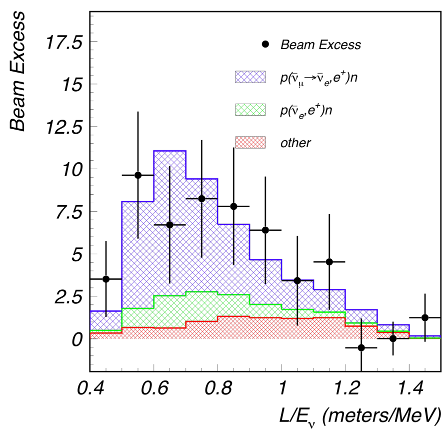
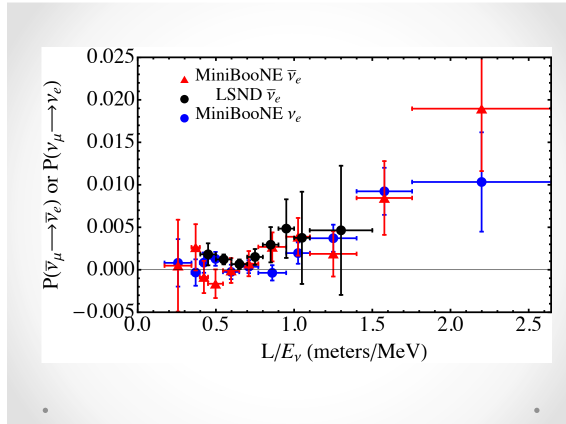
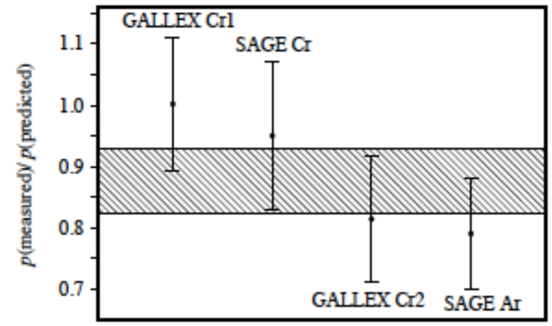
A Precision Decay at Rest ν Oscillation Expt: OscSNS

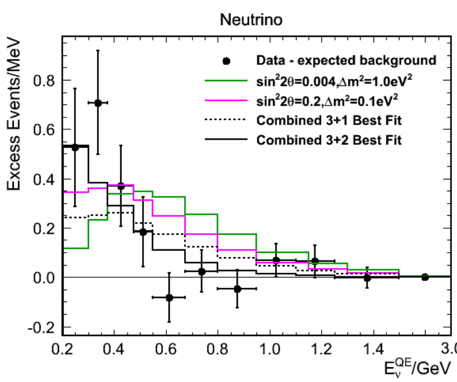
- Short-Baseline Neutrino Anomalies
- 3+N Neutrino Oscillation Models
- Next Step: Observe Oscillations in the Detector
- OscSNS: Decay at Rest Neutrino Experiment

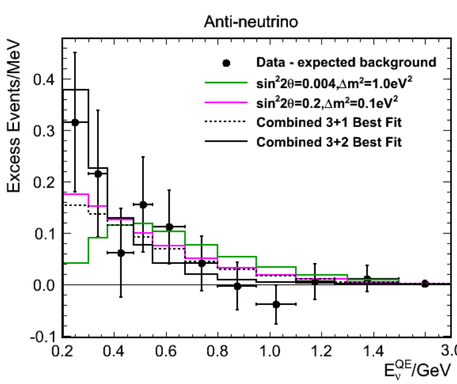
Short-Baseline Neutrino Anomalies





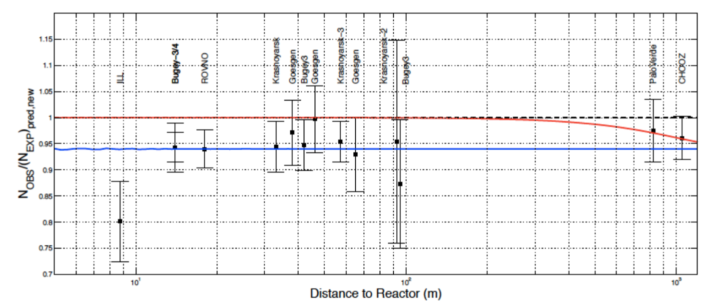






N_{eff} From CMB

Model	Data	N_{eff}	Ref.
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[26]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[26]
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$	[29]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[26]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[18]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[18]
	W-7+ACT	5.3 ± 1.3	[23]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[23]
	W-7+SPT	3.85 ± 0.62	[24]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[24]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[30]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[31]
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$	[32]
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96	[31]
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45	[32]
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43	[31]
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$	[32]
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[33]
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[33]



More precise information will come from the Planck satellite.

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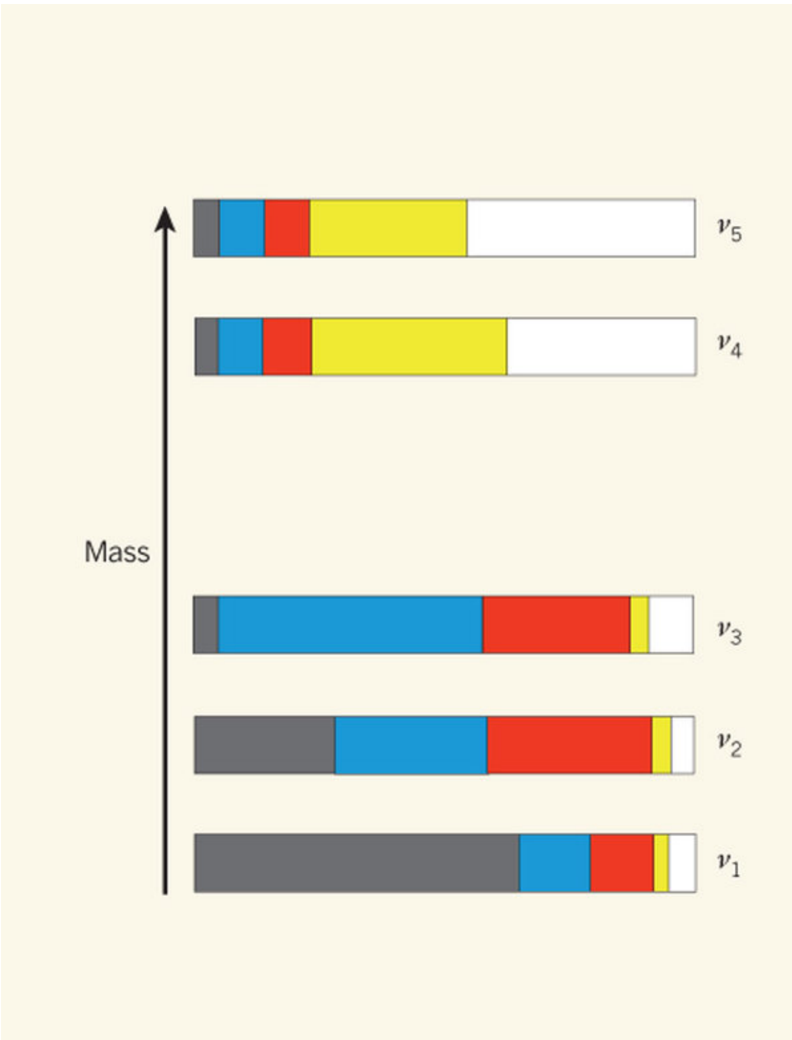
Sterile Neutrinos

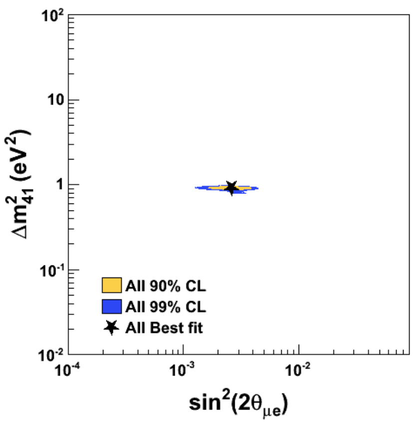


- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\nu_\mu \rightarrow \nu_e \neq \overline{\nu}_\mu \rightarrow \overline{\nu}_e$

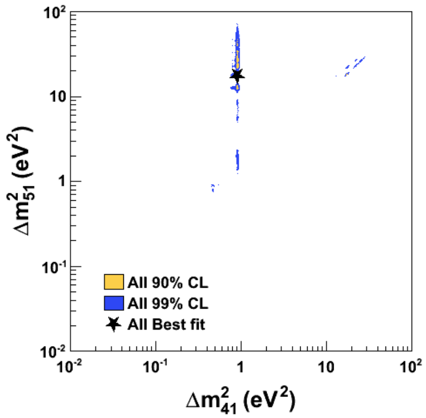
Global 3+N Fits

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

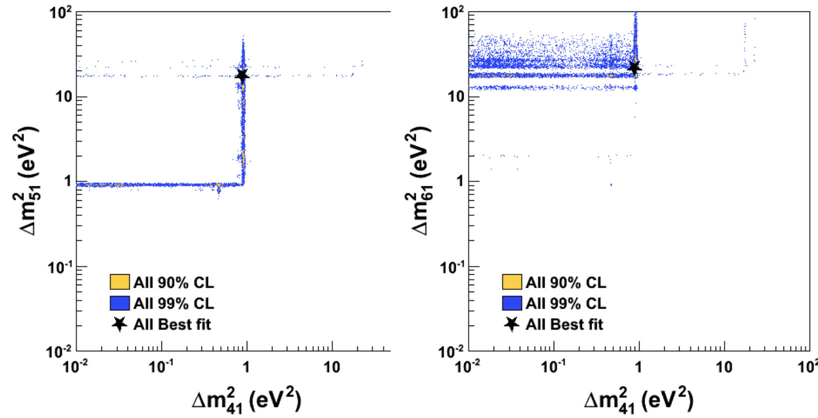
3+1



3+2



3+3



	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+1						
All	233.9 (237)	286.5 (240)	55%	2.1%	54.0 (24)	0.043%
App	87.8 (87)	147.3 (90)	46%	0.013%	14.1 (9)	12%
Dis	128.2 (147)	139.3 (150)	87%	72%	22.1 (19)	28%
ν	123.5 (120)	133.4 (123)	39%	25%	26.6 (14)	2.2%
$\overline{\nu}$	94.8 (114)	153.1 (117)	90%	1.4%	11.8 (7)	11%
App vs. Dis	-	-	-	-	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	-	-	-	-	15.6 (3)	0.14%
3+2						
All	221.5 (233)	286.5 (240)	69%	2.1%	63.8 (52)	13%
App	75.0 (85)	147.3 (90)	77%	0.013%	16.3 (25)	90%
Dis	122.6 (144)	139.3 (150)	90%	72%	23.6 (23)	43%
ν	116.8 (116)	133.4 (123)	77%	25%	35.0 (29)	21%
$\overline{\nu}$	90.8 (110)	153.1 (117)	90%	1.4%	15.0 (16)	53%
App vs. Dis	-	-	-	-	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	-	-	-	-	13.9 (7)	5.3%
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\overline{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

Table 2: The χ^2 values, degrees of freedom (dof) and probabilities associated with the best-fit and null hypothesis in each scenario. Also shown are the results from the Parameter Goodness-of-fit tests. P_{best} refers to the χ^2-probability at the best fit point and P_{null} refers to the χ^2-probability at null.

3+1	Δm^2_{41}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$
All	0.92	0.17	0.15
App	0.15	0.39	0.39
Dis	18	0.18	0.18
ν	7.8	0.059	0.26
$\overline{\nu}$	0.92	0.23	0.13

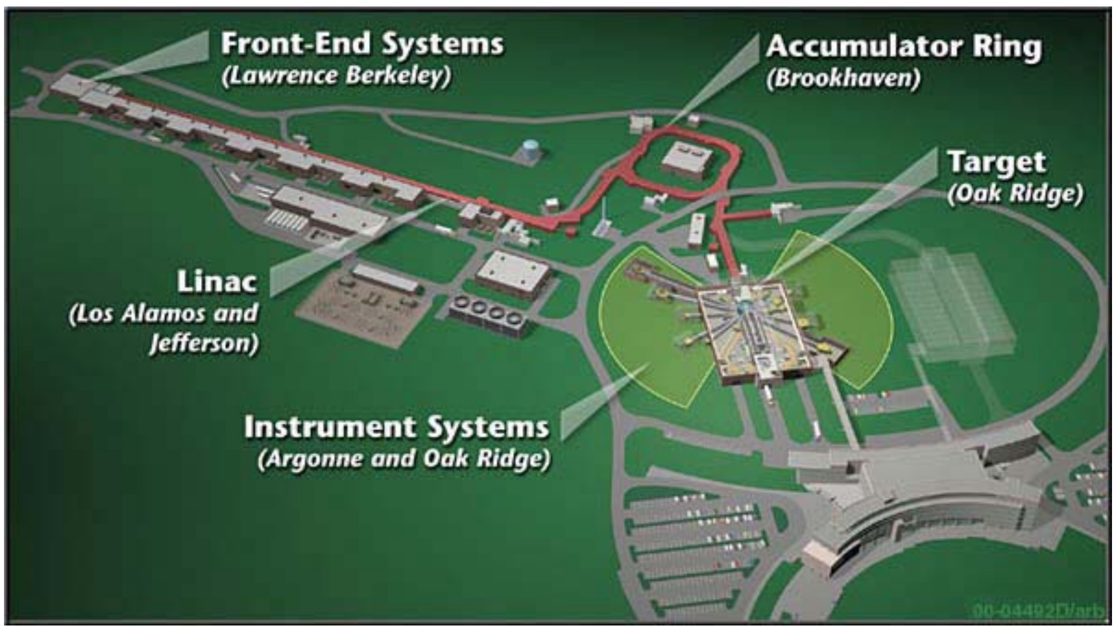
3+2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	ϕ_{54}
All	0.92	17	0.13	0.15	0.16	0.069	1.8π
App	0.31	1.0	0.31	0.31	0.17	0.17	1.1π
Dis	0.92	18	0.015	0.12	0.17	0.12	N/A
ν	7.6	17.6	0.05	0.27	0.18	0.052	1.8π
$\overline{\nu}$	0.92	3.8	0.25	0.13	0.12	0.079	0.35π

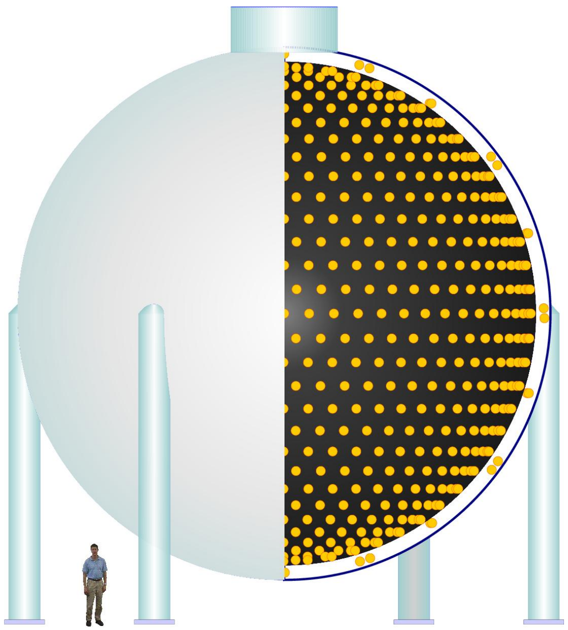
3+3	Δm^2_{41}	Δm^2_{51}	Δm^2_{61}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 6}\rvert$	$\lvert U_{e6}\rvert$	ϕ_{54}	ϕ_{64}	ϕ_{65}
All	0.90	17	22	0.12	0.11	0.17	0.11	0.14	0.11	1.6π	0.28π	1.4π
App	0.15	1.8	2.7	0.37	0.37	0.12	0.12	0.12	0.12	1.4π	0.32π	0.94π
Dis	0.92	7.2	18	0.013	0.12	0.019	0.16	0.15	0.069	N/A	N/A	N/A
ν	13	17	26	0.076	0.24	0.16	0.067	0.10	0.017	1.1π	1.8π	0.037π
$\overline{\nu}$	7.5	9.1	18	0.024	0.28	0.098	0.11	0.18	0.029	1.8π	2.0π	0.61π

Table 3: The oscillation parameter best-fit points in each scenario considered. The values of Δm^2 shown are in units of eV^2

