLUX

Daya Bay's reactor antineutrino flux measurement is consistent with previous short baseline experiments.

- Global comparison of measurement and prediction (Huber+Mueller):



- Effective baseline of Daya Bay: $L_{eff} = 573$m
  - Flux weighted detector-reactor distances of 3 ADs in near sites only.
- Effective fission fractions α_k of Daya Bay ^{235}U: ^{238}U: ^{239}Pu: ^{241}Pu = 0.586: 0.076: 0.288: 0.050
  - Mean fission fractions from 3 ADs in near sites only.

Binned log-likelihood fit

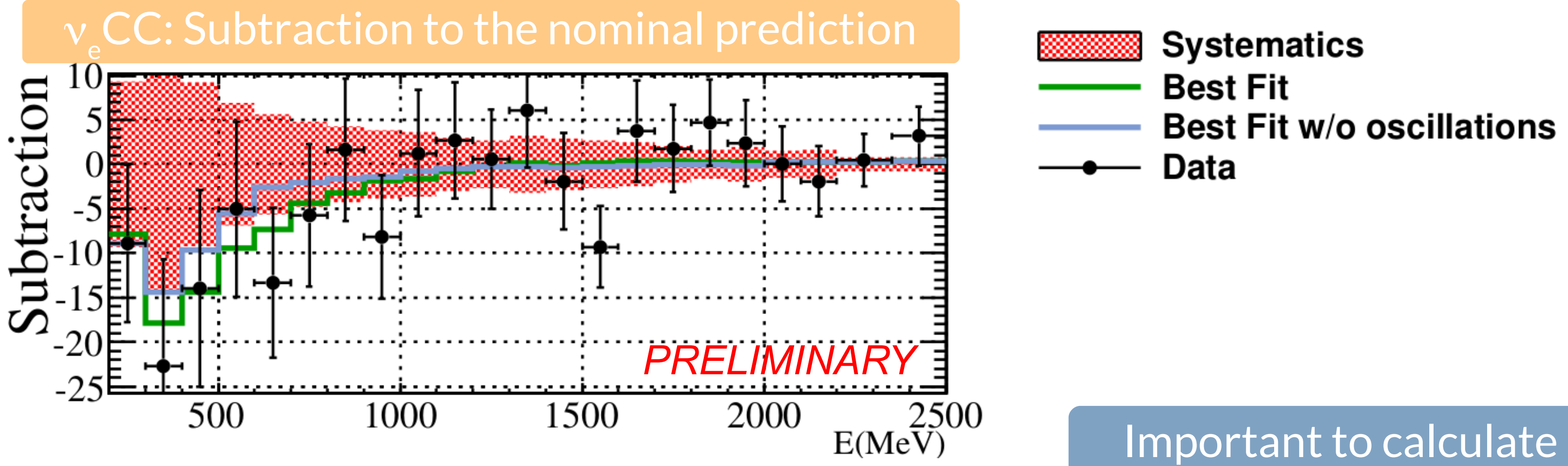
T2K **arXiv:1410.8811**

Binned log-likelihood ratio analysis

$$\chi^2 = \chi^2_{\upsilon_e} + \chi^2_{\gamma} + \mathit{penalty\ term}(\vec{f})$$

Nuisance parameters to model the systematics

ν_eCC: Subtraction to the nominal prediction



Important to calculate the significance

Best fit parameters

$$\Delta m^2_{41bf} = 2.14\,\mathrm{eV}^2$$

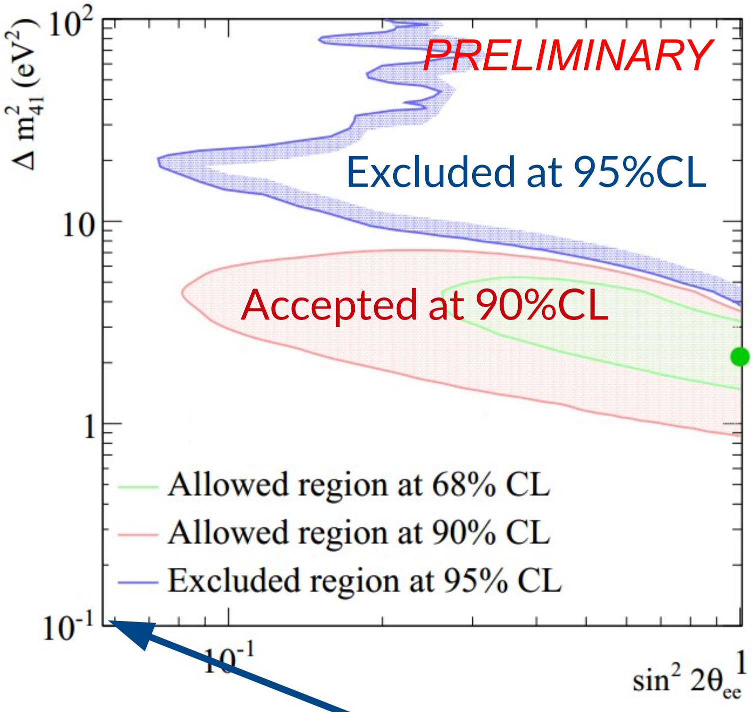
$$\sin^2(2\theta_{ee})_{bf} = 1.00$$

Confidence intervals

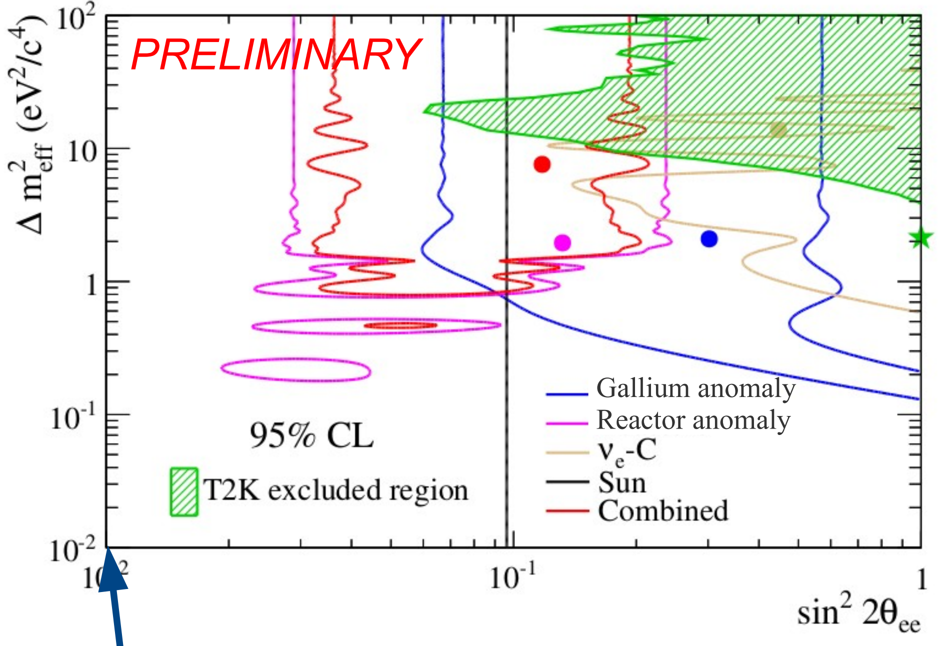
T2K **arXiv:1410.8811**

*Used the **Feldman & Cousins** method to extract the confidence contours*

ND280 results



Excluded by ND280

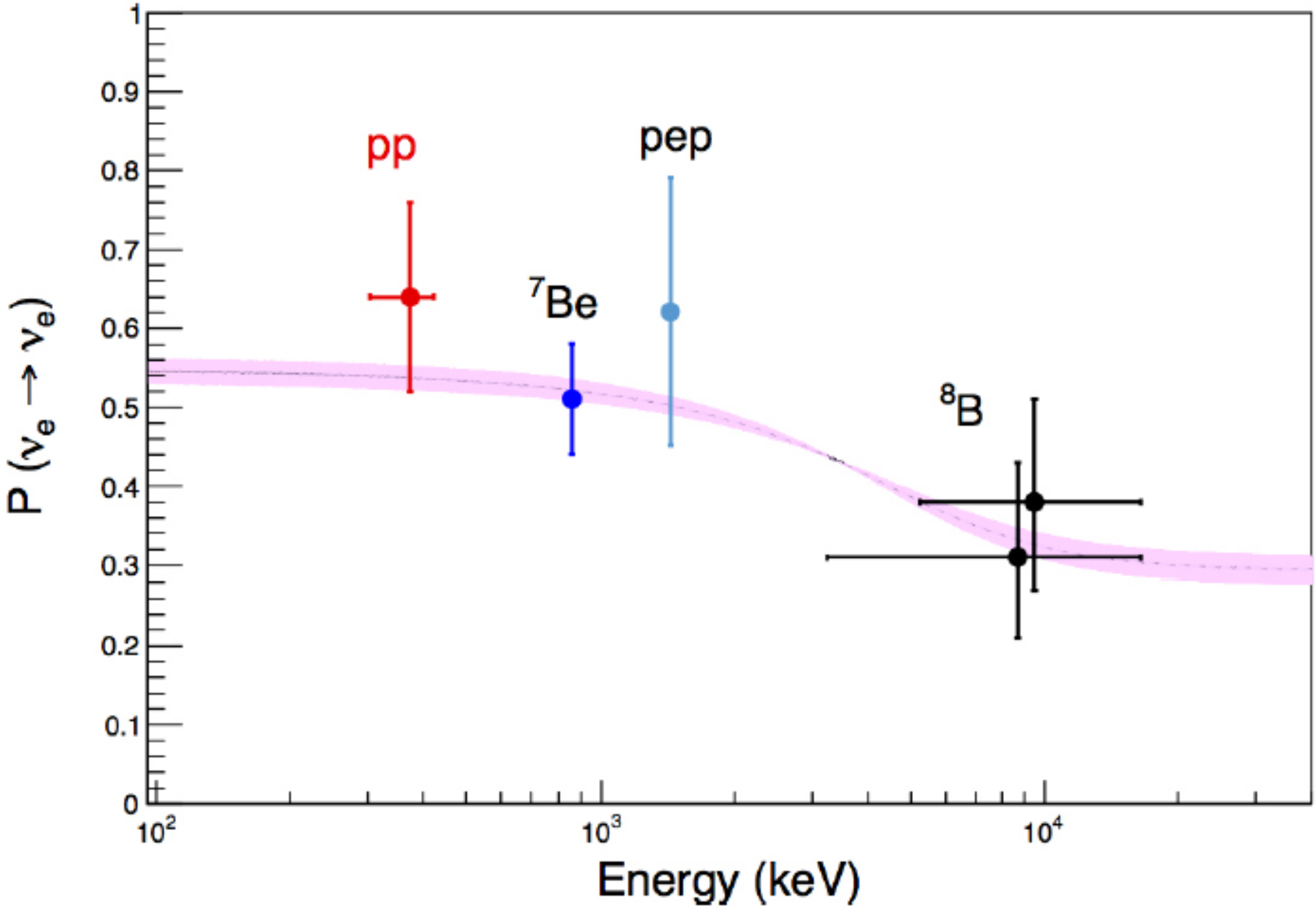


Null hypothesis excluded at ~94%CL

BOREXINO Solar Measurements

(+-19% pp errors still too large to give competitive limits)