OscSNS

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

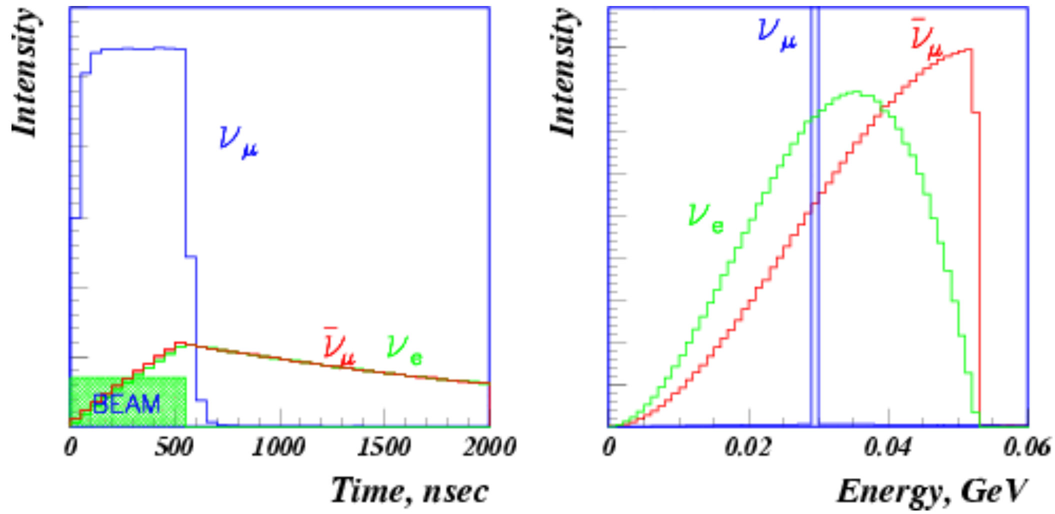




SNS Design Parameters

Linac Length	493 m
Accumulator Ring Circumference	221 m
Beam Power on Target	1.4 MW
Beam Energy on Target	1.3 GeV
Average Beam Current	1.1 mA
Repetition Rate	60 Hz
Ion Type, Source-Linac	H^-
LINAC-Beam Duty Factor	6.2%
Number of Injected Turns	1225
Particles Stored in Ring	1.5×10^{14}
Extracted Pulse Length	695 ns
Peak Current on Target	45 A
Target	Mercury
Beam Spot on Target	7 x 20 cm
Moderators Ambient	2 (Water)
Moderators Cryogenic	2 (LH_2)
Neutron Beam Ports	18
Protons Accelerated per Year	2×10^{23} (~0.3 g)

OscSNS



$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ $\Delta(L/E)$ ~ 3% ; $\bar{\nu}_e$ p -> e^+ n

ν_e -> ν_s $\Delta(L/E)$ ~ 3% ; ν_e C -> e^- N_{gs}

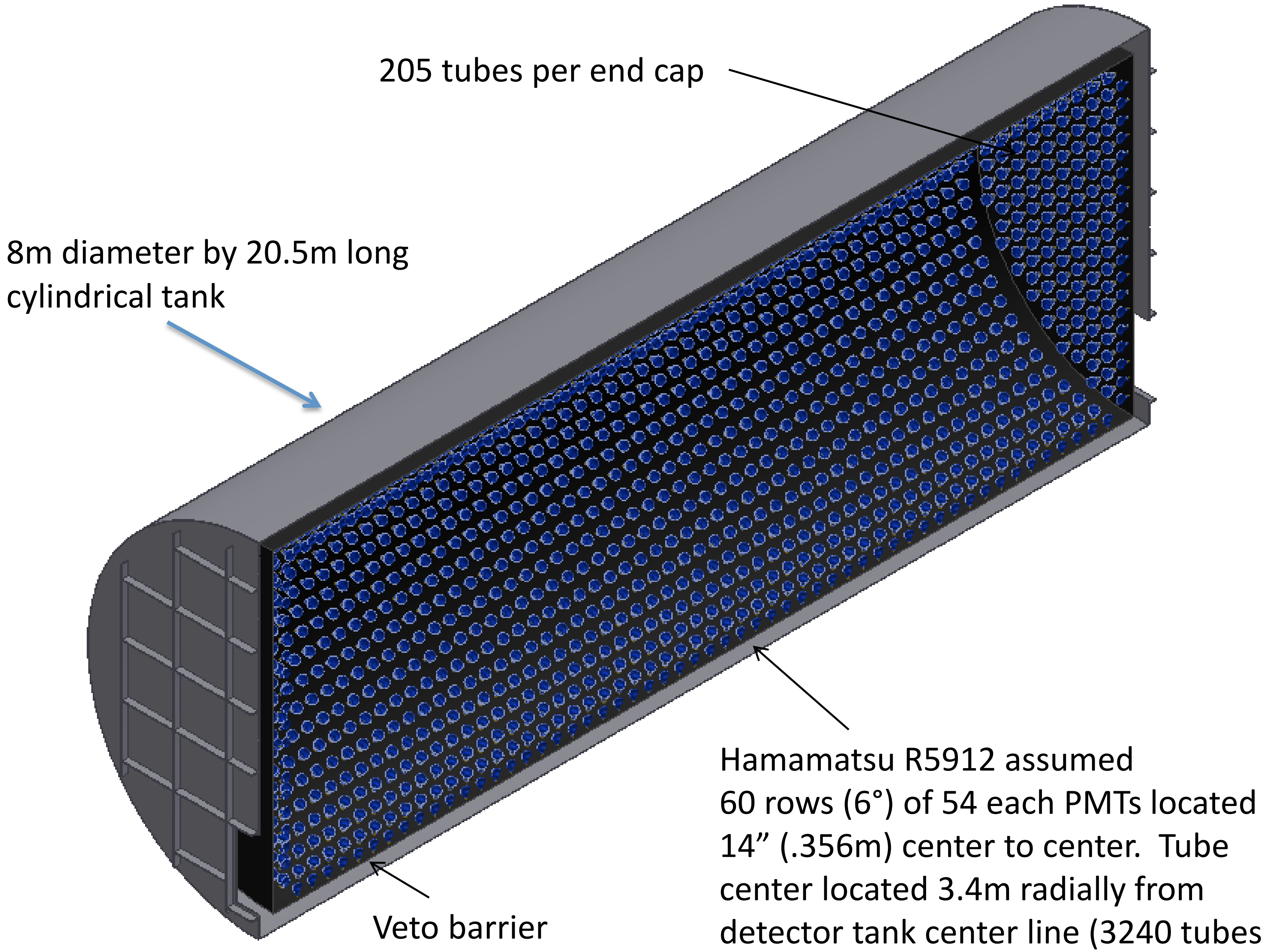
ν_μ -> ν_s $\Delta(L/E) < 1\%$; **Monoenergetic** ν_μ !; ν_μ C -> ν_μ C*(15.11)

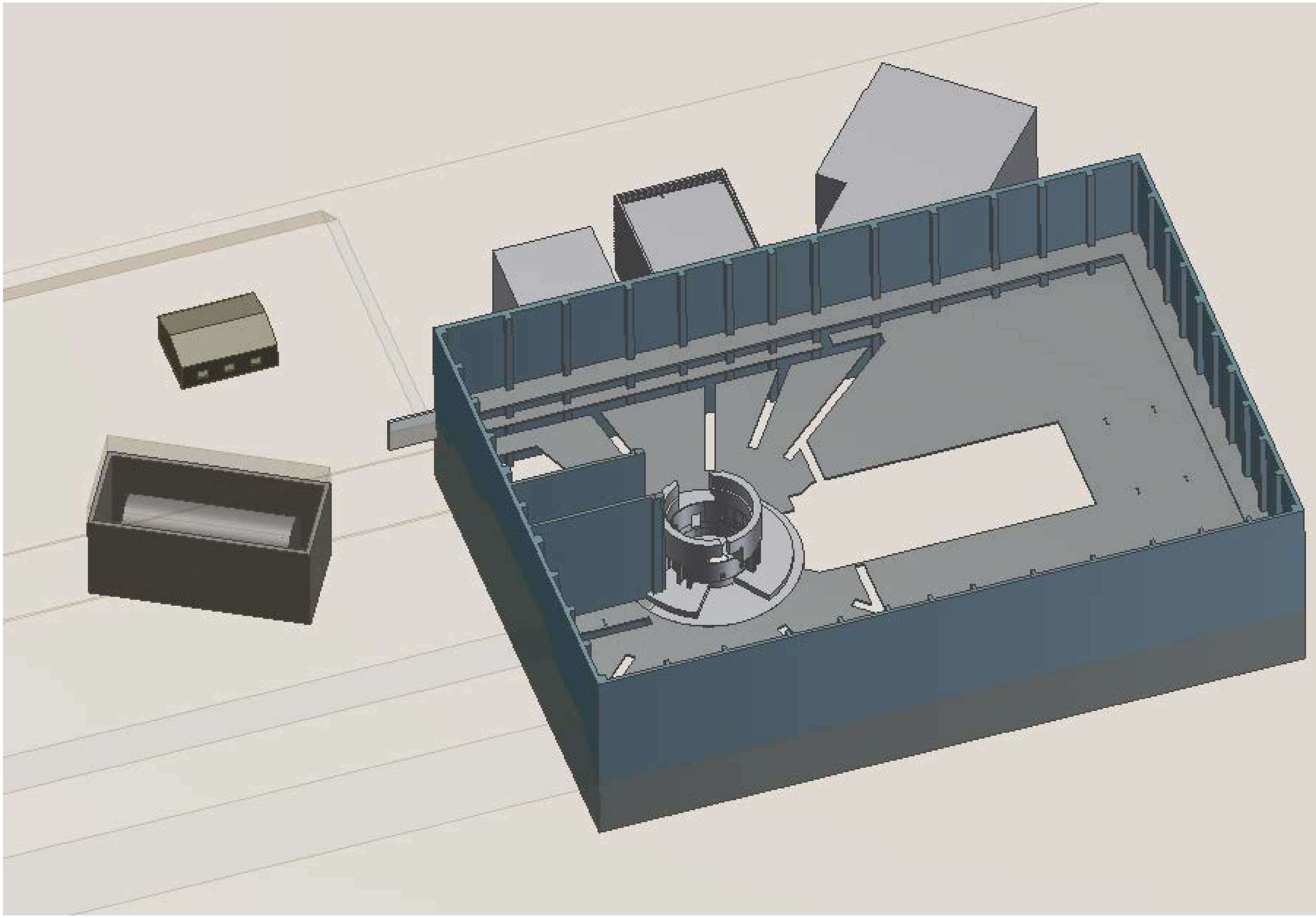
$\bar{\nu}_\mu$ -> $\bar{\nu}_s$; $\bar{\nu}_\mu$ C -> $\bar{\nu}_\mu$ C*(15.11)

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

Spallation Neutron Source at ORNL

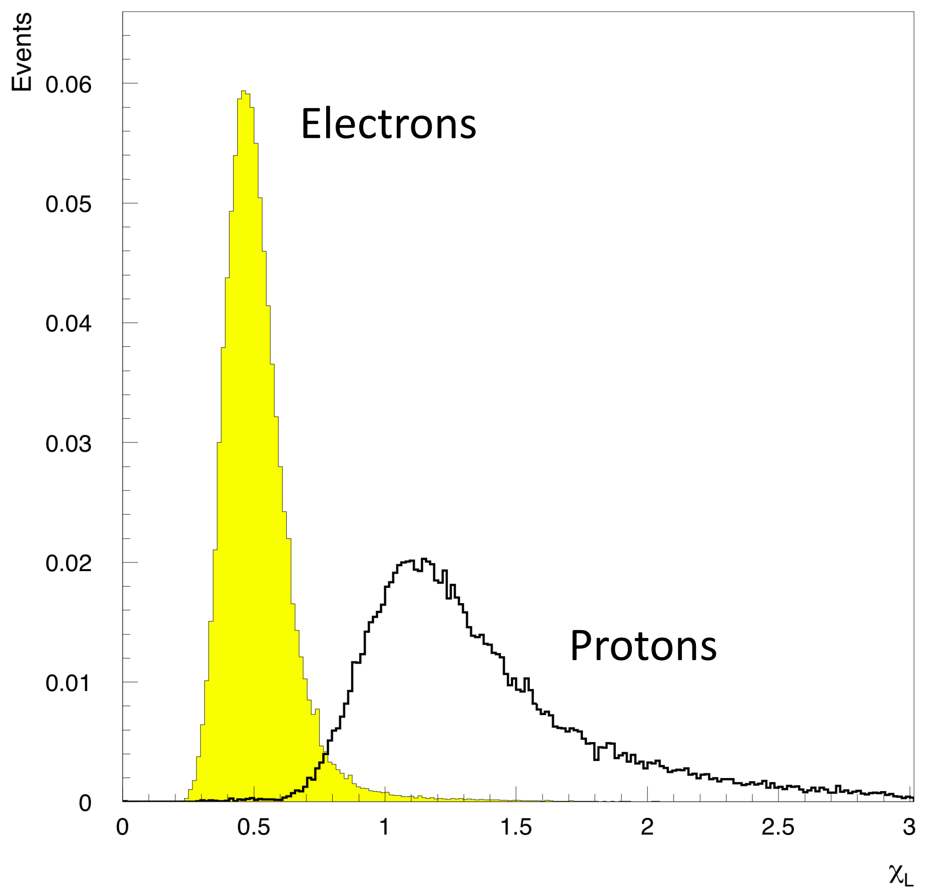
Assumed
detector
location


205 tubes per end cap
8m diameter by 20.5m long
cylindrical tank
Hamamatsu R5912 assumed
60 rows (6°) of 54 each PMTs located
14” (.356m) center to center. Tube
center located 3.4m radially from
detector tank center line (3240 tubes)
Veto barrier



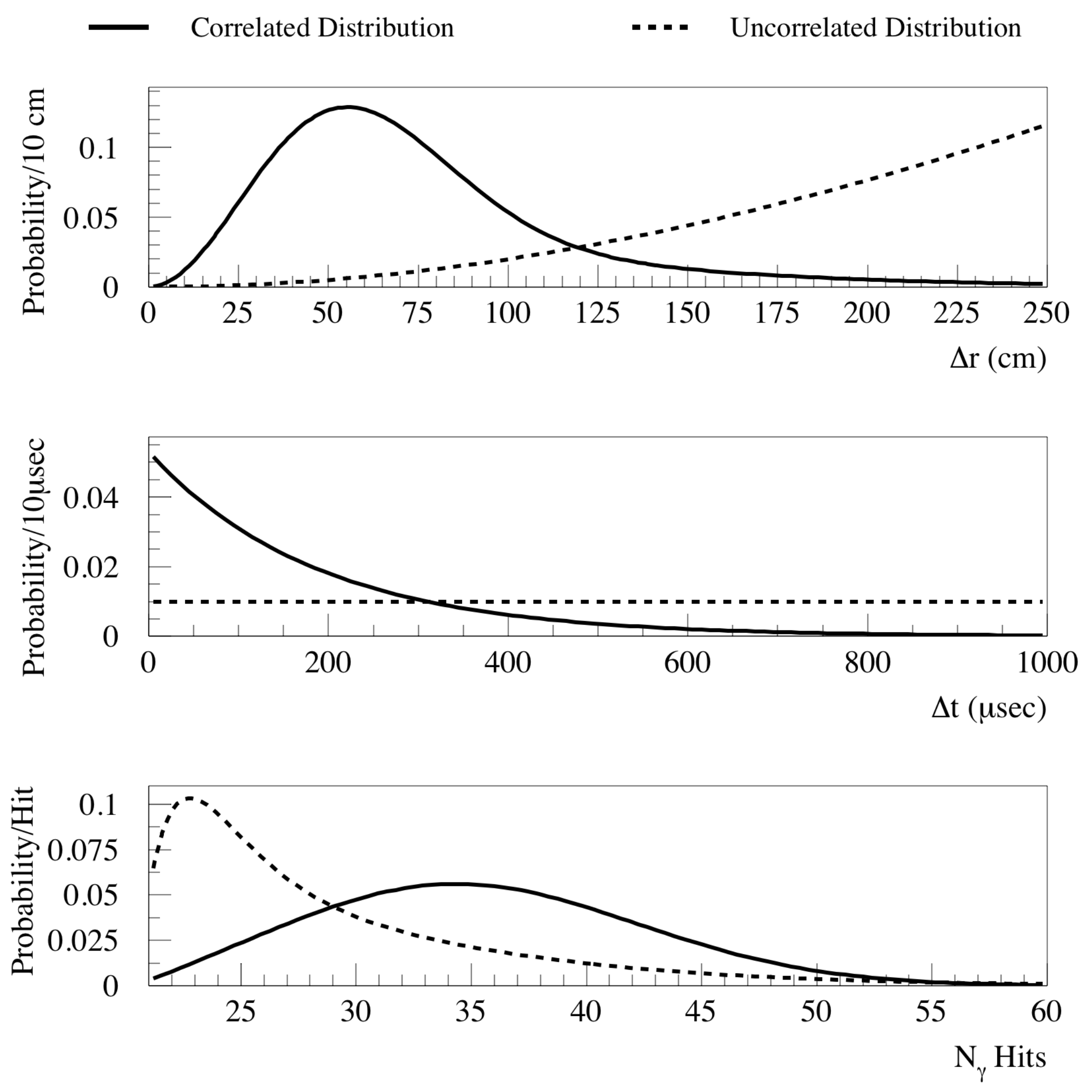
Particle Identification

(with 0.031 g/l of b-PBD)



Particle Identification depends on Cherenkov cone fit, position fit, and fraction of late light

2.2 MeV γ Identification



OscSNS Advantages Over Other Neutrino Oscillation Experiments

- Well understood ν fluxes: ν_μ, ν_e, $\bar{\nu}_\mu$
- Well understood ν cross sections
- Low duty factor
- Absence of nuclear effects
- Very low backgrounds (~0.1%)
- Beam comes for free from the SNS, which runs >1/2 the year
- Search for both appearance & disappearance oscillations
- Possibility of observing oscillations in the detector for Δm^2 > 1 eV^2!