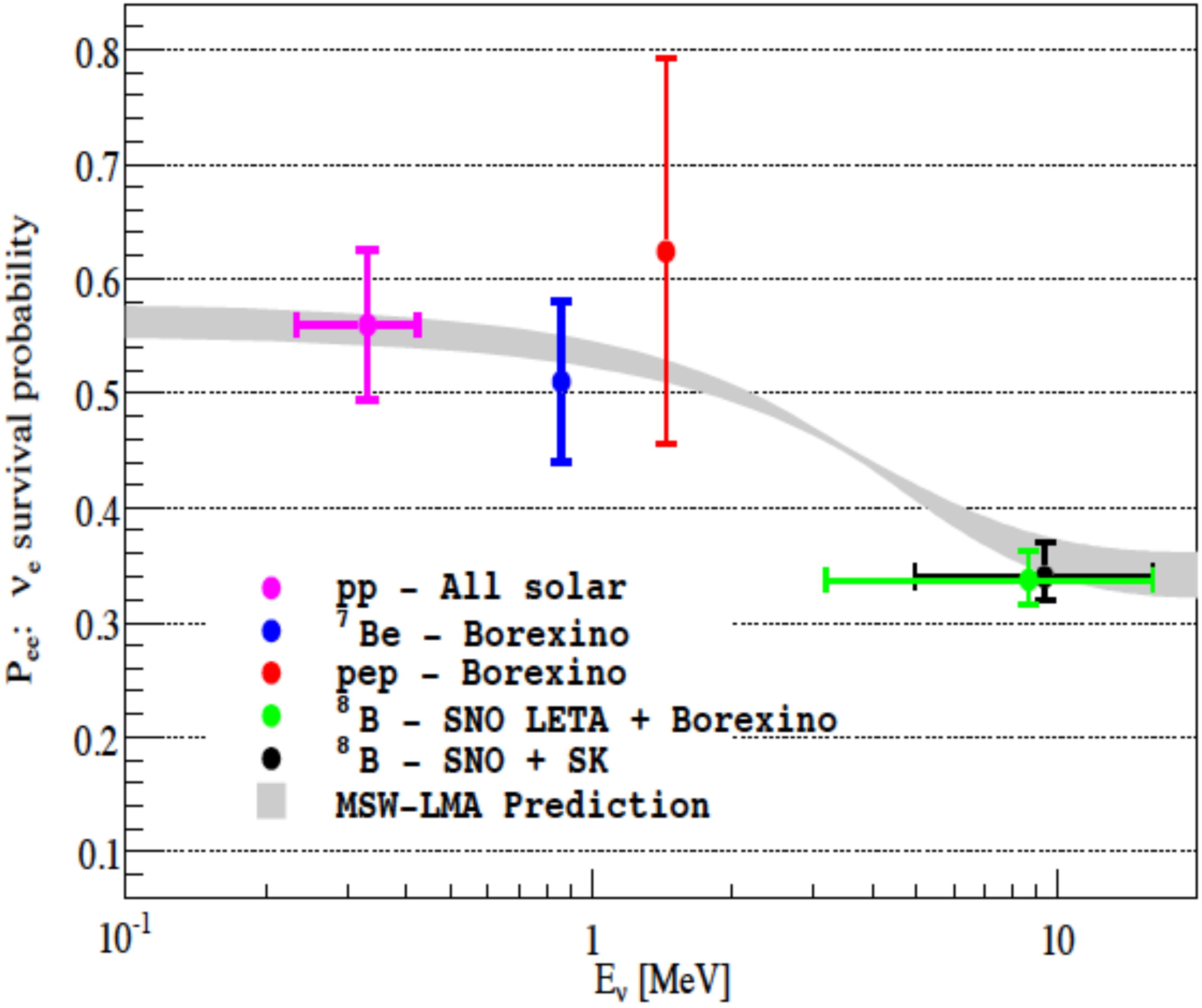
doi:10.1038/nature13702



Solar Measurements

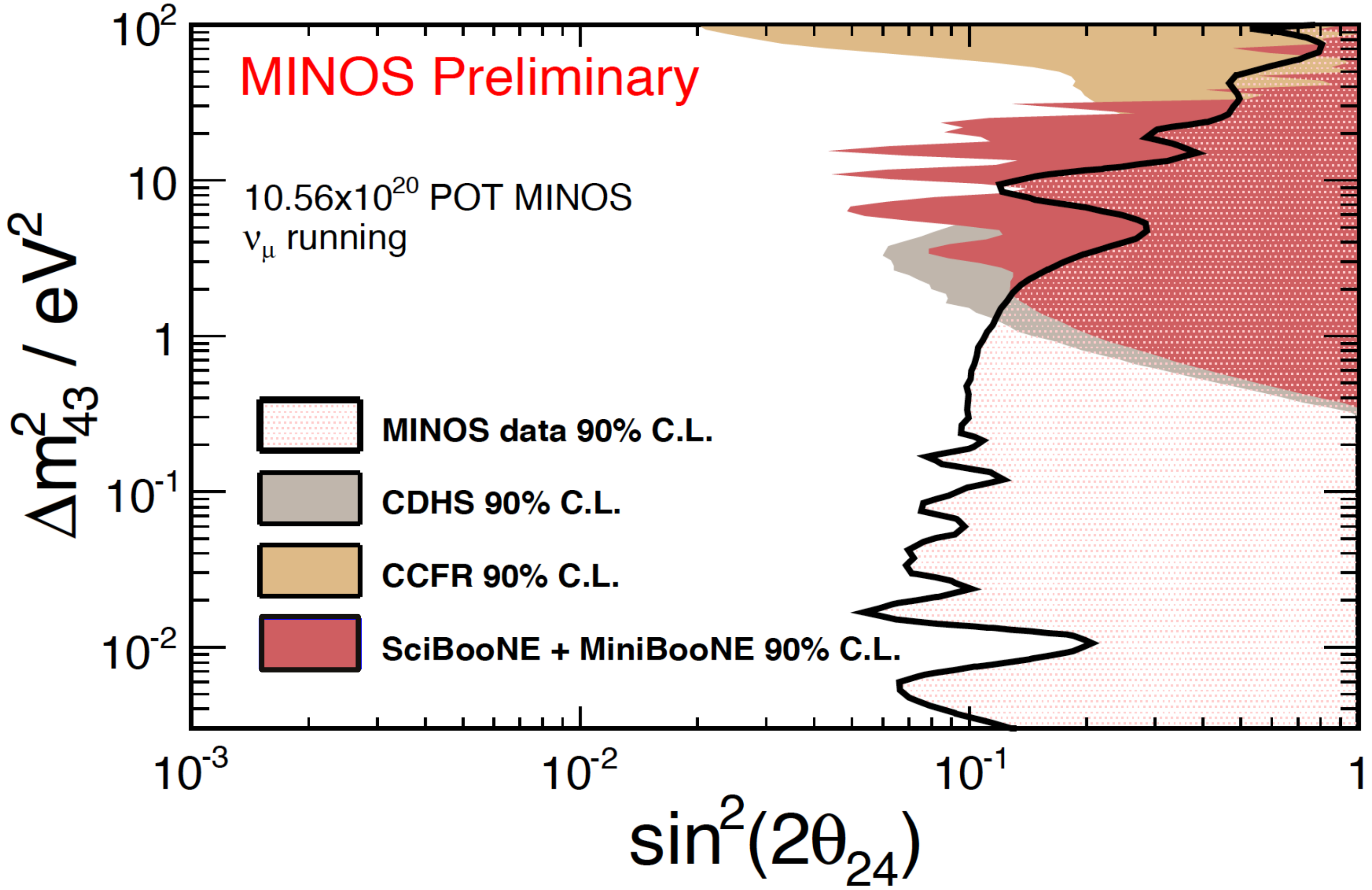
(Errors still too large to give competitive limits)

arXiv:1410.0779



Searches for ν_μ Disappearance

MINOS Disappearance Limit



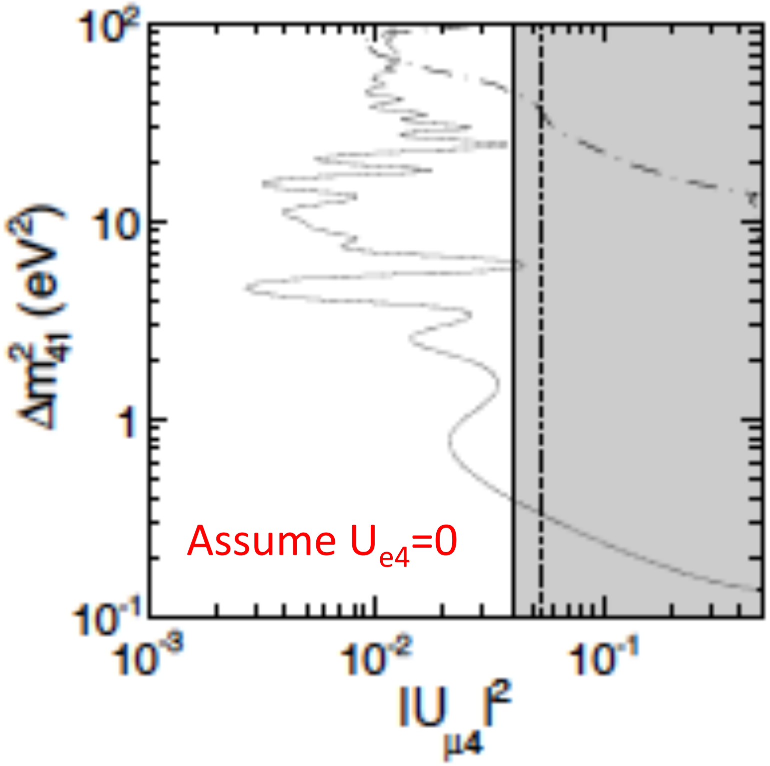
Future:
MINOS+

- Limit is Feldman-Cousins corrected

MINOS 90% C.L. exclusion limit ranges over 4 orders of magnitude in Δm^2_{43}!
Strongest constraint on ν_μ disappearance into ν_s for $\Delta m^2_{43} < 1$ eV^2

SuperK Limits on ν_μ Disappearance

arXiv:1410.2008



Assume U_{e4}=0

FIG. 7. The 90% and 99% upper limits on $|U_{\mu4}|^2$ from the sterile vacuum fit to Super-K is shown in the solid and dashed and vertical lines, respectively. The gray filled region is excluded at 90%. This analysis is not sensitive to Δm^2, but the experiments who also measure $|U_{\mu4}|^2$ are, so here the one-dimensional Super-K result is shown in two dimensions.The dotted line is the 90% limit placed by the joint analysis of MiniBooNE and SciBooNE [35] and the dot-dash line is the 90% limit placed by the CCFR experiment [34].