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
- Negligible DIF Background (backward direction)
- Lower Neutrino Background (x4) (60m vs 30m)
- For LSND parameters, expect ~350 ν_{e} oscillation events & ~80 background events per year!

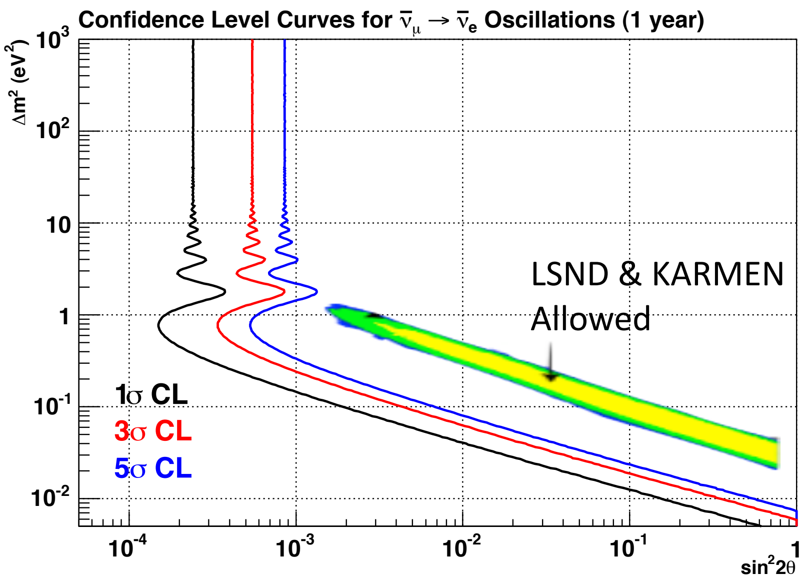
Goals of the OscSNS Experiment

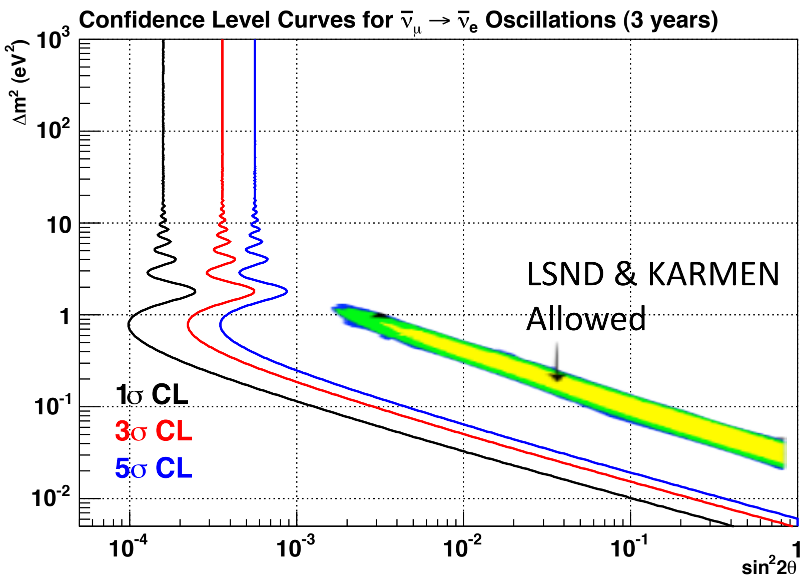
- Prove the existence of sterile neutrinos by comparing NC reactions in near and far detector and by observing oscillations in the detector of a NC reaction
- Short baseline ν_e and $\overline{\nu}_e$ appearance
- Short baseline ν_e, ν_μ and $\overline{\nu}_\mu$ disappearance
- The resolution of the current short-baseline anomalies
- Neutrino cross section measurements

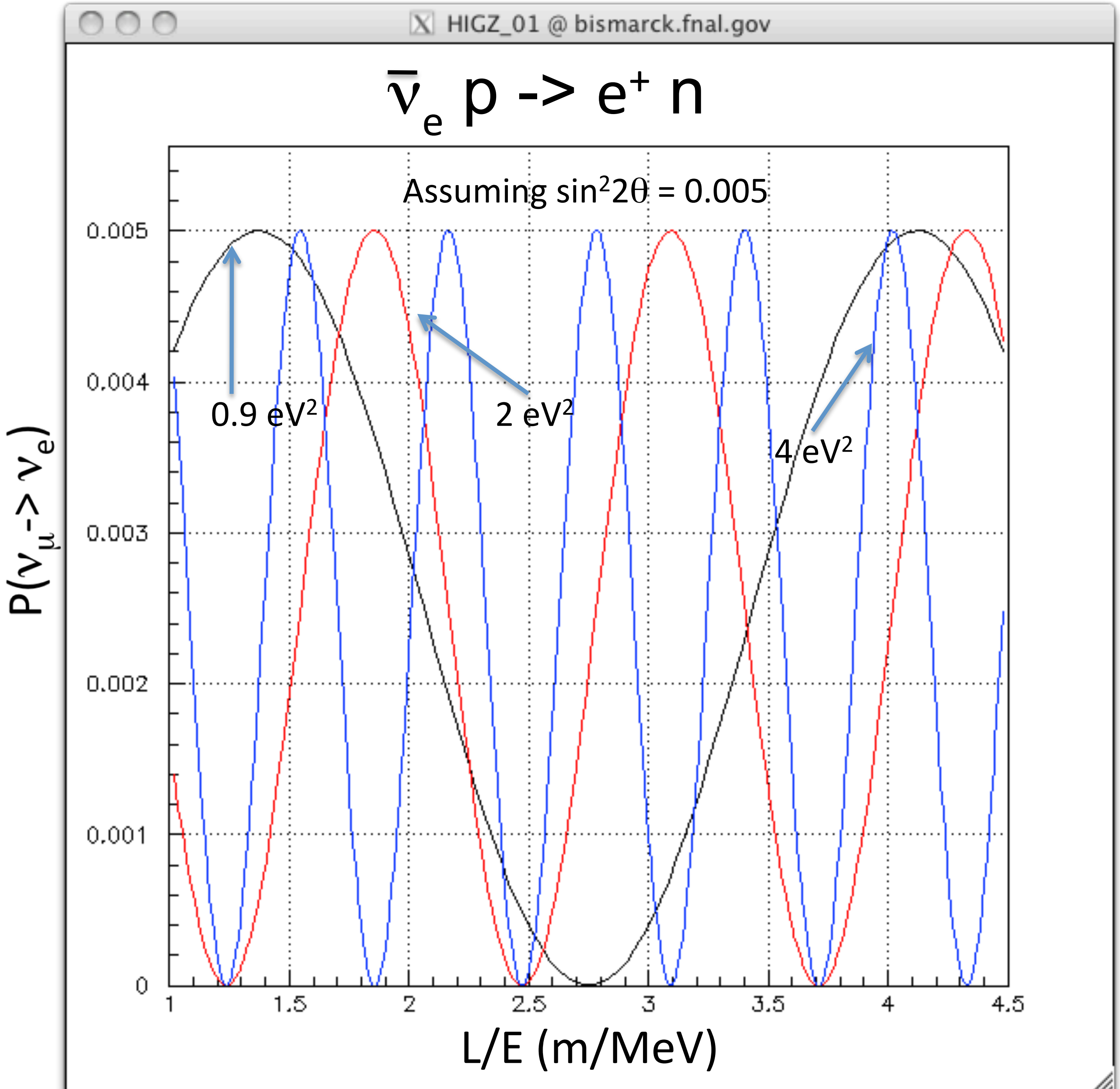
OscSNS at ORNL

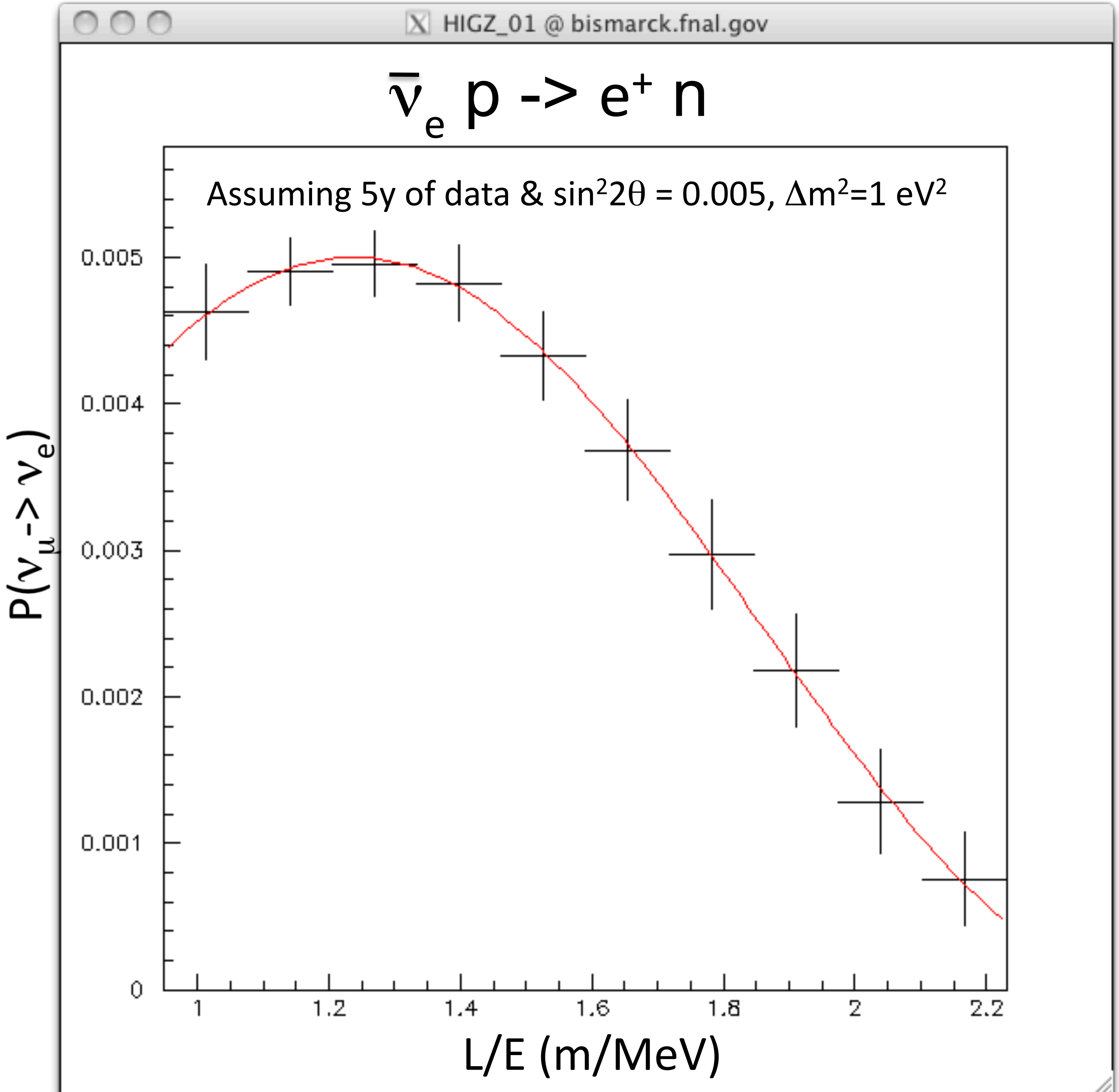
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance sensitivity for 1 & 3 years of running:

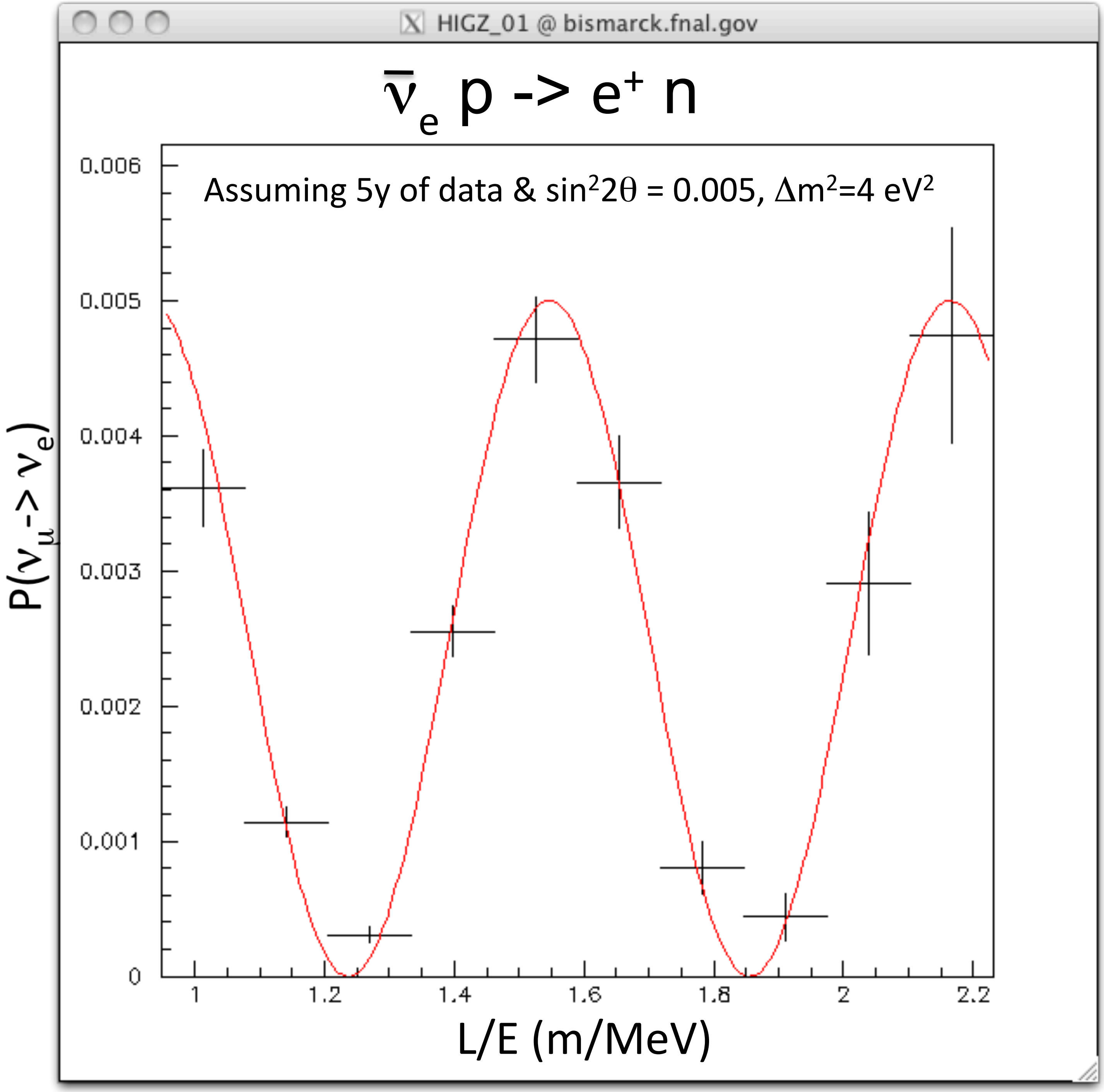
$\bar{\nu}_e$ p -> e^+ n; n p -> d γ (2.2 MeV)






HIGZ_01 @ bismarck.fnal.gov
ν̄e p -> e+ n
Assuming sin²2θ = 0.005
0.9 eV²
2 eV²
4 eV²
P(νμ-> νe)
0.005
0.004
0.003
0.002
0.001
0
1
1.5
2
2.5
3
3.5
4
4.5
L/E (m/MeV)


HIGZ_01 @ bismarck.fnal.gov
$\bar{\nu}_e$ p -> e^+ n
Assuming 5y of data & $\sin^2 2\theta$ = 0.005, Δm^2=1 eV^2
$P(\nu_\mu \rightarrow \nu_e)$
0.005
0.004
0.003
0.002
0.001
0
1
1.2
1.4
1.6
1.8
2
2.2
L/E (m/MeV)

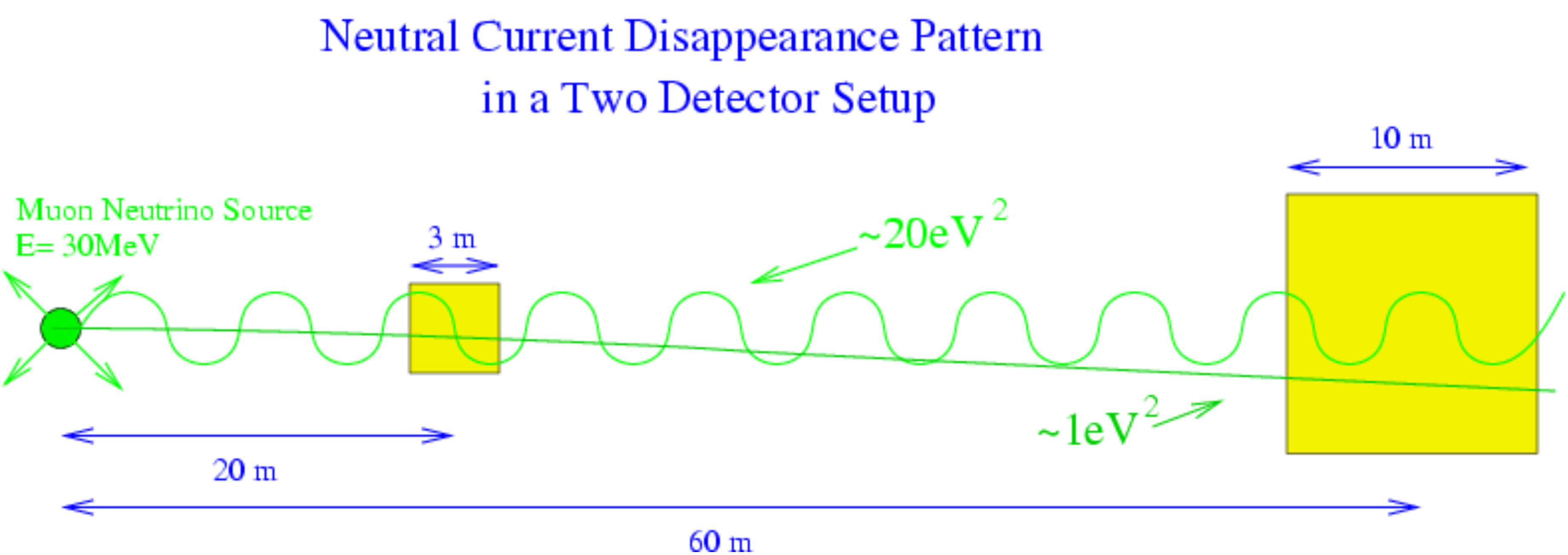


HIGZ_01 @ bismarck.fnal.gov
$\bar{\nu}_e$ p -> e^+ n
Assuming 5y of data & $\sin^2 2\theta = 0.005$, $\Delta m^2 = 4\ eV^2$
$P(\nu_\mu \rightarrow \nu_e)$
0.006
0.005
0.004
0.003
0.002
0.001
0
1
1.2
1.4
1.6
1.8
2
2.2
L/E (m/MeV)

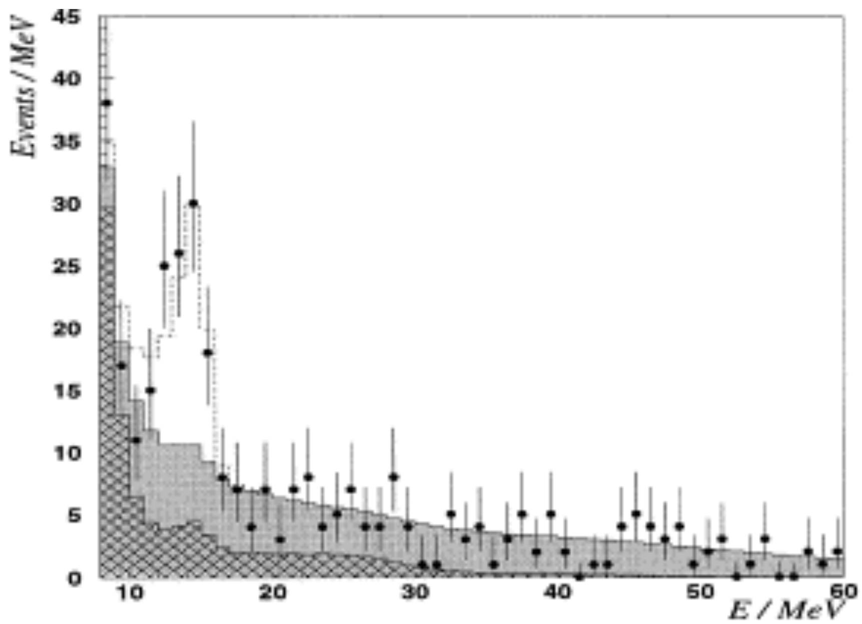
Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:

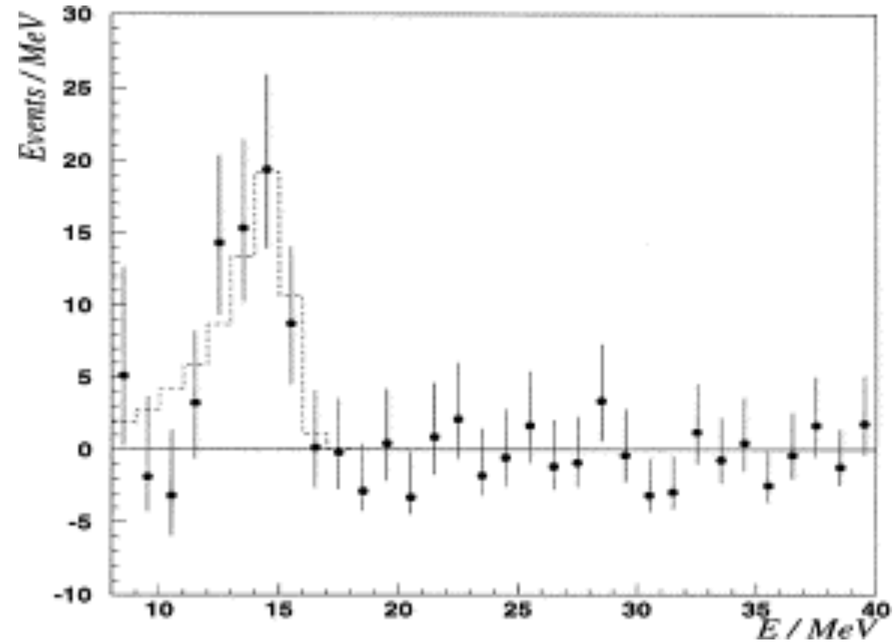
ν_μ C -> ν_μ C*(15.11)

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



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



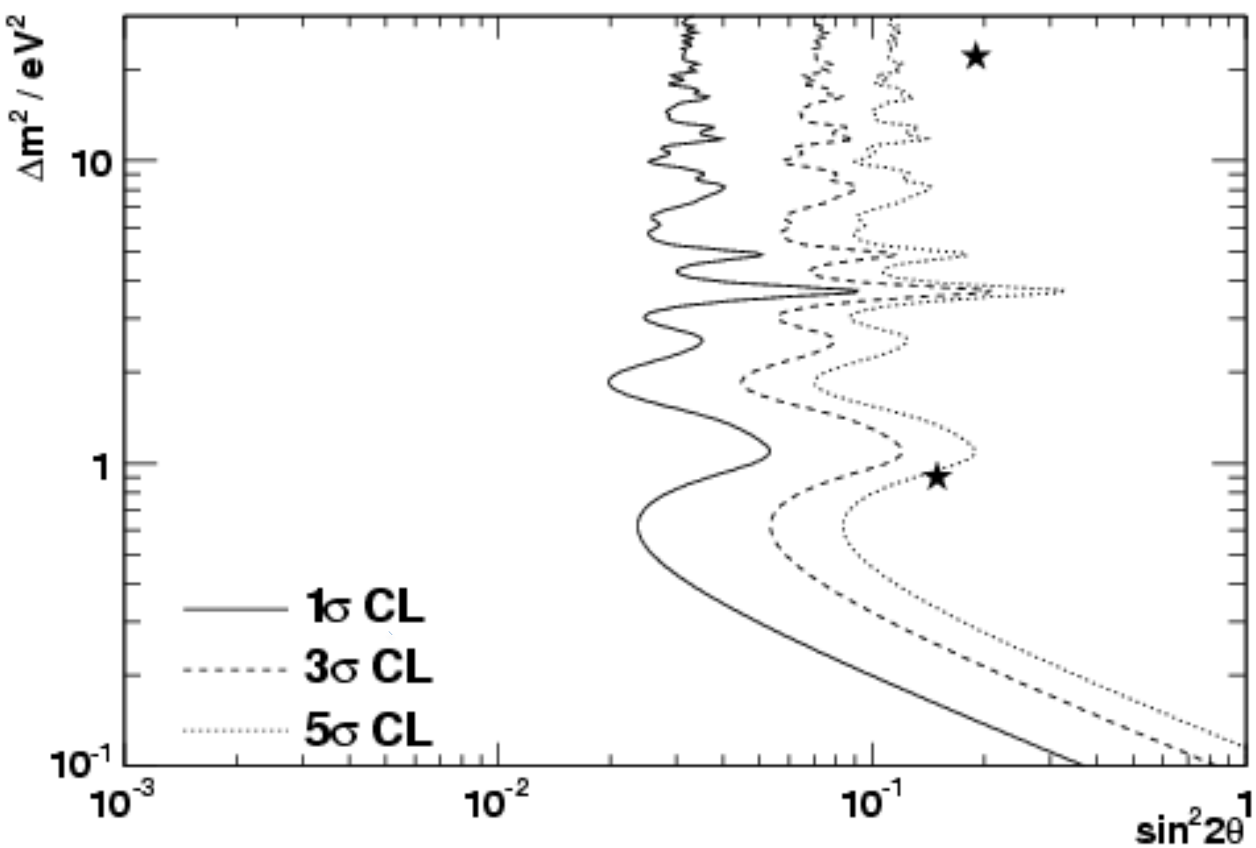


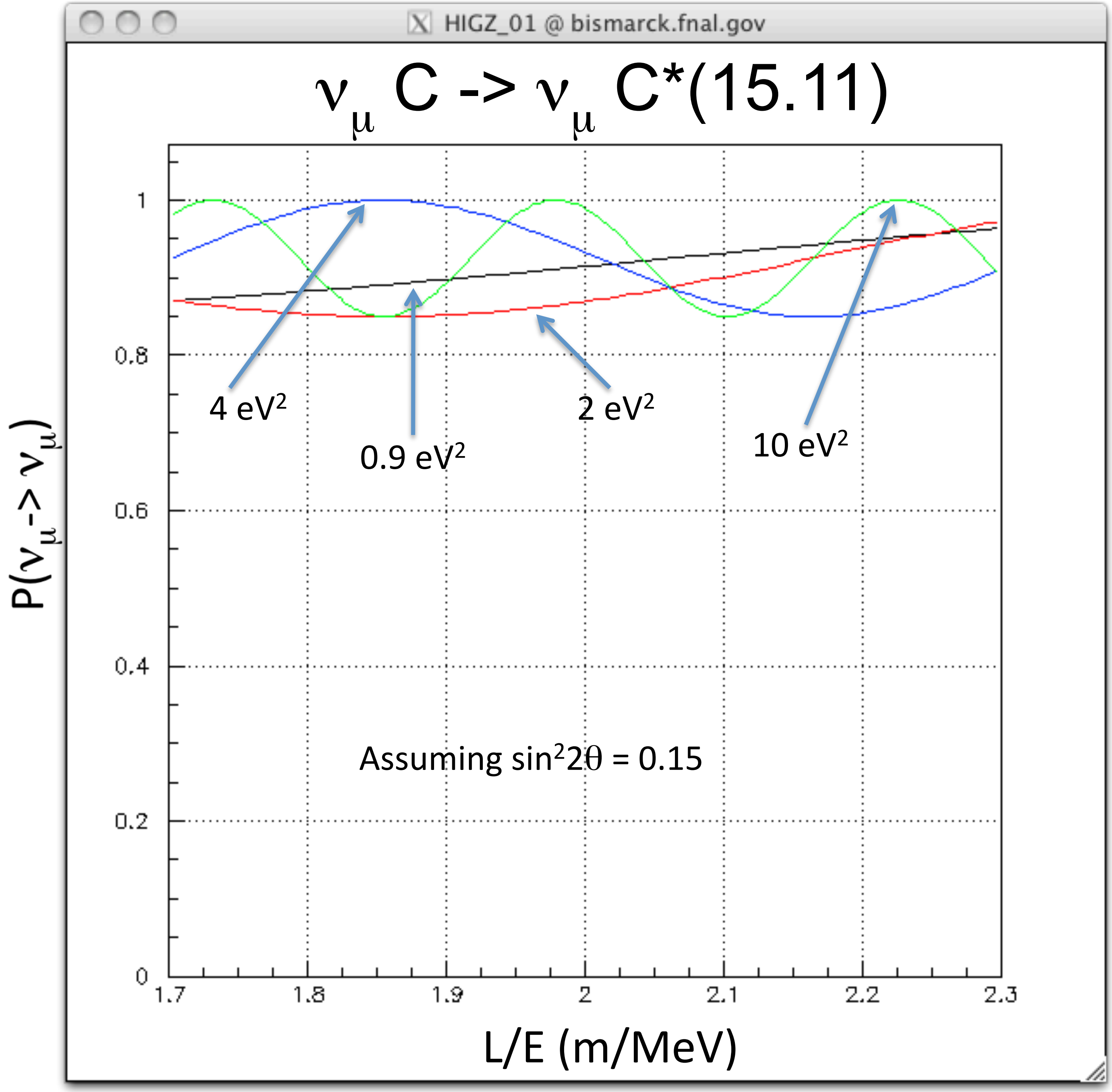
σ_{NC} = (3.2+-0.5+-0.4)x10^{-42} cm^2 (B. Armbruster et al., Phys. Lett. B423 (1998) 15)

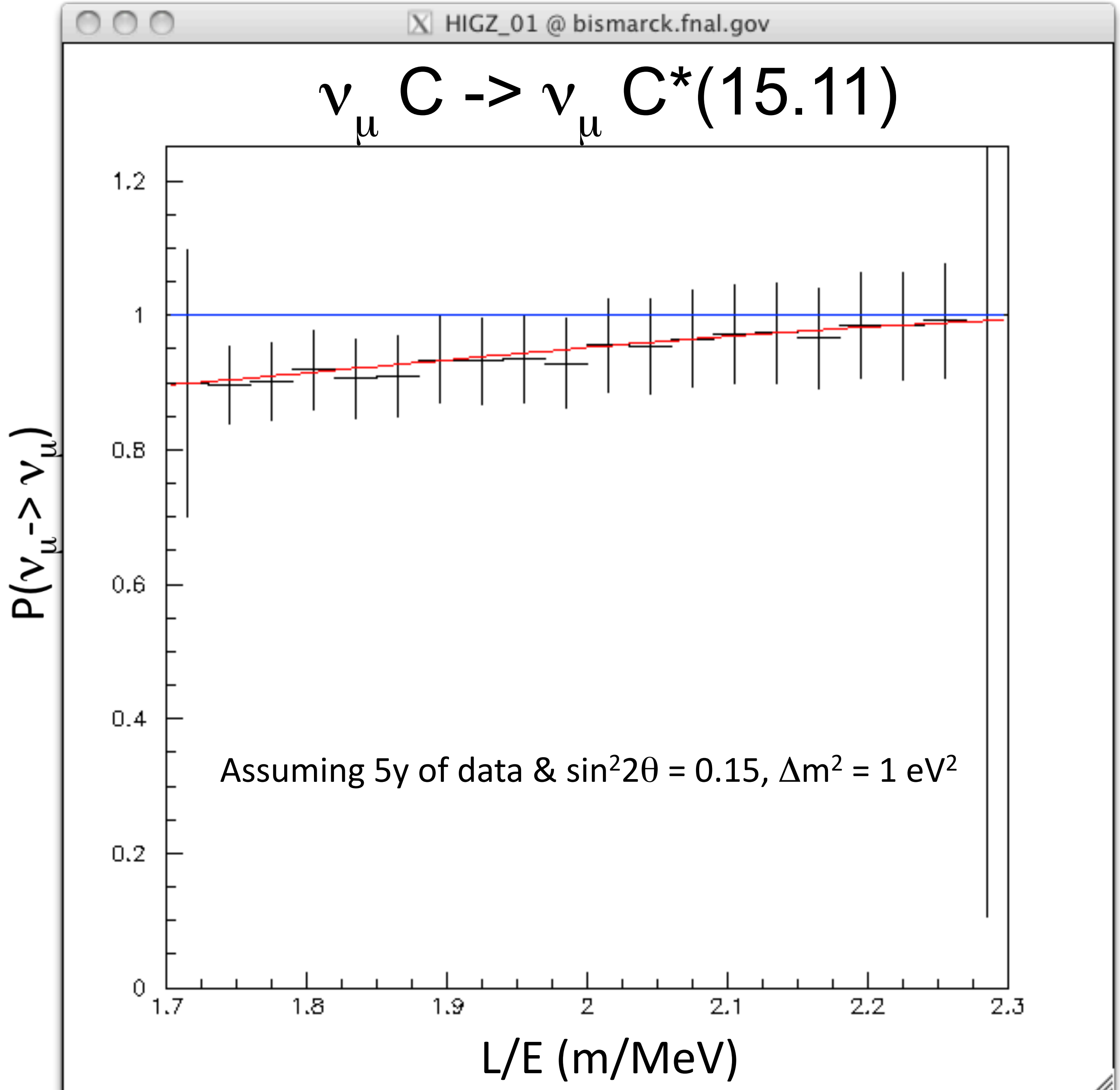
σ_{NC} ~2.8x10^{-42} cm^2 (Kolbe, Langanke, & Vogel, Nucl. Phys. A652 (1999) 91)