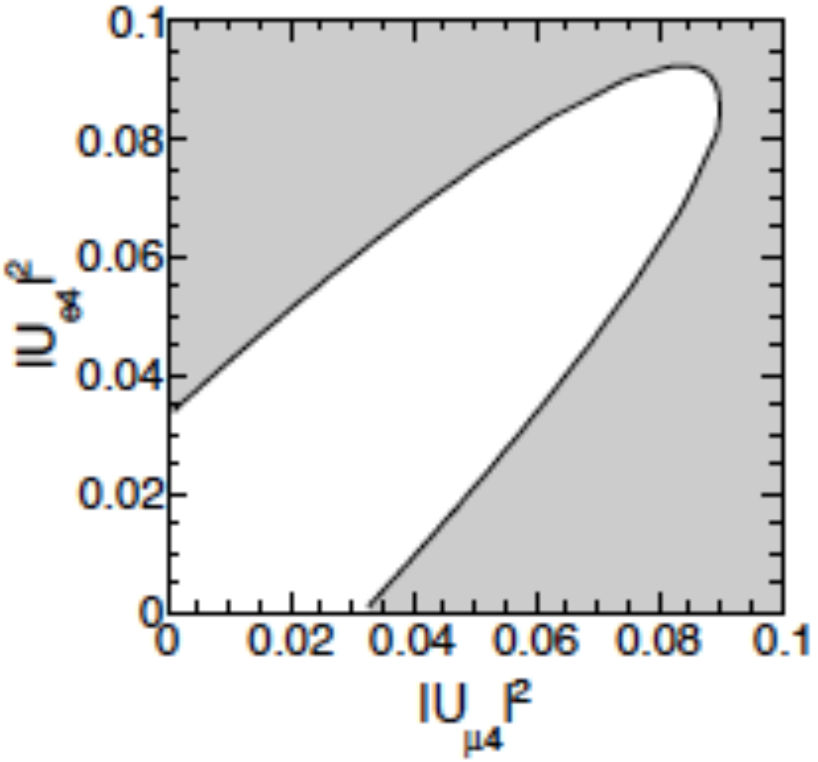
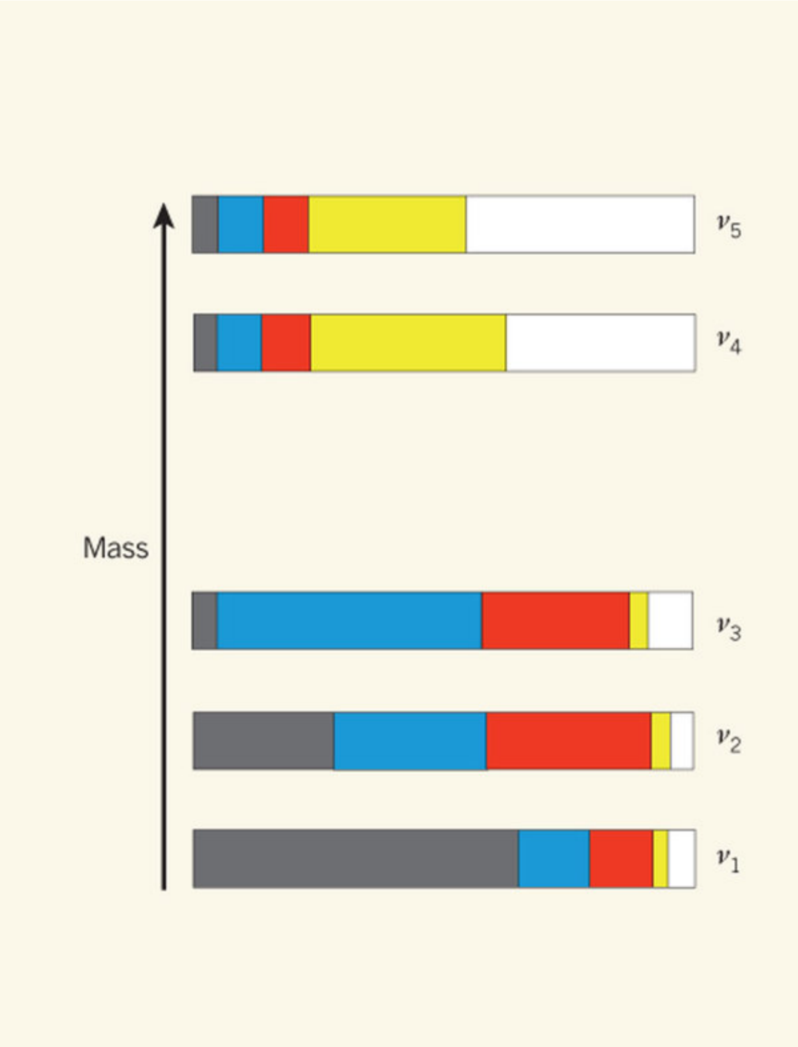


FIG. 9. The 90% sensitivity contour for the sterile vacuum fit with the effect P_{ee} from Eq. (B1) included. Allowing the freedom in the electron sample normalization reduces the sensitivity to $|U_{\mu4}|^2$ as can be seen from the bowing outward on the right side of the contour. Note that on this plot $|U_{\mu4}|^2$ is shown in linear scale so the correlation with $|U_{e4}|^2$ is clear.

3+N Sterile Neutrino Models



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

Note: There are also other, more exotic possibilities

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 #ν increases, the formalism gets rapidly more complicated!

#ν	$\#\Delta m_{ij}^2$	$\#\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
4	3	6	3
5	4	10	6
6	5	15	10

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

3+N Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, $P(\bar{\nu}_\mu \to \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \to \bar{\nu}_x) P(\bar{\nu}_e \to \bar{\nu}_x)$

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

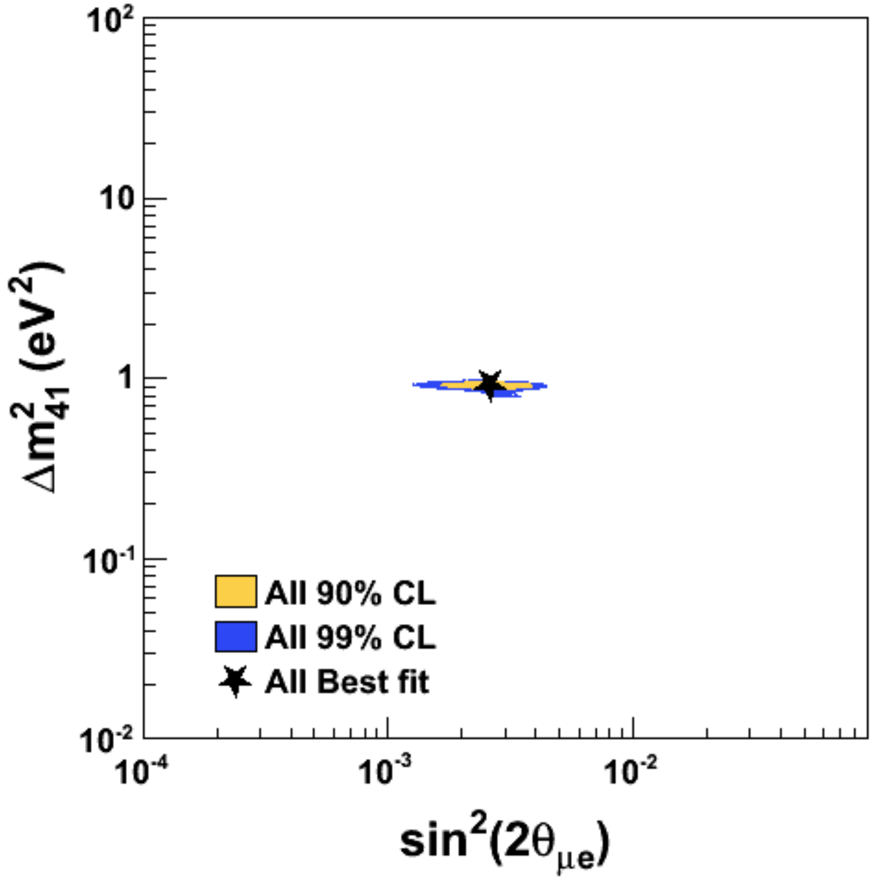
LSND/MiniBooNE: $P(\bar{\nu}_\mu \to \bar{\nu}_e) \sim 0.25\%$