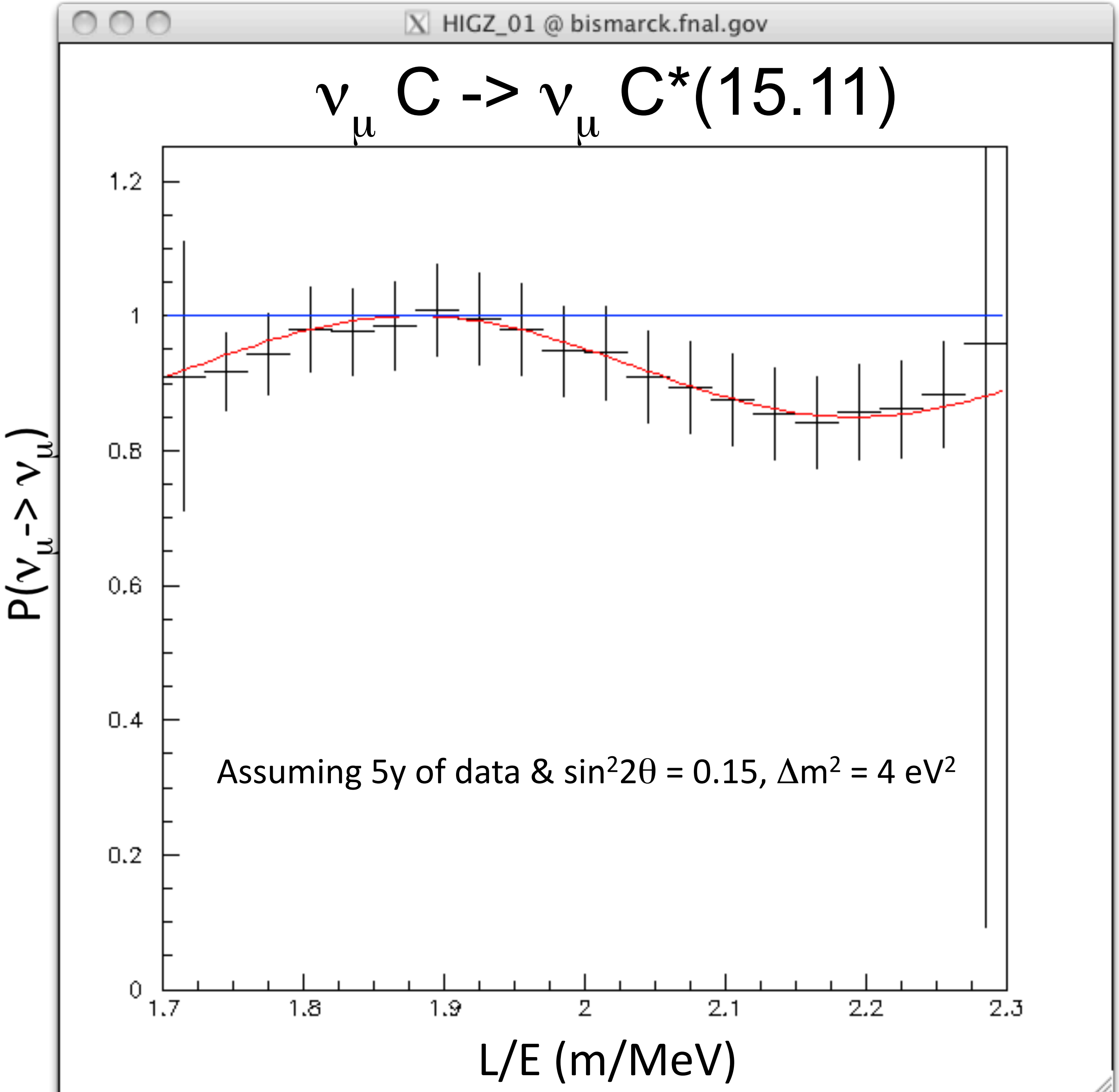
Measurement of Oscillation Parameters with Two Detectors

ν_μ disappearance

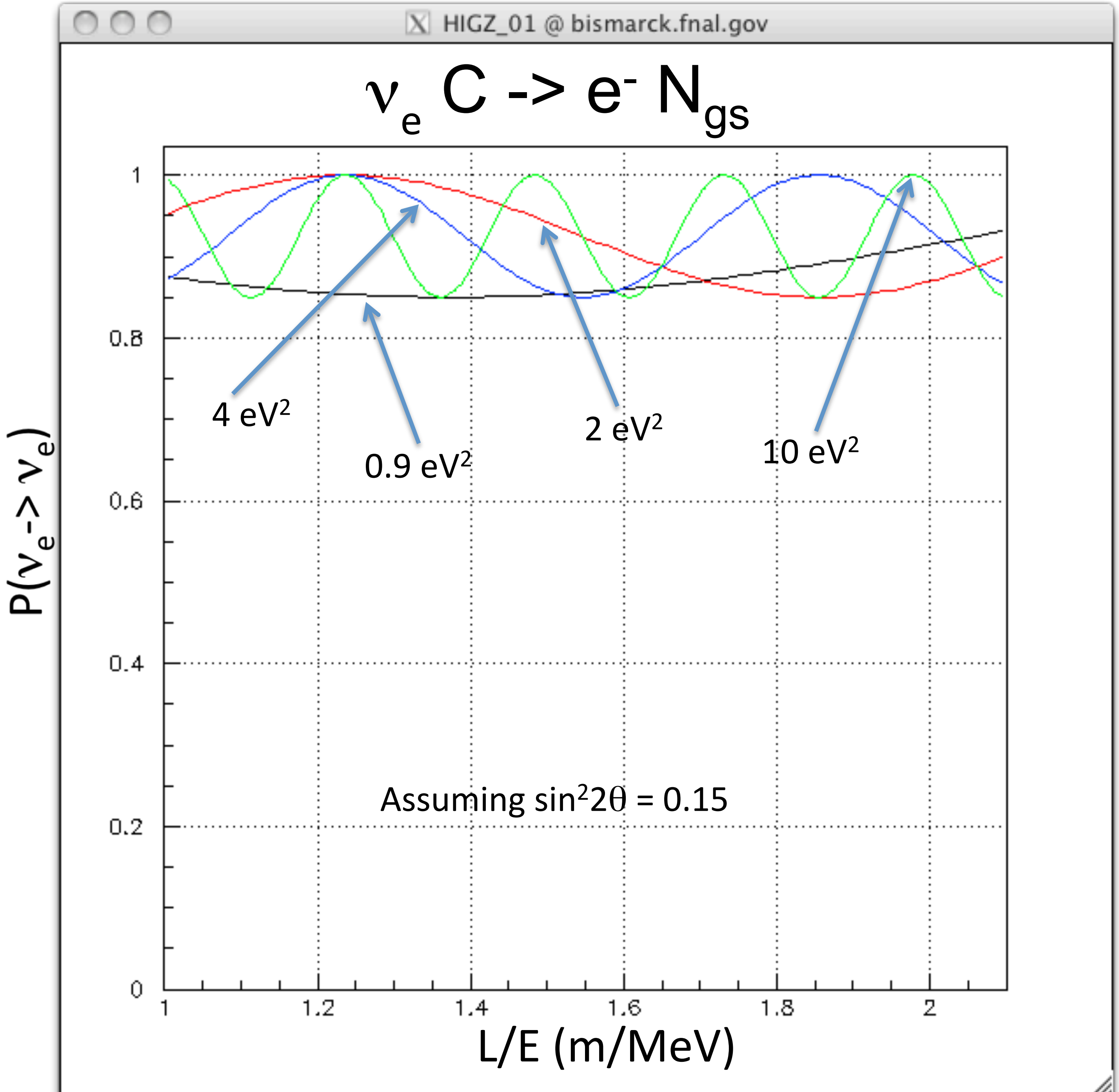


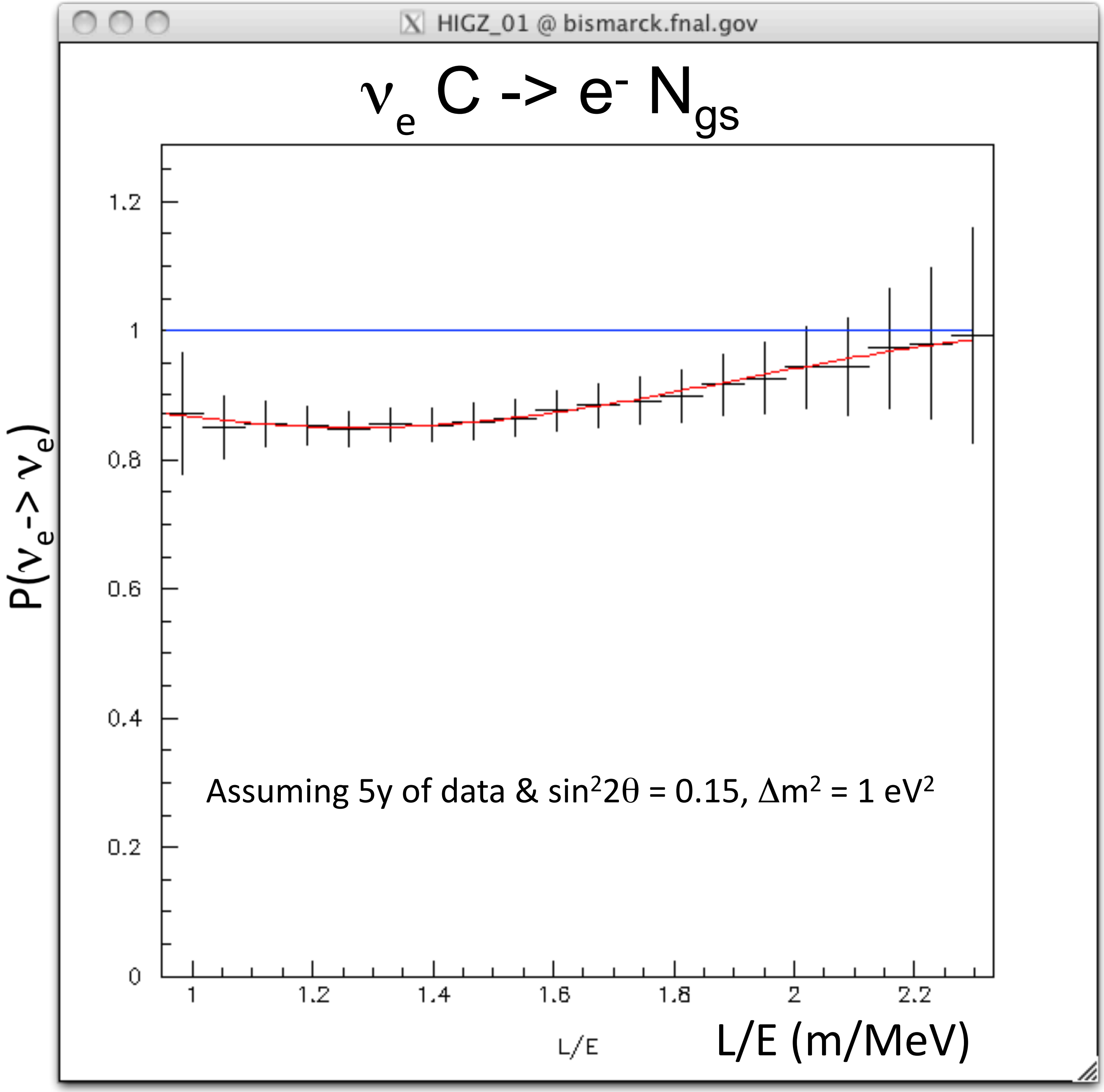

HIGZ_01 @ bismarck.fnal.gov
νμ C -> νμ C*(15.11)
P(νμ -> νμ)
L/E (m/MeV)
4 eV2
0.9 eV2
2 eV2
10 eV2
Assuming sin22θ = 0.15
0
0.2
0.4
0.6
0.8
1
1.7
1.8
1.9
2
2.1
2.2
2.3


HIGZ_01 @ bismarck.fnal.gov
ν_μ C -> ν_μ C*(15.11)
$P(\nu_\mu -> \nu_\mu)$
1.2
1
0.8
0.6
0.4
0.2
0
1.7
1.8
1.9
2
2.1
2.2
2.3
Assuming 5y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 1$ eV^2
L/E (m/MeV)

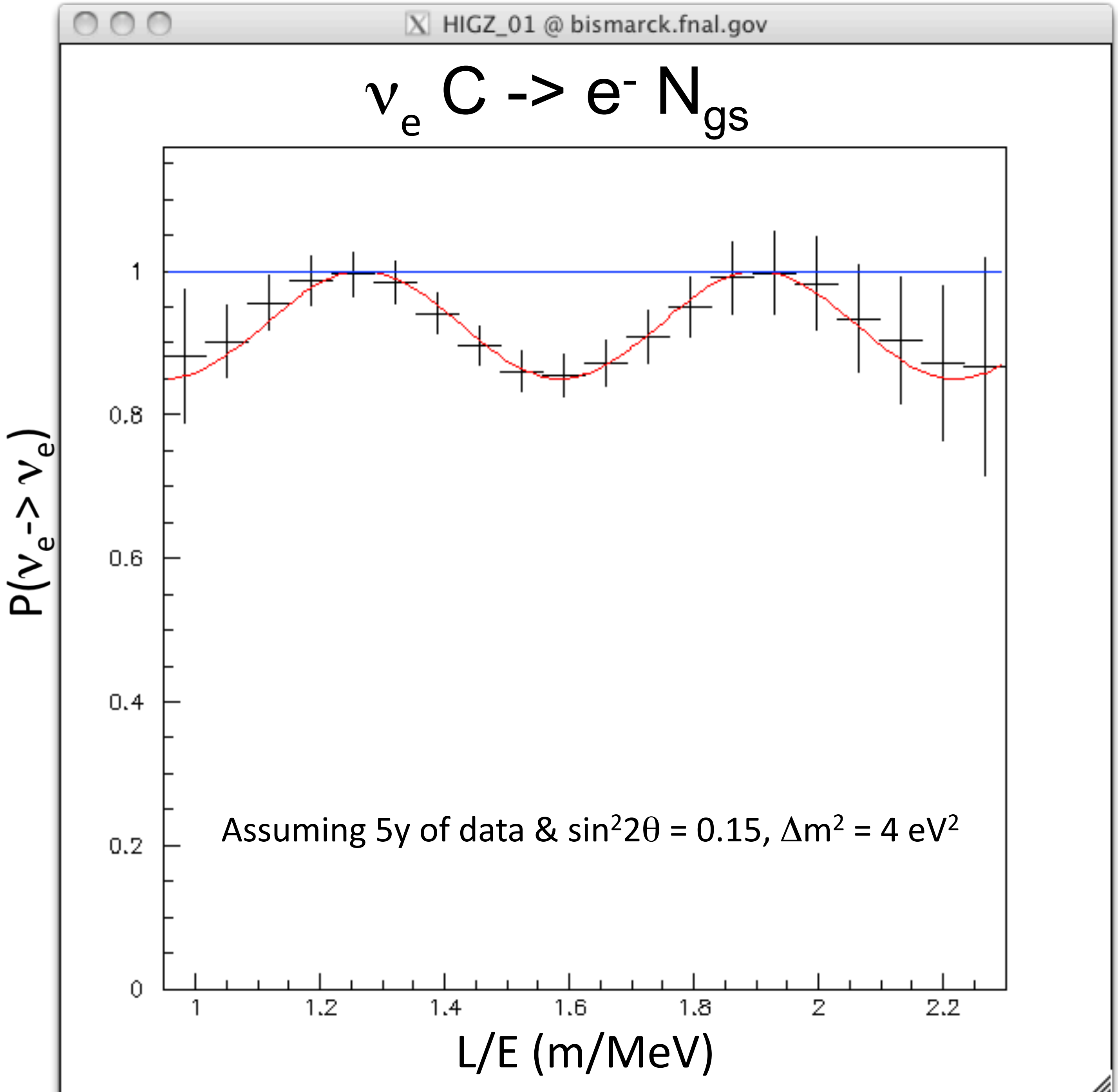


HIGZ_01 @ bismarck.fnal.gov
ν_μ C -> ν_μ C*(15.11)
P(ν_μ-> ν_μ)
1.2
1
0.8
0.6
0.4
0.2
0
1.7
1.8
1.9
2
2.1
2.2
2.3
L/E (m/MeV)
Assuming 5y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 4\ eV^2$


HIGZ_01 @ bismarck.fnal.gov
ν_e C -> e$^-$ N$_{gs}$
P(ν_e-> ν_e)
1
0.8
0.6
0.4
0.2
0
1
1.2
1.4
1.6
1.8
2
L/E (m/MeV)
4 eV^2
0.9 eV^2
2 eV^2
10 eV^2
Assuming $\sin^2 2\theta = 0.15$



HIGZ_01 @ bismarck.fnal.gov
ν_e C -> e^- N_{gs}
$P(\nu_e \to \nu_e)$
1.2
1
0.8
0.6
0.4
0.2
0
1
1.2
1.4
1.6
1.8
2
2.2
L/E
L/E (m/MeV)
Assuming 5y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 1\ eV^2$



HIGZ_01 @ bismarck.fnal.gov
ν_e C -> e^- N_{gs}
$P(\nu_e \to \nu_e)$
1
0.8
0.6
0.4
0.2
0
1
1.2
1.4
1.6
1.8
2
2.2
L/E (m/MeV)
Assuming 5y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 4$ eV^2

OscSNS Event Rates at 60m

Channel	Events/year
ν_e C -> e^- N_{gs}	4650
ν_e C -> e^- N^*	2247
ν_μ C -> ν_μ C^*(15.11)	1463
ν C -> ν C^*(15.11)	6322
ν_e e^- -> ν_e e^-	1320
ν_μ e^- -> ν_μ e^-	450
100% $\overline{\nu}_\mu$ -> $\overline{\nu}_e$, $\overline{\nu}_e$ p -> e^+ n	99,275
0.4% $\overline{\nu}_\mu$ -> $\overline{\nu}_e$, $\overline{\nu}_e$ p -> e^+ n	397

Conclusion

- 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.
- Sterile ν would contribute to the dark matter of the universe and would have a big impact on astrophysics and cosmology.
- The world neutrino & antineutrino data can be fit fairly well to a 3+N oscillation model with large ν_μ disappearance (>7%).
- The OscSNS experiment can measure neutrino oscillations with high significance (>5σ) and prove that sterile neutrinos exist!
- OscSNS can also make numerous cross section measurements, including precision measurements of ν e -> ν e elastic scattering.