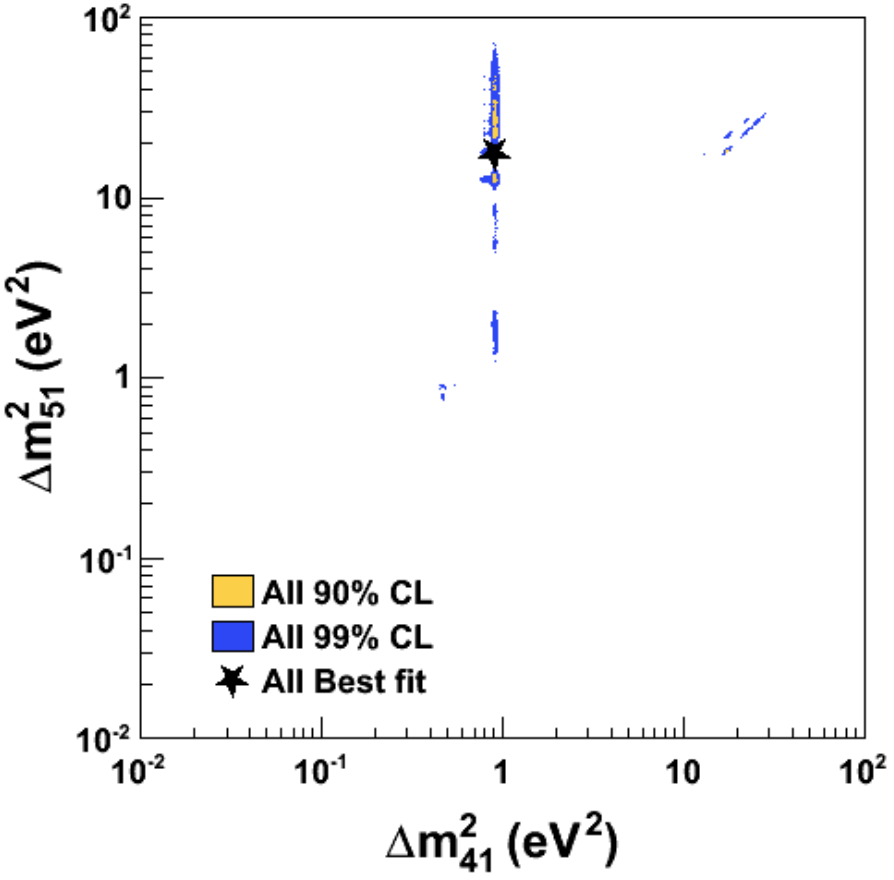
Therefore: **$P(\bar{\nu}_\mu \to \bar{\nu}_x) > 7\%$**

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

Global 3+N Fits to World Data

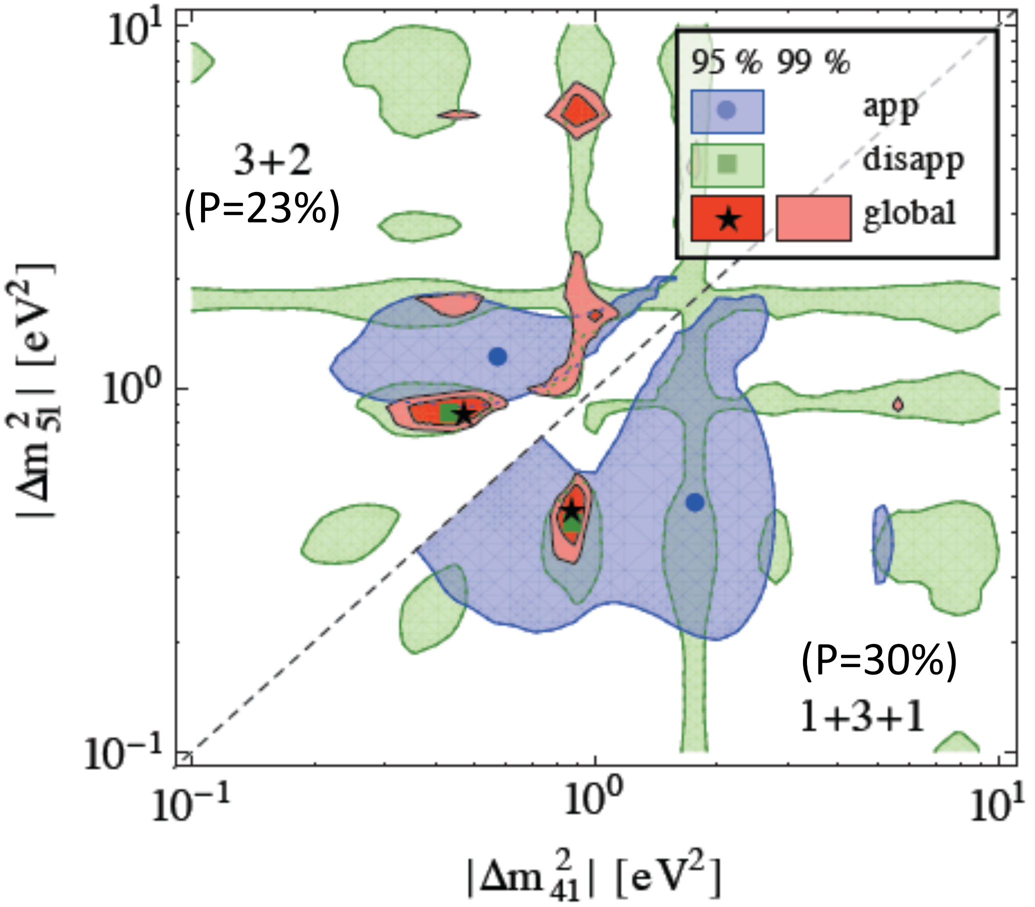
J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, & J. Spitz, arXiv:1207.4765


3+1 (P=55%)


3+2 (P=69%)

Global 3+2 & 1+3+1 Fits

Kopp, Machado, Maltoni, & Schwetz, arXiv:1303.3011



Note that there are problems associated with the Parameter Goodness of Fit (arXiv:1408.7075).

Future Short-Baseline ν Experiments

- There is a diverse set of experiments, spanning vastly different energy Scales (from ~1 MeV to ~10 TeV), that have been proposed to test the 3+N models & resolve the present anomalies:

- Accelerator ν Experiments: MicroBooNE+LAr1+ICARUS, MINOS+, NuStorm , LBNE, OscSNS at ORNL/J-PARC, IsoDAR, nuPRISM

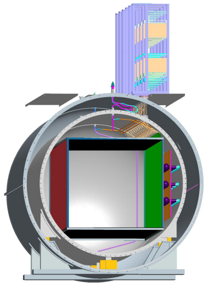
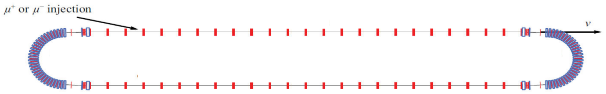
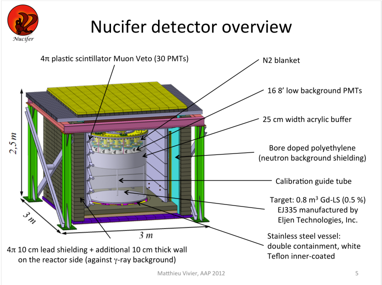


Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.



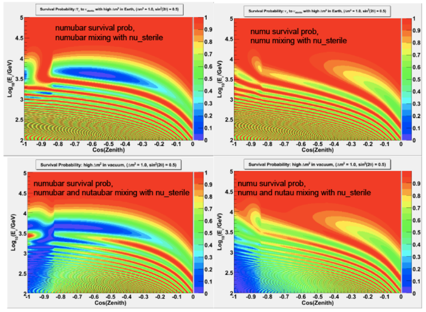


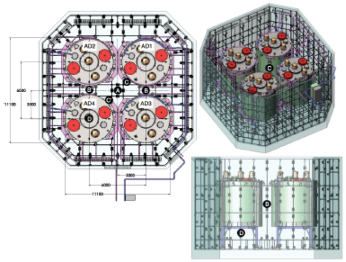
Nucifer detector overview

Matthieu Vivier, AAP 2012 5

- Reactor ν Experiments: SCRAAM, NUCIFER, PROSPECT

- Radioactive Source ν Experiments: BOREXINO-SOX, KamLAND, Daya Bay, Baksan, LENS





- Atmospheric ν Experiments: IceCube

A Staged Multi-LAr TPC Short-Baseline Program

Existing enclosure vacated by SciBooNE detector

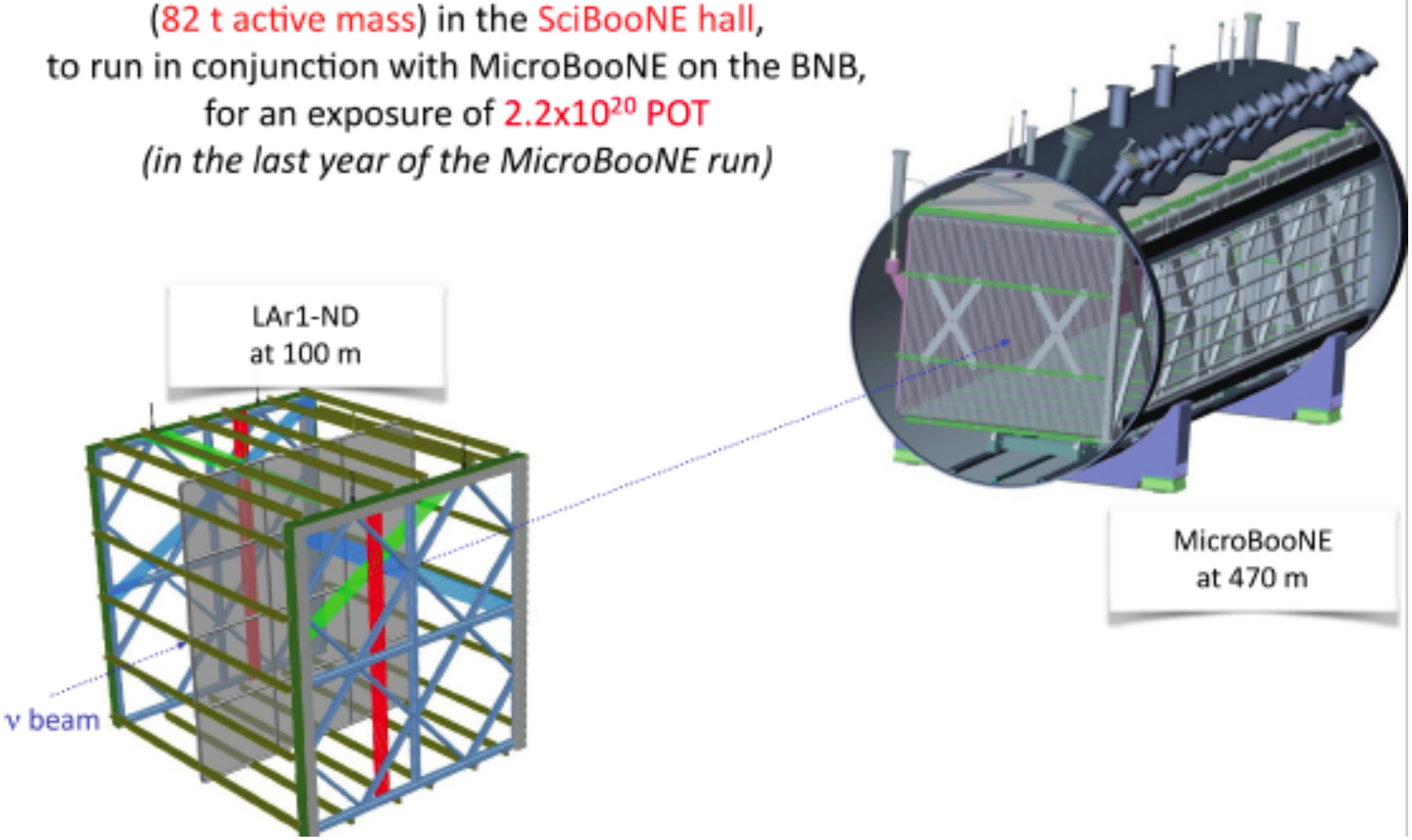
Phase 0: MicroBooNE
86 t active volume TPC
L = 470 m
start in 2014