2. Questions & Answers

A. What major scientific discoveries have occurred in your research area since the 2007 LRP was drafted?

Since the 2007 LRP was drafted, there has been ever increasing evidence for the existence of sterile neutrinos. This evidence includes global fits to world data, the excess of $\bar{\nu}_e$ *and* ν_e *events from MiniBooNE, the reactor neutrino anomaly, the radioactive source anomaly, and cosmological data, and has resulted in increased theoretical interest.*

B. What compelling and unique science is to be done in the next 5 years?

A neutrino oscillation experiment at the SNS (e.g. OscSNS) could prove if sterile neutrinos explain the above anomalies. Such an experiment represents a unique opportunity for U.S. science because of the existence of the SNS. JPARC, while inferior as the ideal neutrino source, could provide competition.

C. What science would you expect to pursue in the program in 2020 and beyond?

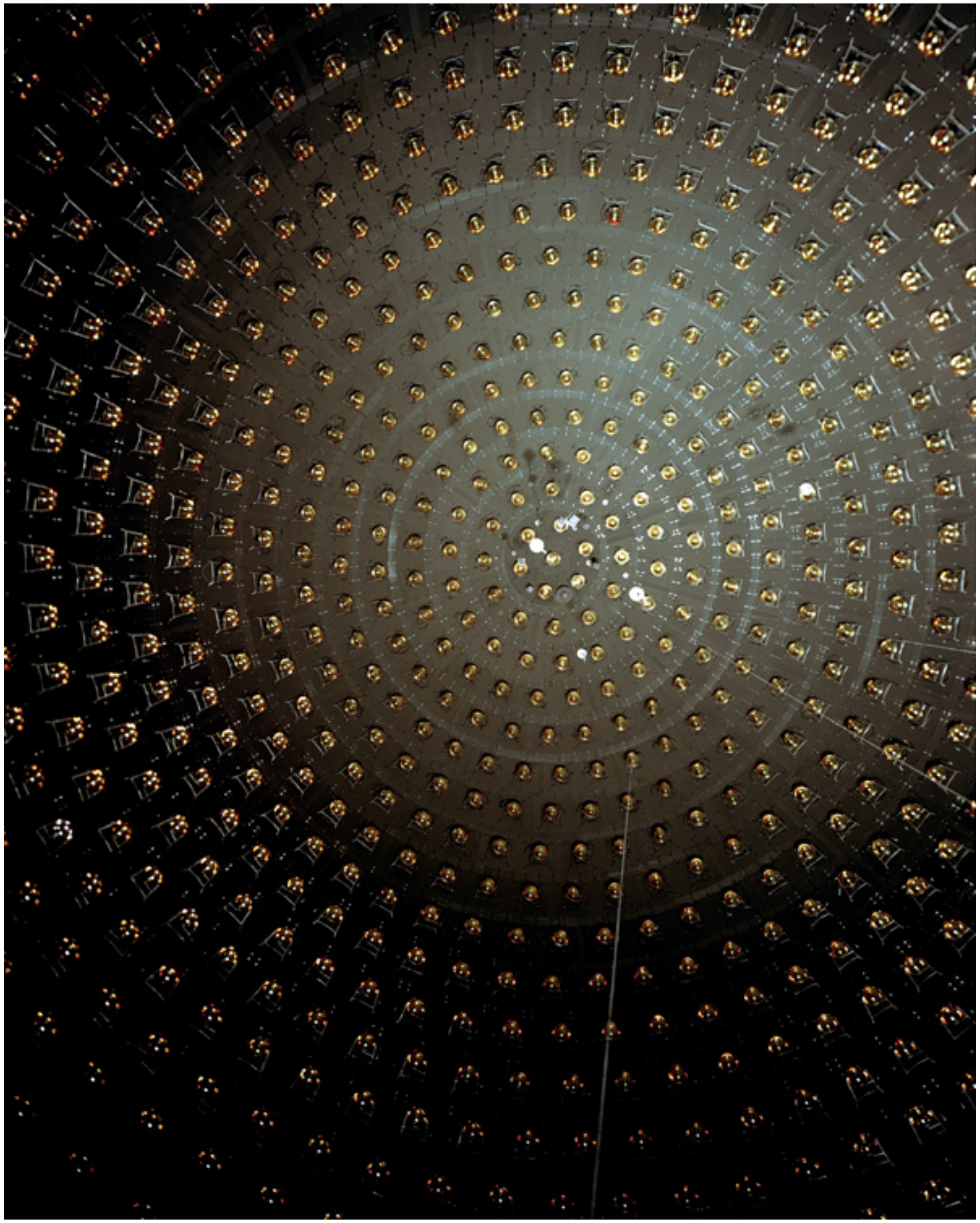
The discovery of light, sterile neutrinos would open up a whole new area of neutrino physics research. In addition to being important for nuclear and particle physics, sterile neutrinos would have a large impact on astrophysics and cosmology. In particular, sterile neutrinos could play a role in dark matter.

D. What is the international context, and how does it affect your vision?

The SNS is unique in the world and provides the U.S. with the rare opportunity to do a significant experiment in neutrino physics. Studies with radioactive sources or reactors allow investigation of the disappearance of ν_e $\bar{\nu}_e$. *A stopped pion and muon source uniquely allows the precise investigation of the disappearance of both* ν_μ *and* ν_e *as well as* $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ *oscillationis.*

Backup

MiniBooNE Detector Tank

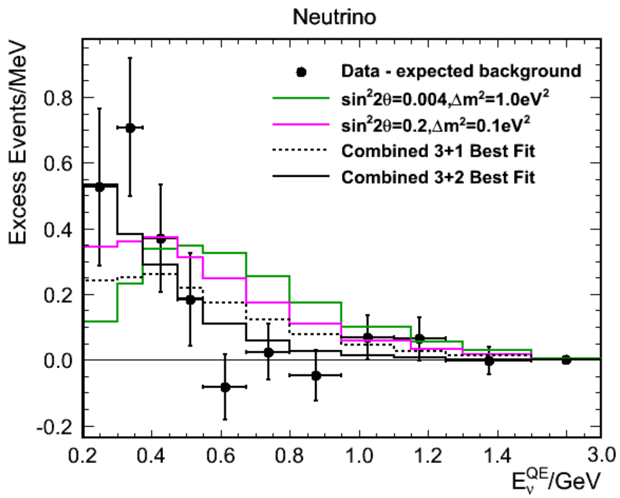


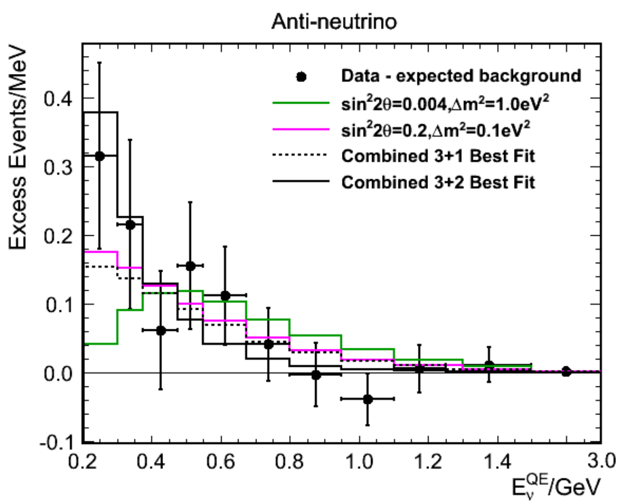
800 tons of mineral oil; add ~0.031 g/l of b-PBD

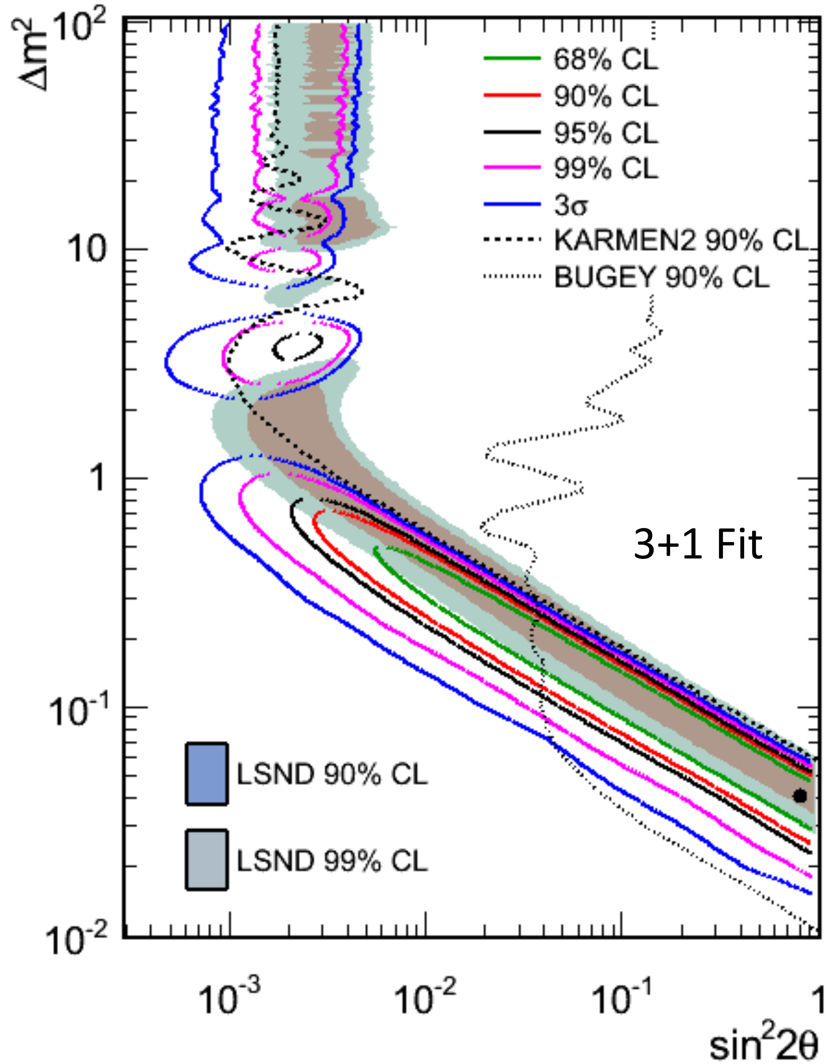
10% -> 25% Photocathode coverage with 8” Hamamatsu Phototubes: R1408, R5912

Charge Resolution:
1.4 PE, 0.5 PE
Time Resolution:
1.7 ns, 1.1ns

MiniBooNE Event Excesses

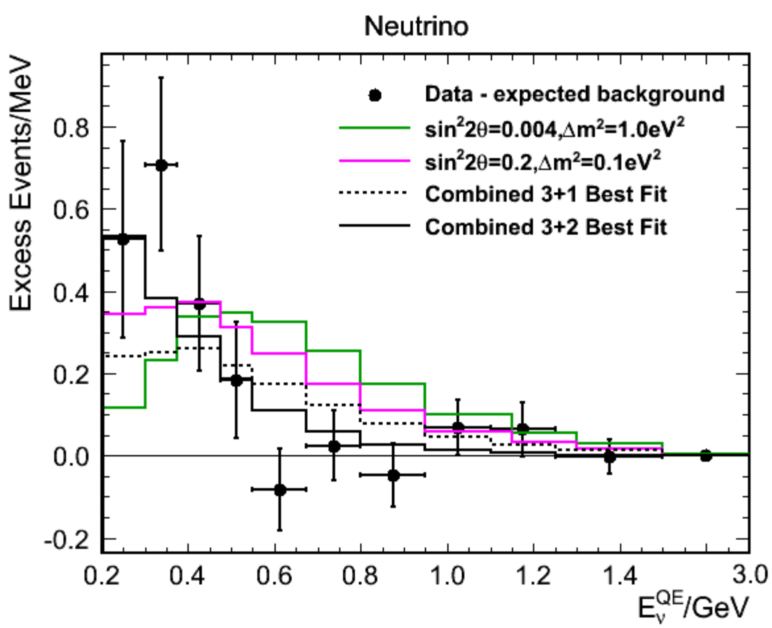


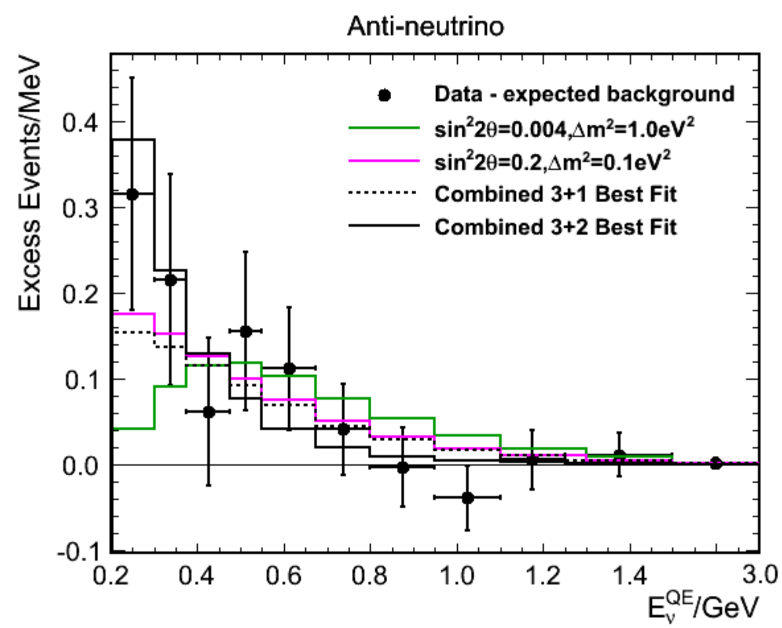




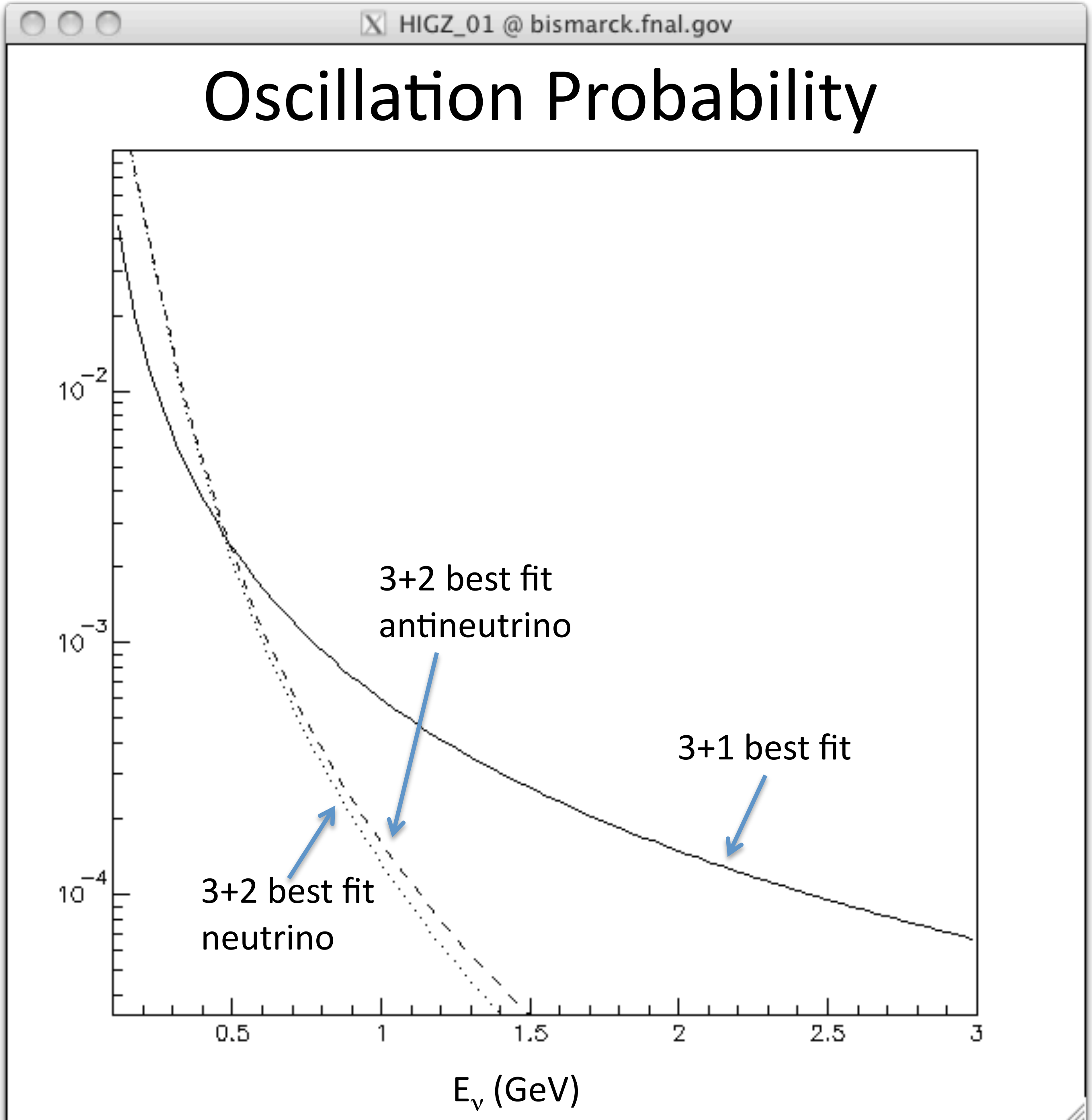
Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)

MiniBooNE Event Excesses

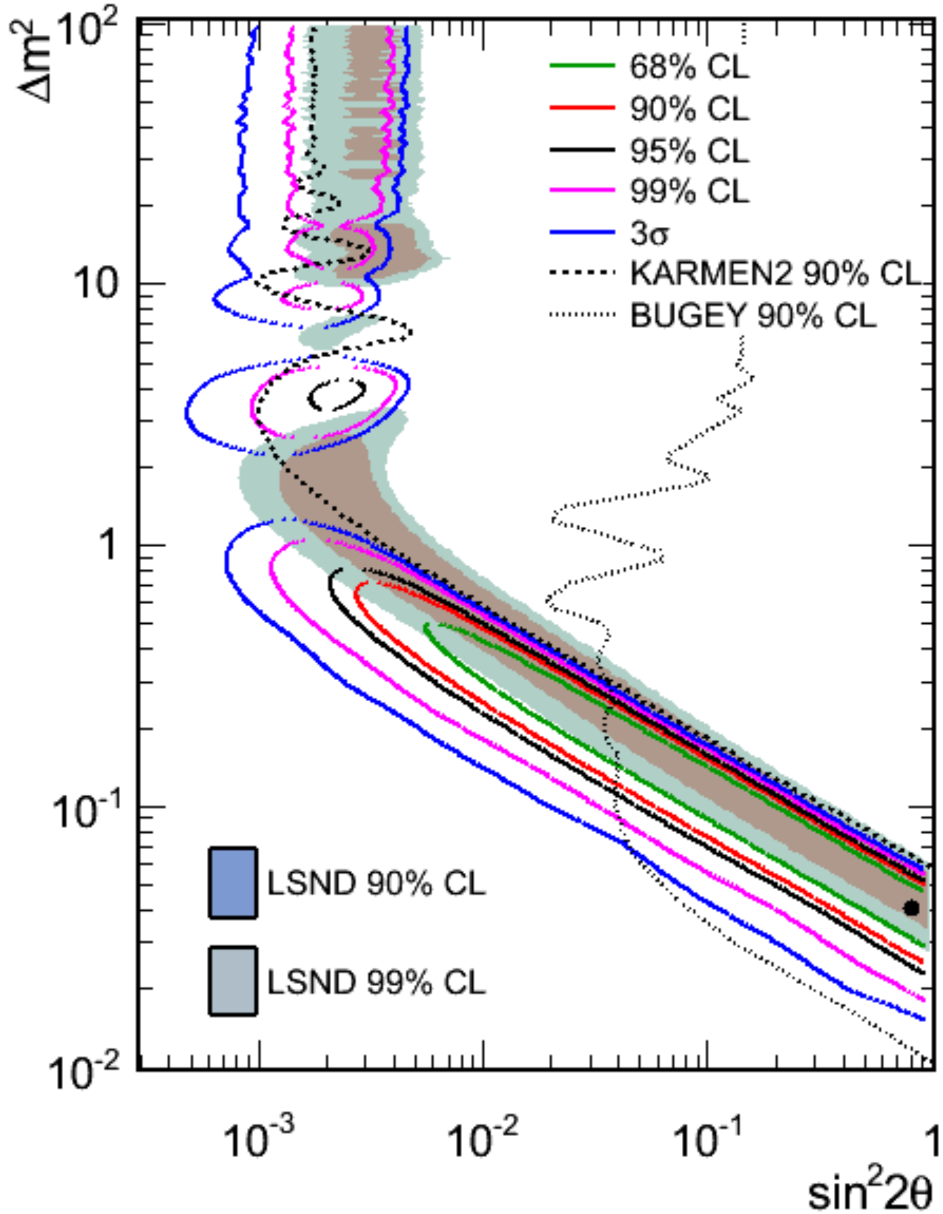




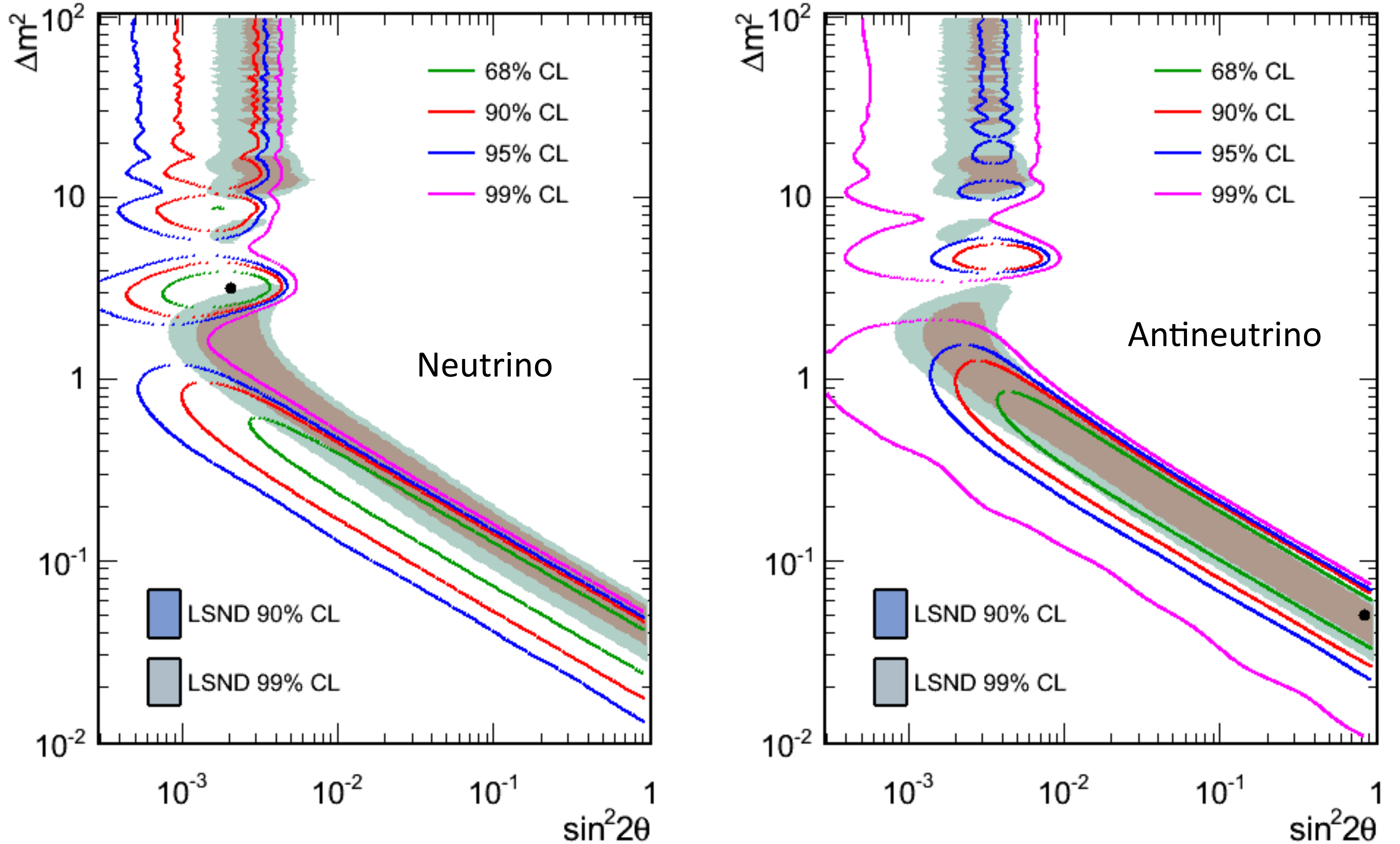
Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)


HIGZ_01 @ bismarck.fnal.gov
Oscillation Probability
3+2 best fit
antineutrino
3+1 best fit
3+2 best fit
neutrino
10^{-2}
10^{-3}
10^{-4}
0.5
1
1.5
2
2.5
3
E_ν (GeV)

MiniBooNE Combined Neutrino + Antineutrino 3+1 Fit

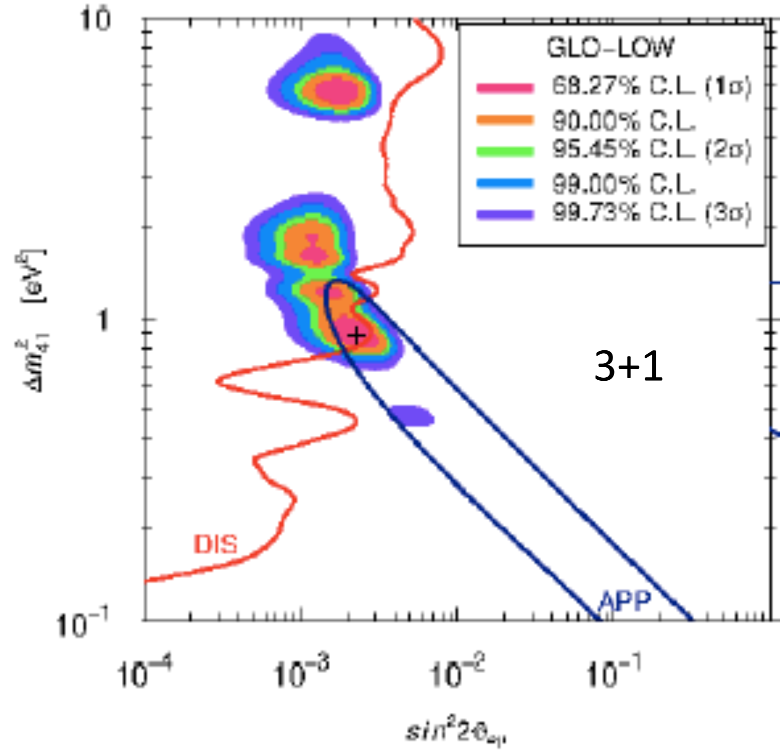


MiniBooNE Allowed Regions



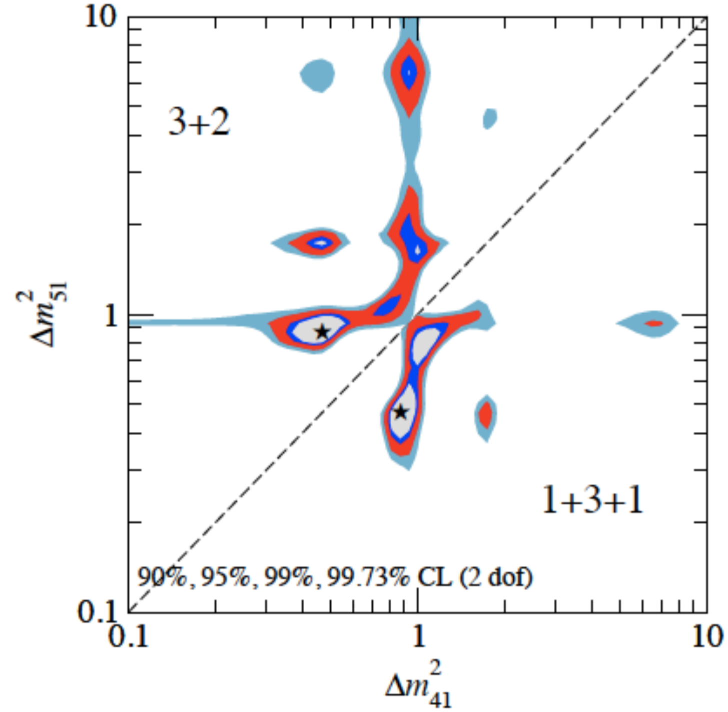
3+N Global Fits to World ν Data

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%)

The OscSNS White Paper

April 30, 2012

S. Habib, I. Stancu
University of Alabama, Tuscaloosa, AL 35487

B. M. Yeh
Brookhaven National Laboratory, Upton, NY 11973

R. Svoboda
University of California, Davis, CA 95616

B. Osmanov, H. Ray
University of Florida, Gainesville, FL 32611

R. Tayloe
Indiana University, Bloomington, IN 47405

G. T. Garvey, W. Huelsnitz, W. C. Louis, G. B. Mills,
Z. Pavlovic, R. Van de Water, D. H. White
Los Alamos National Laboratory, Los Alamos, NM 87545

R. Imlay
Louisiana State University, Baton Rouge, LA 70803

B. P. Roe
University of Michigan, Ann Arbor, MI 48109

M. Chen
Oak Ridge National Laboratory, Oak Ridge, TN 37831

Y. Efremenko
Oak Ridge National Laboratory, Oak Ridge, TN 37831
University of Tennessee, Knoxville, TN 37996

F. T. Avignone, S. R. Mishra, C. Rosenfeld
University of South Carolina, Columbia, SC 29208

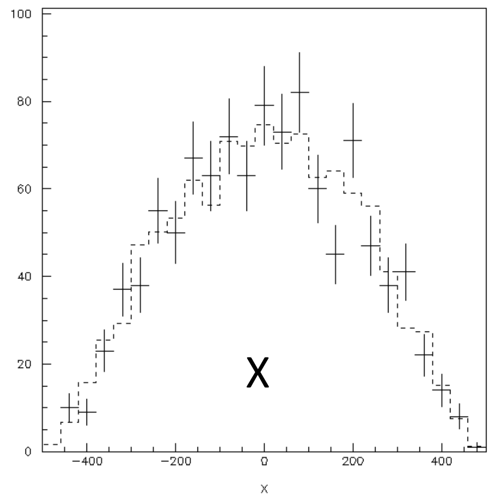
J. M. Link
Virginia Tech, Blacksburg, VA 24060