Phase 1: LAr1-ND
82 t active volume TPC
L = 100 m
2017-2018

Phase 2: LAr1-FD
1000 t active volume TPC
L = 700 m
2020+

Summary of the LAr1-ND Proposal

A LArTPC Near Detector
(82 t active mass) in the SciBooNE hall,
to run in conjunction with MicroBooNE on the BNB,
for an exposure of 2.2x10^{20} POT
(in the last year of the MicroBooNE run)

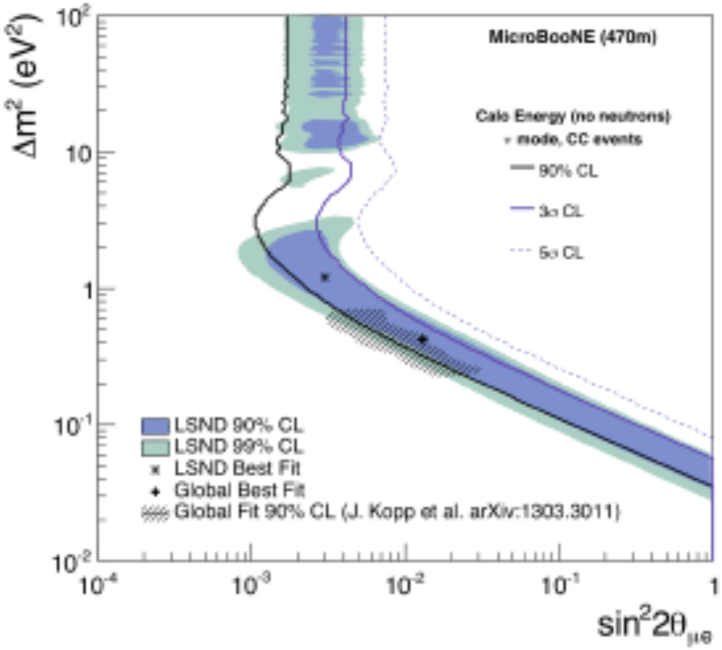


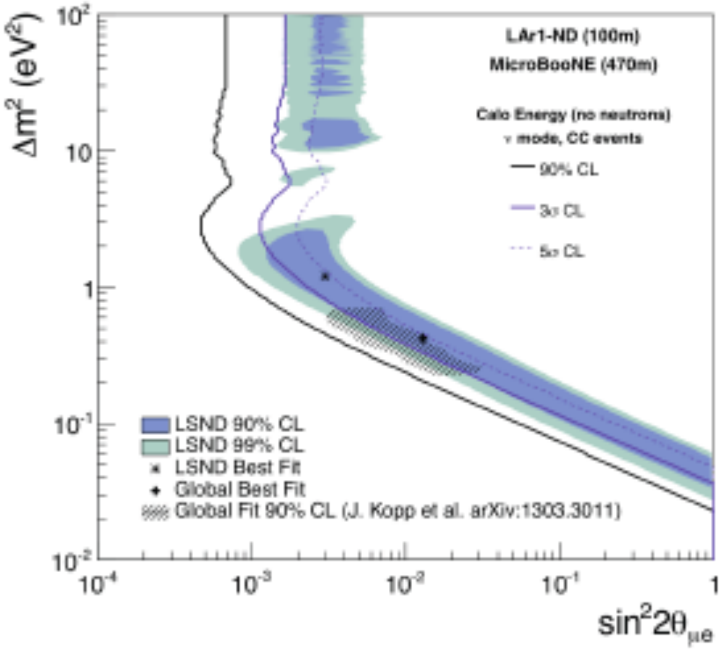
ν_μ –> ν_e Appearance

6.6x10^{20} POT exposure for MicroBooNE alone, assuming 20% systematic uncertainties on ν_e background prediction

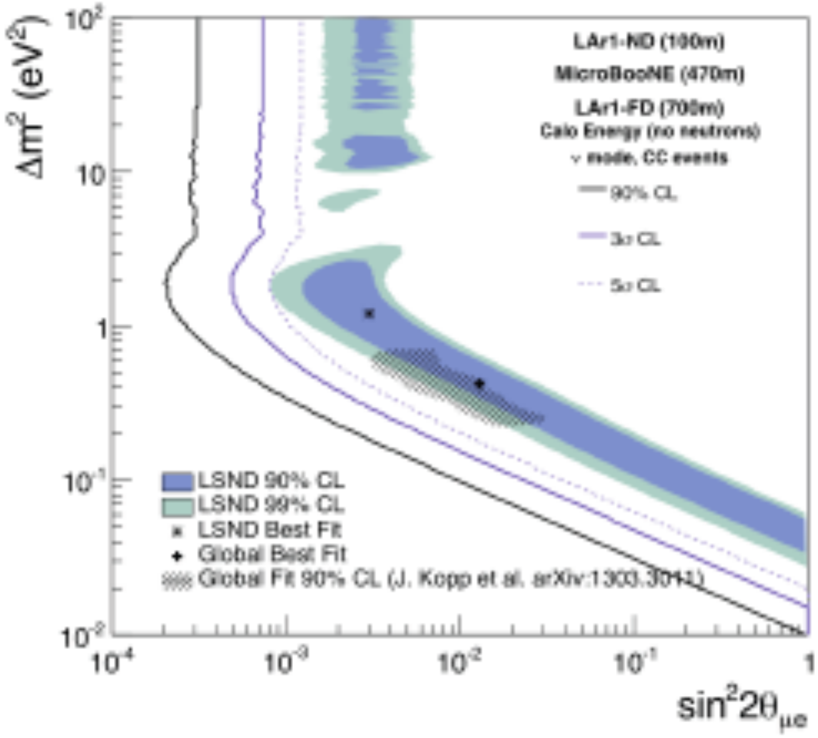
+ND

Same MicroBooNE exposure + 2.2x10^{20} POT exposure for LAr1-ND to constrain background prediction



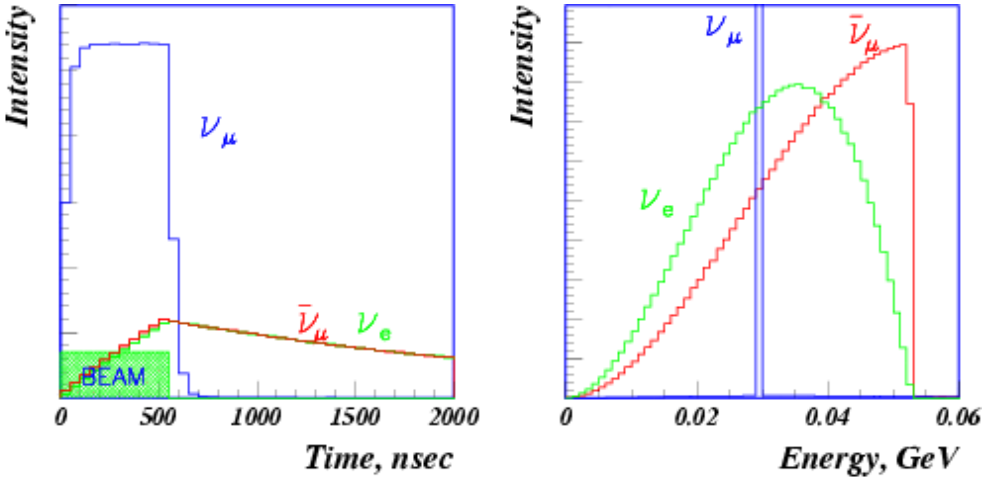


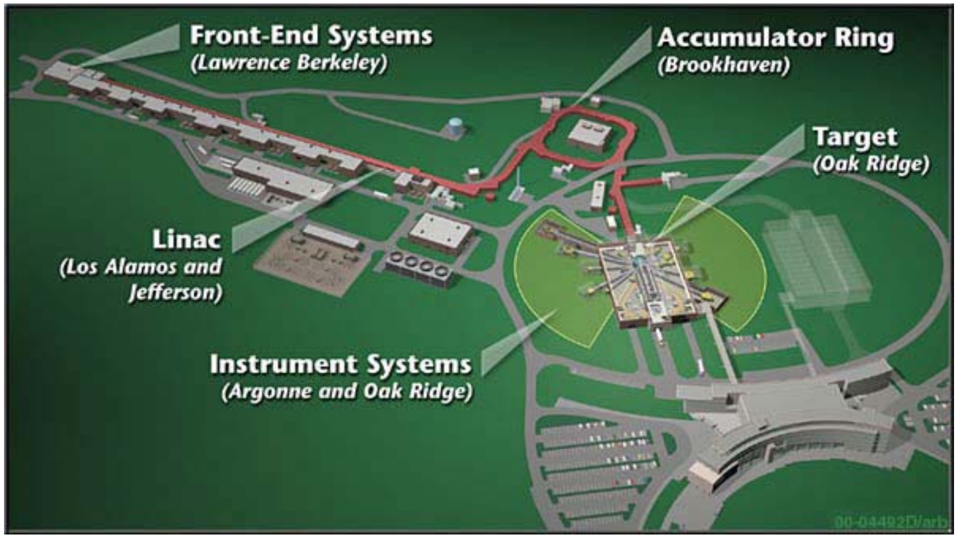
The Full LAr1 Short-Baseline Neutrino Program with LAr1-FD

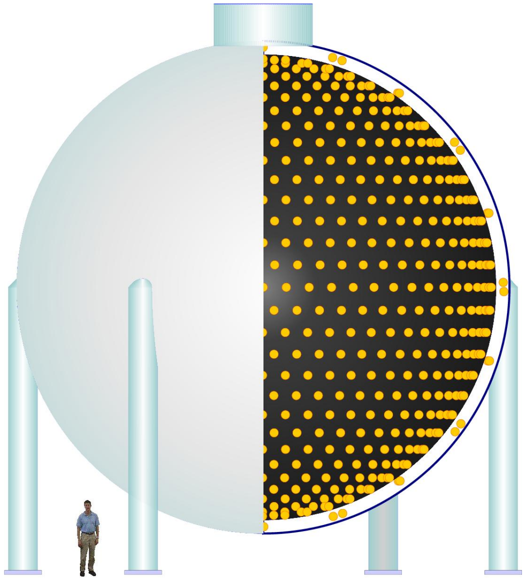


OscSNS (arXiv:1307.7097)

- Spallation neutron source at ORNL
- ~1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos

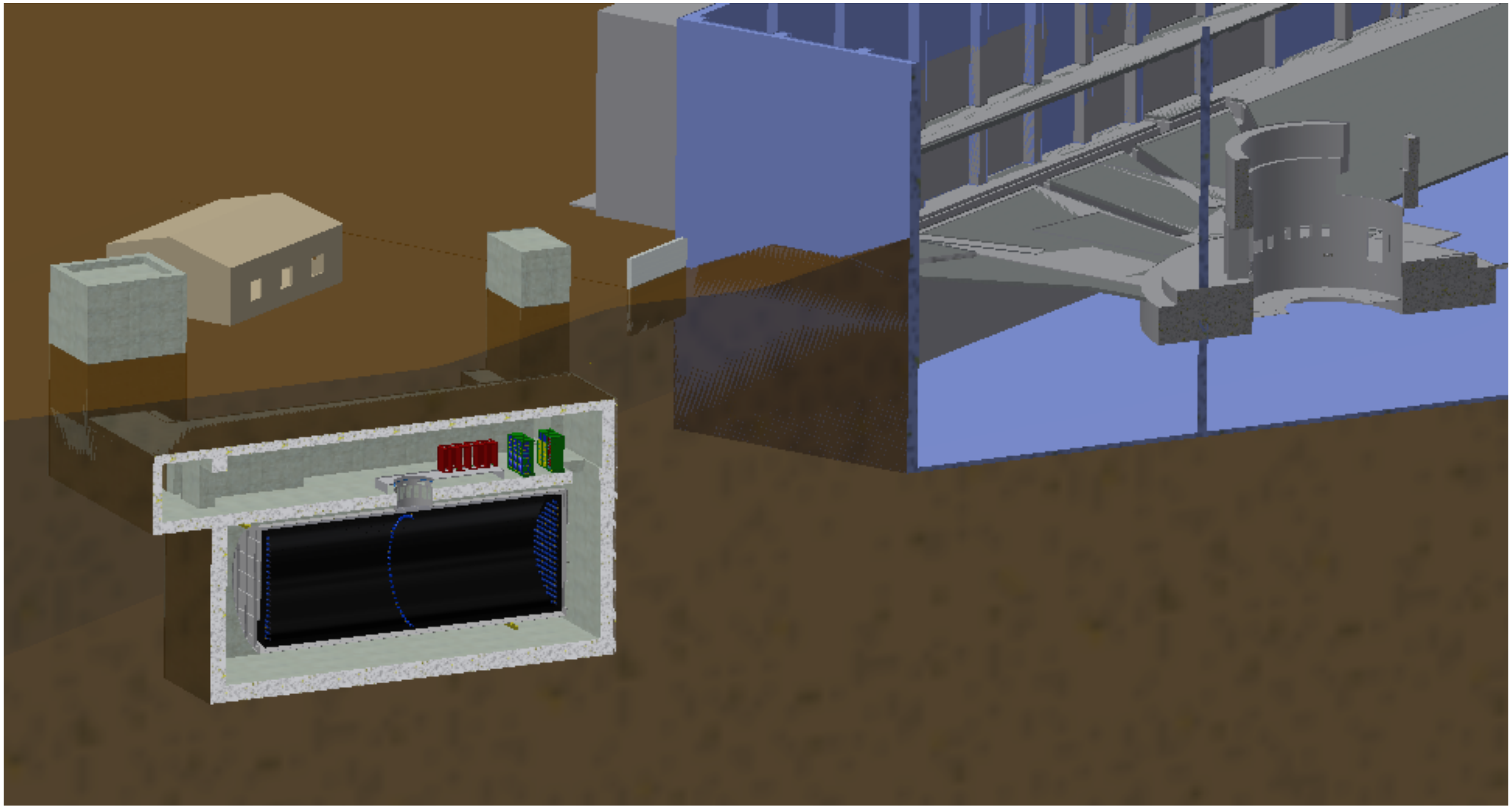






Photograph of OscSNS Location

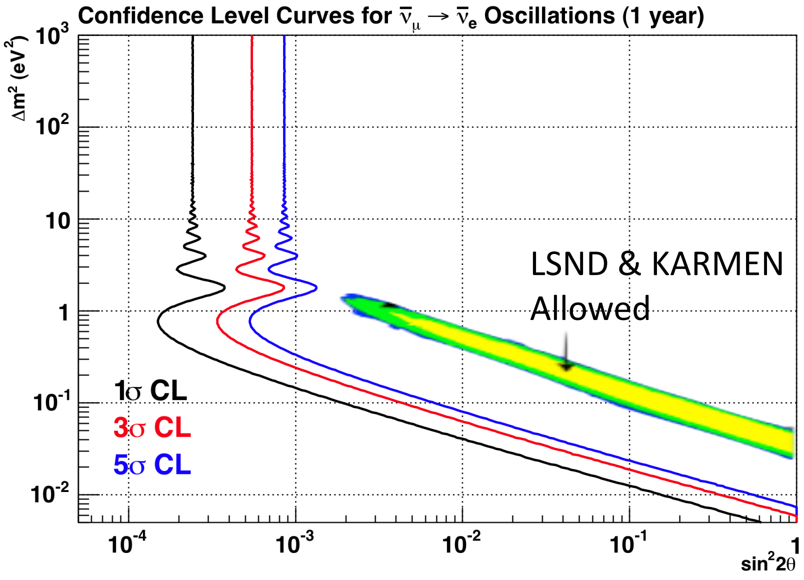
Schematic Drawing of OscSNS Detector

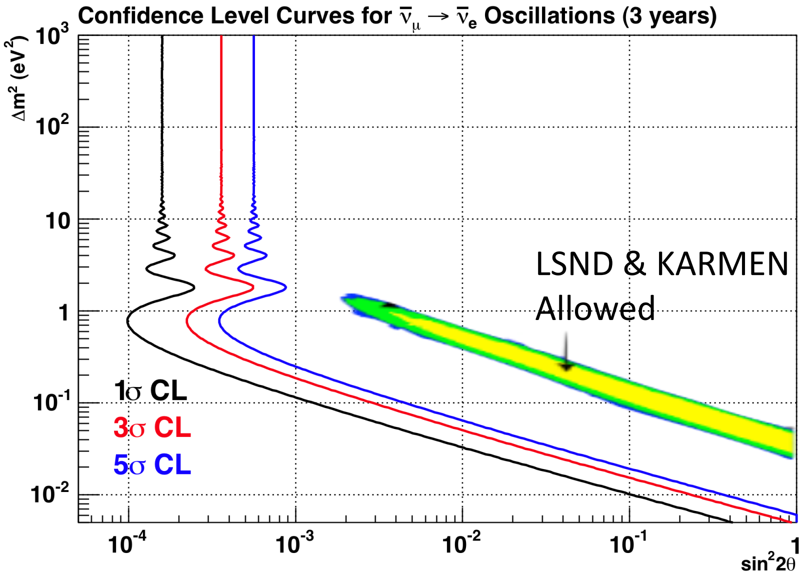


$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ Appearance

$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ appearance sensitivity for 2 & 6 years of running:

$\bar{\nu}_e$ p -> e^+ n; n p -> d γ (2.2 MeV)





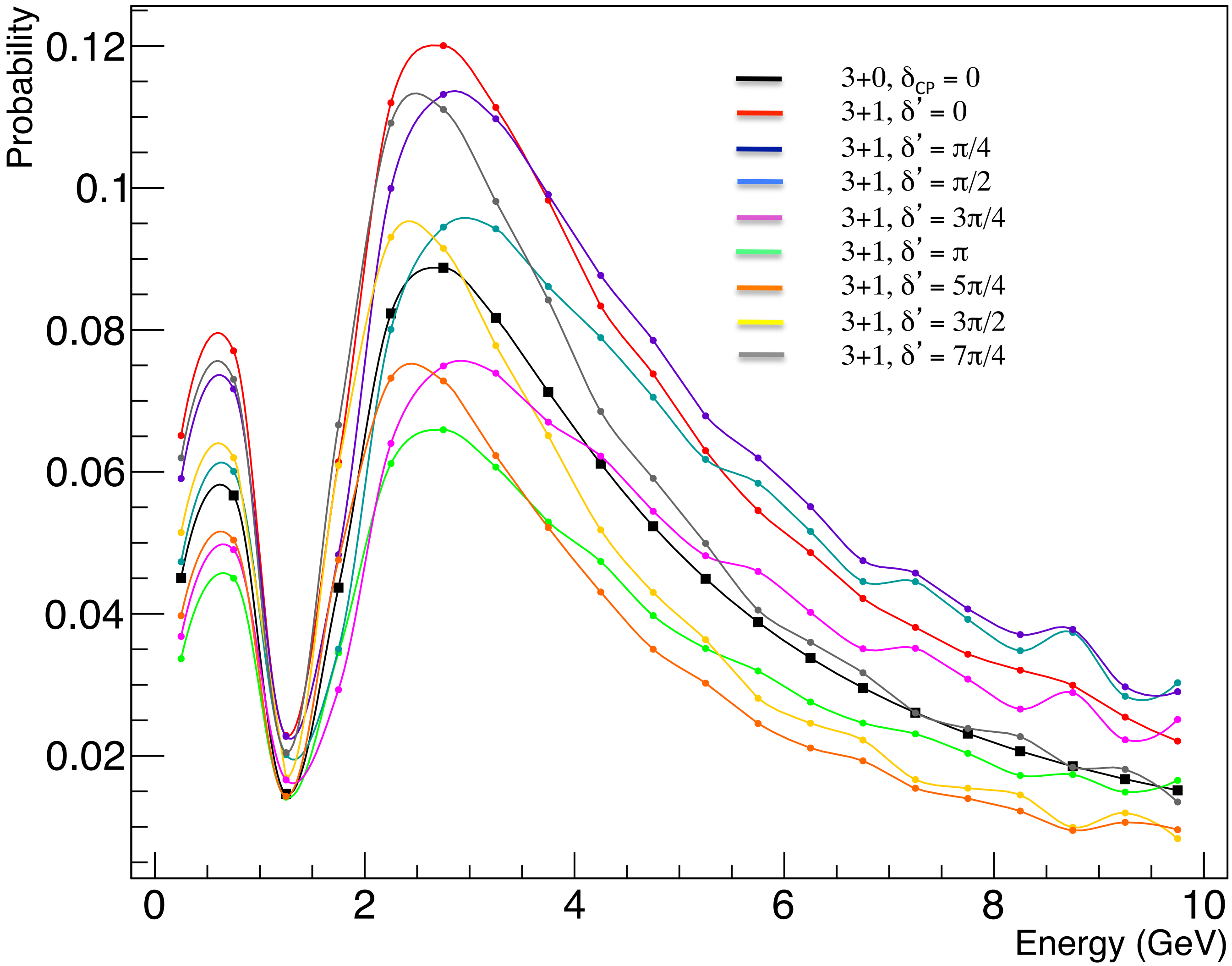
OscSNS does not have bias in the neutrino energy reconstruction and has less dependence on ν_e and ν_μ disappearance than other experiments!

Conclusion

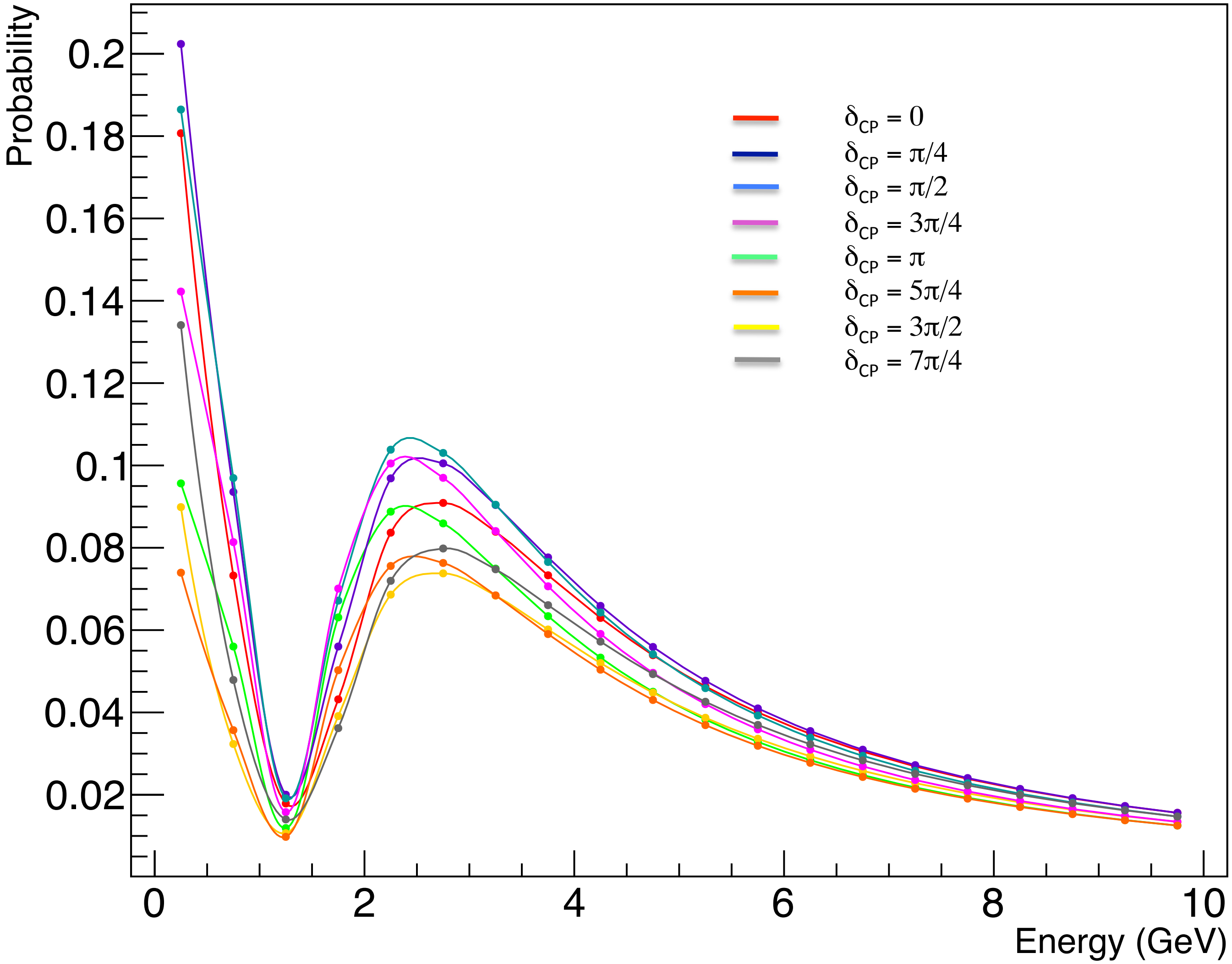
- The anomalies in short baseline ν experiments cannot be explained by the 3 ν paradigm and suggest the existence of sterile ν (although there are other, more exotic possibilities).
- Sterile ν would contribute to the dark matter of the universe and would have a big impact on particle physics, nuclear physics, astrophysics and cosmology.
- The world neutrino & antineutrino data can be fit fairly well to a 3+N oscillation model, although there is some tension between appearance and disappearance experiments.
- Short-baseline neutrino oscillations can also affect long-baseline oscillations! (Due to cross terms, as discussed in arXiv:1308.5700, a measurement of $\sin^2 2\theta_{13}$ can change by up to ~20-40%.)
- Future experiments have the golden opportunity of proving whether short-baseline oscillations and light, sterile neutrinos exist!

Backup

LBNE: Δm^2_{14} = 0.45 eV^2, $\sin^2 2\theta$ = 0.0085



3-Neutrinos Only



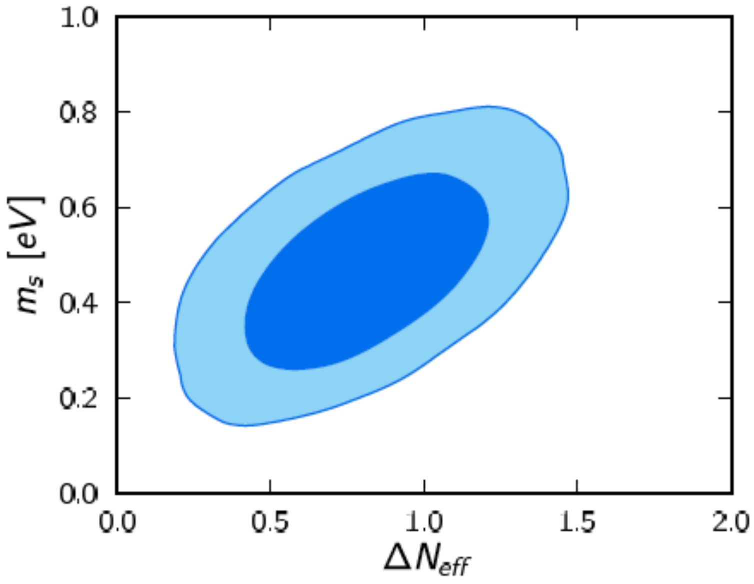
OscSNS $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ Experiment vs LSND

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

- More Detector Mass (x5)
- Higher Intensity Neutrino Source (x2)
- Lower Duty Factor (x1000) (less cosmic background)
- Separation of ν_μ & $\nu_e/\bar{\nu}_\mu$ Fluxes with timing
- Negligible DIF ν Background (backward direction)
- Lower Neutrino Background (~x2) (60m vs 30m)
- For LSND parameters, expect ~100-200 ν_e oscillation events & ~50 background events per year!

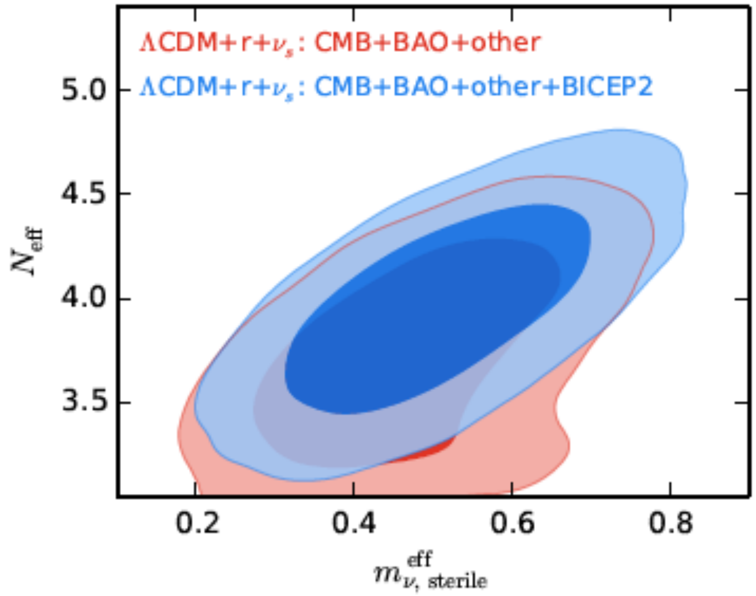
Global Cosmology Fits

Including HST H_0 measurement, galaxy cluster data, & BICEP2, the data favor nonzero ΔN_{eff} & m^{eff}_s



Dvorkin, Wyman, Rudd, & Hu, arXiv:1403.8049

$\Delta N_{eff} = 0.81 \pm 0.25$, $m^{eff}_s = 0.47 \pm 0.13$ eV

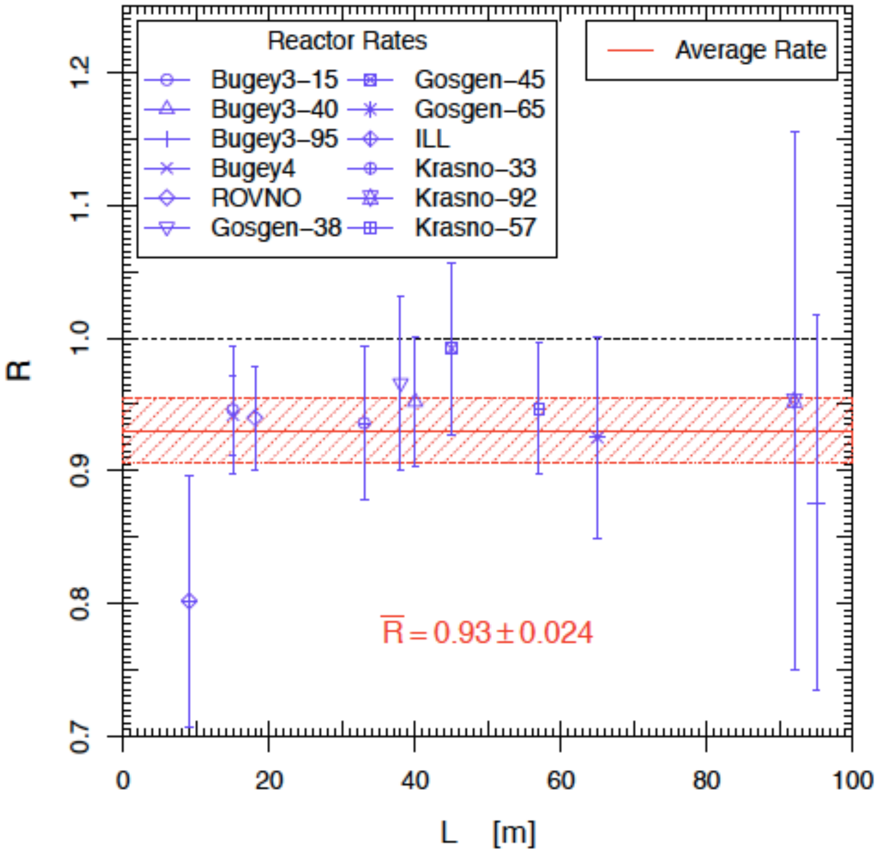


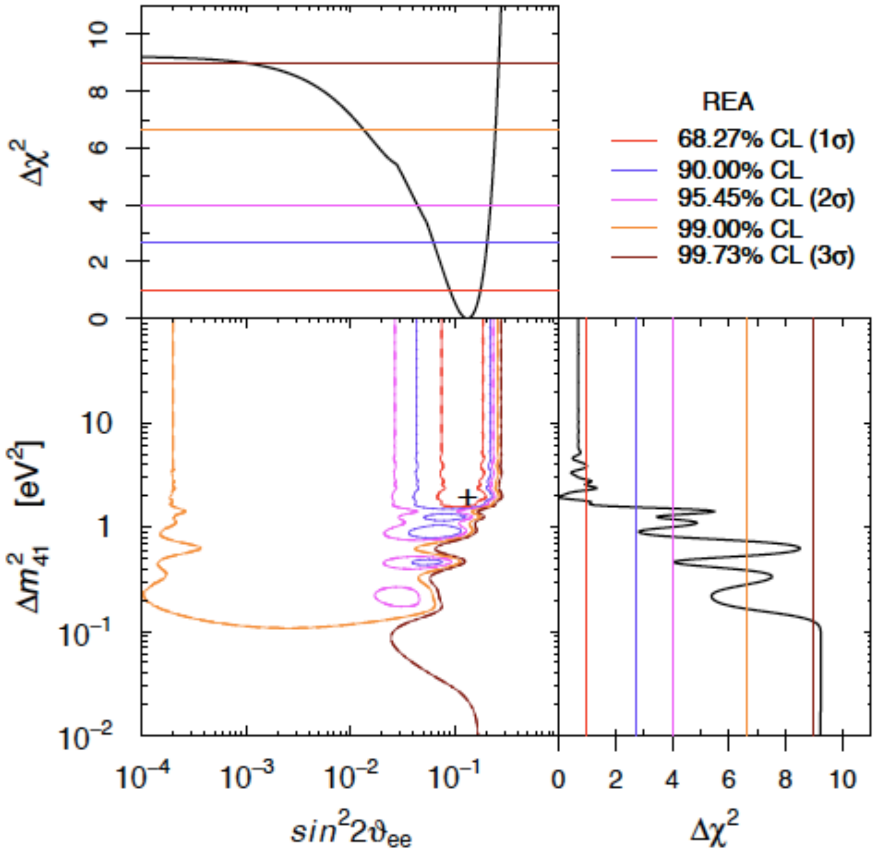
Zhang, Li, & Zhang, arXiv:1403.7028

$N_{eff} = 3.96 \pm 0.32$, $m^{eff}_s = 0.51 \pm 0.13$ eV

Reactor Neutrino Anomaly

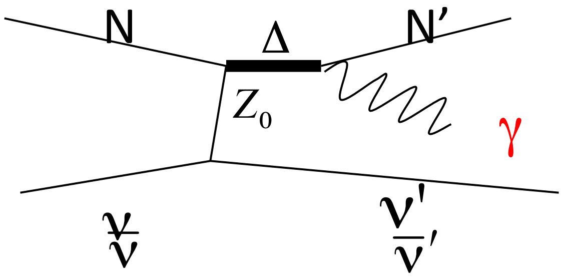
Giunti et al.; arXiv:1210.5715





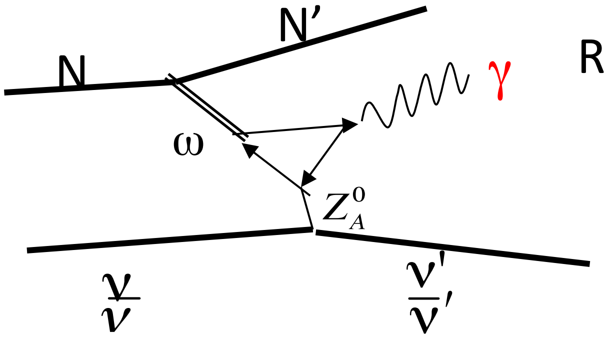
NCγ Backgrounds: Order ($G^2\alpha\alpha_s$) , single γ FS?

Dominant processes accounted for in MC!

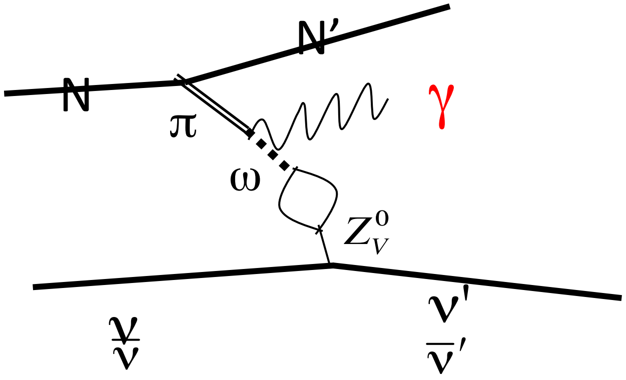


($G^2\alpha/\alpha_S$)

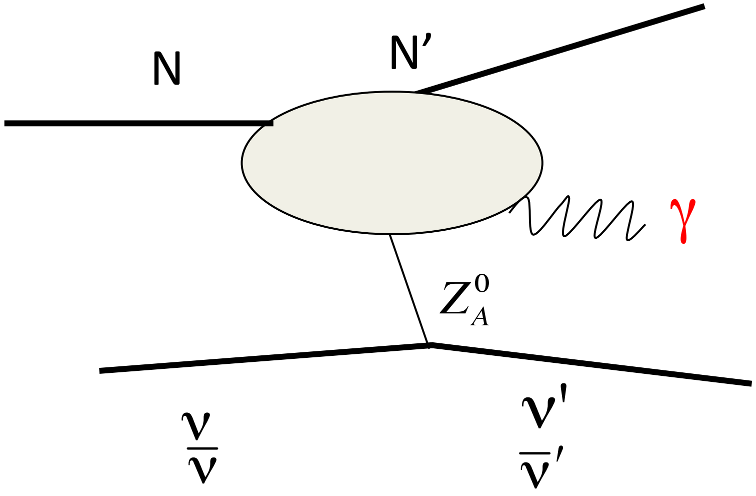
Radiative Delta Decay



Axial Anomaly



Other PCAC



So far no one has found a NC process to account for the ν low-energy excess. Publications:

R. Hill, arXiv:0905.0291

Jenkins & Goldman, arXiv:0906.0984

Zhang & Serot, arXiv:1210.3610

Wang, Alvarez-Ruso, & Nieves, arXiv:1407.6060

BooNE Technical Note 304

September 1, 2014

FITTING THEORY TO DATA IN THE PRESENCE OF BACKGROUND UNCERTAINTIES

BYRON ROE

Abstract. When fitting theory to data in the presence of background uncertainties, the question of whether the spectral shape of the background happens to be similar to that of the theoretical model of physical interest has not generally been considered previously. These correlations in shape are considered in the present note and found to make important corrections to the calculations. The discussion is phrased in terms of χ^2 fits, but the general considerations apply to any fits. If these new correlations are not included, the distribution usually does not have a χ^2 behavior, the χ^2 probabilities obtained are overestimated, and the confidence regions will be incorrect. Fake data studies, as used at present, will not be optimum. Problems will also occur in comparisons of related χ^2, such as occur in the Maltoni-Schwetz [1] theorem. Neutrino oscillations are used as examples, but the problems discussed here are general ones.

1. Introduction

When fitting theory to data in the presence of background uncertainties, the question of whether the spectral shape of the background is similar to that of the theoretical model of physical interest has not generally been considered previously. These correlations in shape are considered in the present note and found to make important corrections to the calculations.

Some causal correlations between background and the theoretical model are usually included at present. For example, beam normalization uncertainties affect both the theoretical model and the background. There are also some correlations when the size of the theoretical model affects the size of the background.

However, when the theoretical model parameters are allowed to vary in a fit, there is a