Contact Persons: H. Ray and W. C. Louis

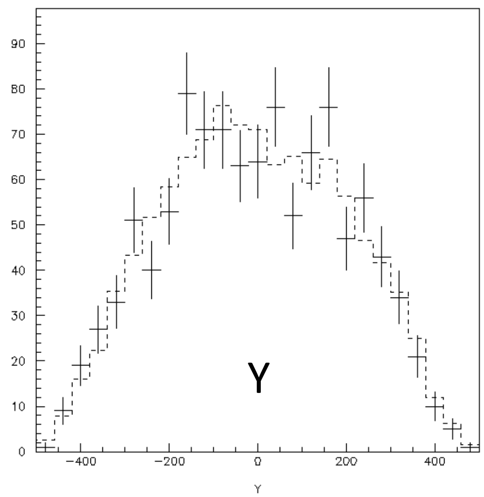
http://www.phys.ufl.edu/~hray/oscsns/

MB Spatial Distributions

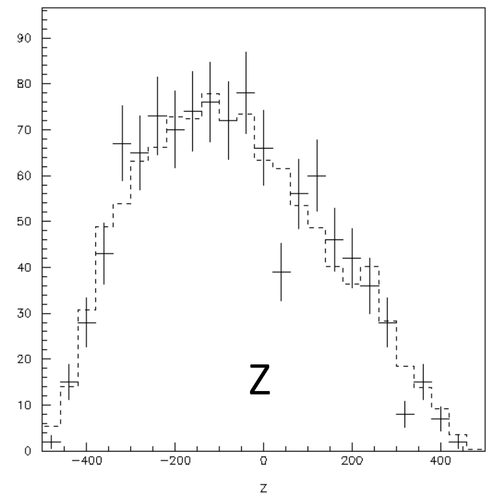
Neutrino



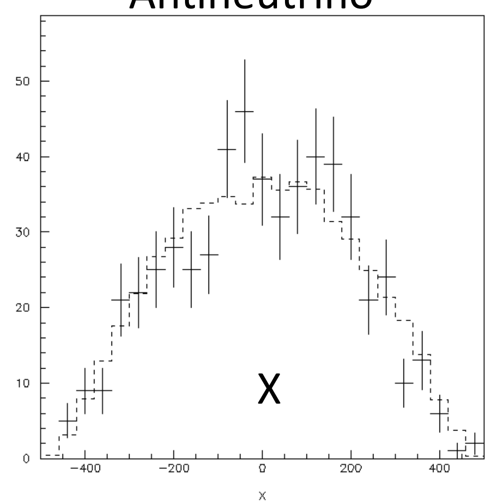
Neutrino



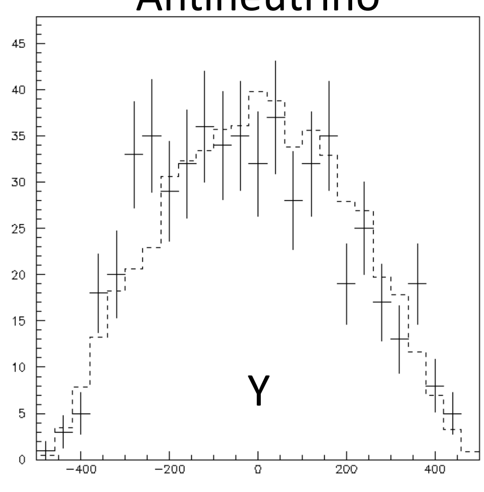
Neutrino



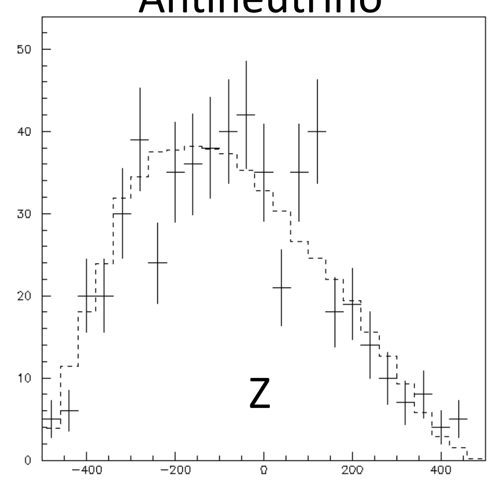
Antineutrino



Antineutrino



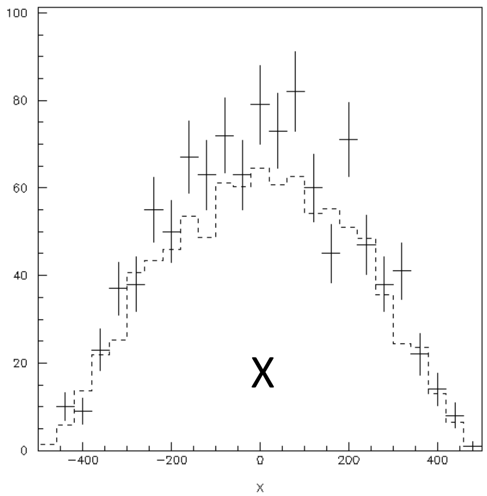
Antineutrino



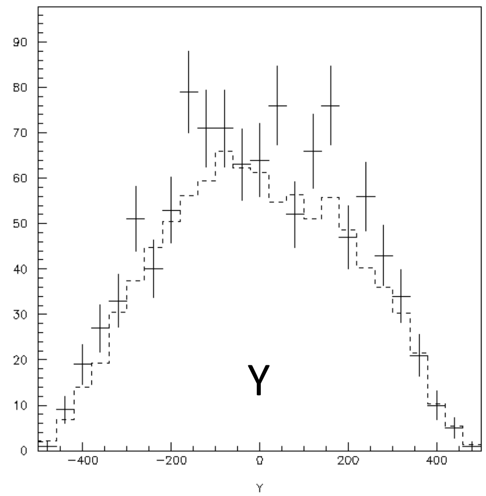
Relative Normalization

MB Spatial Distributions

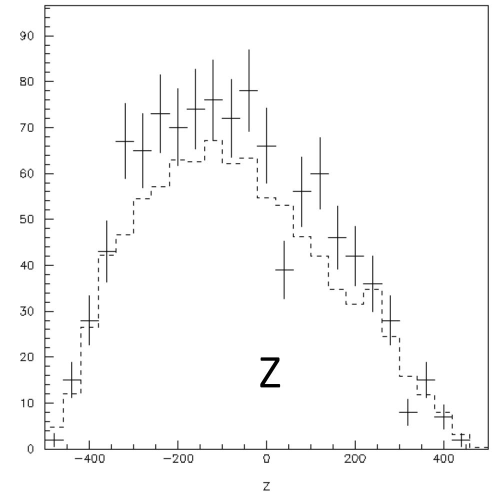
Neutrino



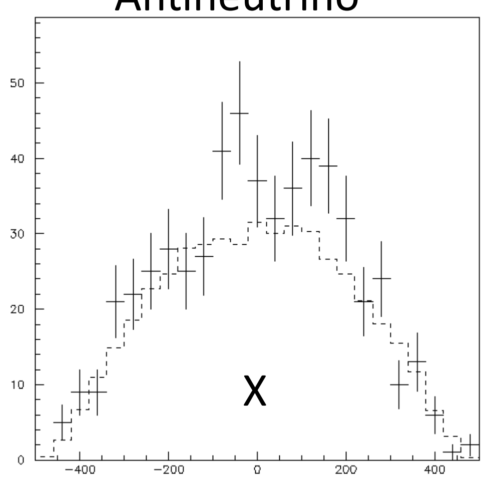
Neutrino



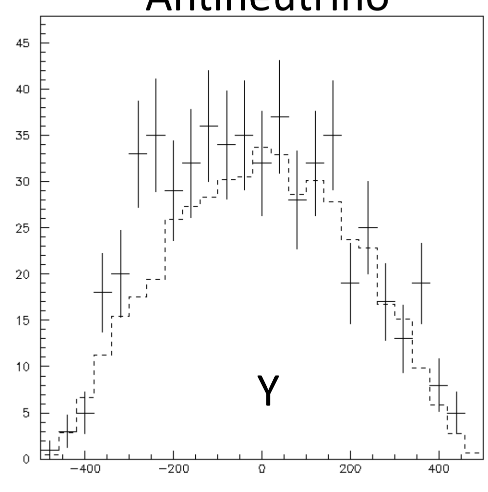
Neutrino



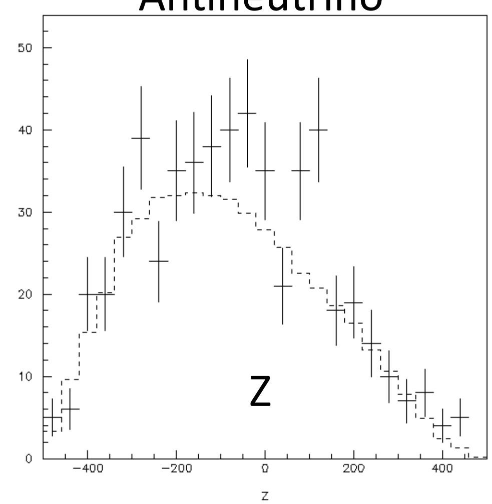
Antineutrino



Antineutrino



Antineutrino



Absolute Normalization

MB Spatial Distributions
(Statistical Errors Only)

Neutrino

$<X_{Data}>-<X_{MC}> = -0.2+-6.8$

$<Y_{Data}>-<Y_{MC}> = -2.2+-6.9$

$<Z_{Data}>-<Z_{MC}> = -4.4+-6.7$

Antineutrino

$<X_{Data}>-<X_{MC}> = -2.1+-8.7$

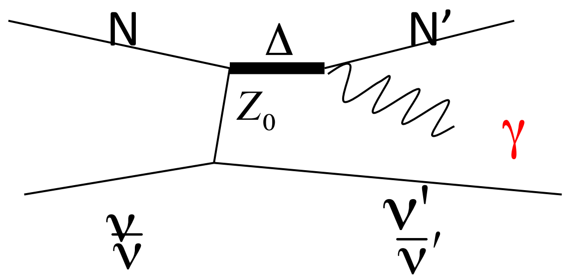
$<Y_{Data}>-<Y_{MC}> = -16.4+-9.2$

$<Z_{Data}>-<Z_{MC}> = 14.0+-8.9$

χ^2 = 6.2/6 DF (Prob = 40%)

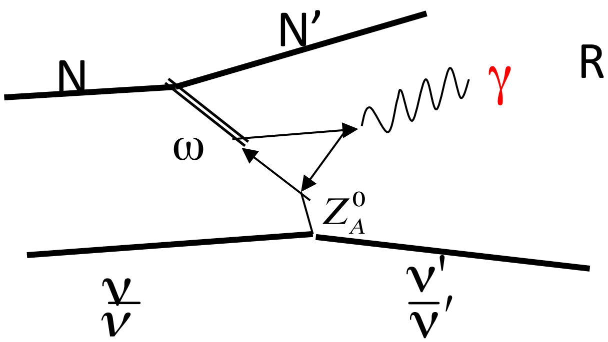
Backgrounds: Order ($G^2\alpha\alpha_s$) , single γ FS?

Dominant process accounted for in MC!

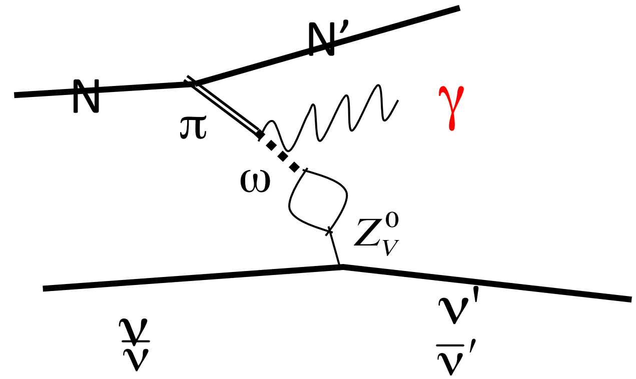


($G^2\alpha/\alpha_S$)

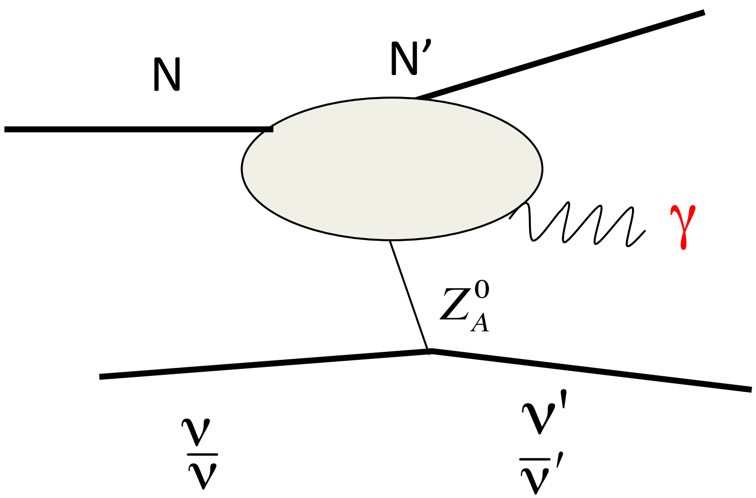
Radiative Delta Decay



Axial Anomaly



Other PCAC



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

R. Hill, arXiv:0905.0291

Jenkins & Goldman, arXiv:0906.0984

Serot & Zhang, arXiv:1011.5913; 1206.3812

NCγ Background Estimates

- <E_ν> ~ 800 MeV for π^0 production in MB
- MB: <$\sigma_{\pi 0}$> ~ $5\text{x}10^{-40}$ cm^2/N
- MB: <σ_γ> ~ $5\text{x}10^{-42}$ cm^2/N
- Richard Hill: <σ_γ> ~ $6.7\text{x}10^{-42}$ cm^2/N (Δ: 5.0; Compton: 0.9; ω: 0.1; Coh: 0.7)
- Xilin Zhang: <σ_γ> ~ $3.7\text{x}10^{-42}$ cm^2/N (Incoh: 3.0; Coh: 0.7); Zhang believes that the background estimates from Hill are overestimated by a factor of ~2 due to nuclear effects

- The NC γ background estimates from Hill & Zhang are fairly consistent with the MB estimates

Corrections to the HARP-CDP Analysis of the LSND Neutrino Oscillation Backgrounds

G. T. Garvey, W. C. Louis, G. B. Mills, & D. H. White
Los Alamos National Laboratory; Los Alamos, NM 87545

(Dated: December 12, 2011)

Several mistakes have been found in recent papers that purport to reanalyze the backgrounds to the LSND neutrino oscillation signal. Once these mistakes are corrected, then it is determined that the background estimates in the papers are close to (if not lower than) the LSND background estimate.

The HARP-CDP group analyzed the pion production data taken by the HARP experiment at CERN with 1.5 GeV/c protons incident on a Be target and performed a reanalysis [1, 2] of the backgrounds to the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation signal [3]. LSND observed a beam-on minus beam-off excess of 117.9 ± 22.4 events. After subtracting a neutrino background of 30.0 ± 6.0 events, LSND determined the oscillation signal to be 87.9 ± 23.2 events [3]. The HARP-CDP group estimates a higher neutrino background of 46.7 ± 20.6 events, which leads to an oscillation signal of 71.2 ± 30.4 events [2]. However, the HARP-CDP group made several errors in making their background estimate. The most egregious errors are discussed below.

HARP-CDP multiplies the intrinsic $\bar{\nu}_e$ background by a factor of 1.6, which is the ratio of "Emulation"/"Best Estimate" $\bar{\nu}_e$ in Table 15 [1]. However, this neglects the fact that HARP-CDP overestimates the decay at rest (DAR) fluxes and does not normalize to the ν_e flux. Thus, HARP-CDP instead should use a factor of 1.21, which is the ratio of "Emulation"/"Best Estimate" $\bar{\nu}_e/\bar{\nu}_\mu$ in Table 15. This increases the intrinsic $\bar{\nu}_e$ background by 4.1 events (from 19.5 to 23.6 total events) instead of by 11.7 events.

In Table 15 of the first HARP-CDP paper [1], the π^+ and π^- decay in flight (DIF) fluxes are factors of 3.3 and 2.5 higher in the "Best Estimate" than in the fluxes used by LSND [3]. However, LSND has made high statistics measurements of ν_μ and $\bar{\nu}_\mu$ scattering [4], and the HARP-CDP "Best Estimate" DIF fluxes are inconsistent with LSND measurements. For example, for $\bar{\nu}_\mu p \to \mu^+ n$ scattering, LSND observes 214 ± 35 events, which is consistent with the flux estimate and a factor of 3.3 times lower than the HARP-CDP flux estimate. For $\nu_\mu C \to \mu^- N_{gs}$ scattering, LSND observes 66.9 ± 9.1 events, which is consistent with the flux estimate and a factor of 2.5 times lower than the HARP-CDP flux estimate. Therefore, it is clear that HARP-CDP is overestimating the DIF flux and overestimating the number of DIF events observed in LSND by factors of 2.5-3.3. As the intrinsic $\bar{\nu}_e$ background all comes from π^- DIF, this implies that the HARP-CDP intrinsic $\bar{\nu}_e$ background estimate should be reduced by a large factor (up to a factor of 3.3).

In Table 17, the first HARP-CDP paper [1] discusses the backgrounds from $\bar{\nu}_\mu p \to \mu^+ n$, where the μ^+ is not observed if it is too low in energy ($T_\mu < 3$ MeV). However, 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 phototube (PMT) hit distribution down to zero. Therefore, the HARP-CDP background estimate of 13.8 events is overestimated, and HARP-CDP should use the LSND value of 10.5 events instead.

The second HARP-CDP paper [2] estimates a background of 2.3 events from $\nu_e C \to e^- N_{gs}$ events, where the N_{gs} beta decay mimics a 2.2 MeV γ from neutron capture. However, this background is overestimated, partly because a 2.2 MeV positron produces more PMT hits than a 2.2 MeV γ. A 2.2 MeV γ produces the same number of PMT hits as an $\sim 1 - 1.5$ MeV positron, including the energy from positron-electron annihilation. In the LSND analysis, these N_{gs} beta decays that mimic 2.2 MeV γs are determined to be very small (~ 0.2 events just to pass the minimal cuts). Indeed, LSND determined that the R distribution of N_{gs} events looks indistinguishable from the R distribution of N inclusive events without a beta.

In summary, using the corrected estimate of the intrinsic $\bar{\nu}_e$ background of 23.6 events, the HARP-CDP excess should be 83.7 events, which agrees reasonably well with the LSND estimate of 87.9 ± 23.2 events. However, this ignores the problem with the HARP-CDP DIF fluxes, which overestimate the intrinsic $\bar{\nu}_e$ backround. For example, if the HARP-CDP intrinsic $\bar{\nu}_e$ flux is reduced by a factor of 3.3 to make the DIF estimates agree with LSND data, then the HARP-CDP $\bar{\nu}_e$ background decreases to 7.1 events and the excess increases to 100.2 ± 23.2 events.

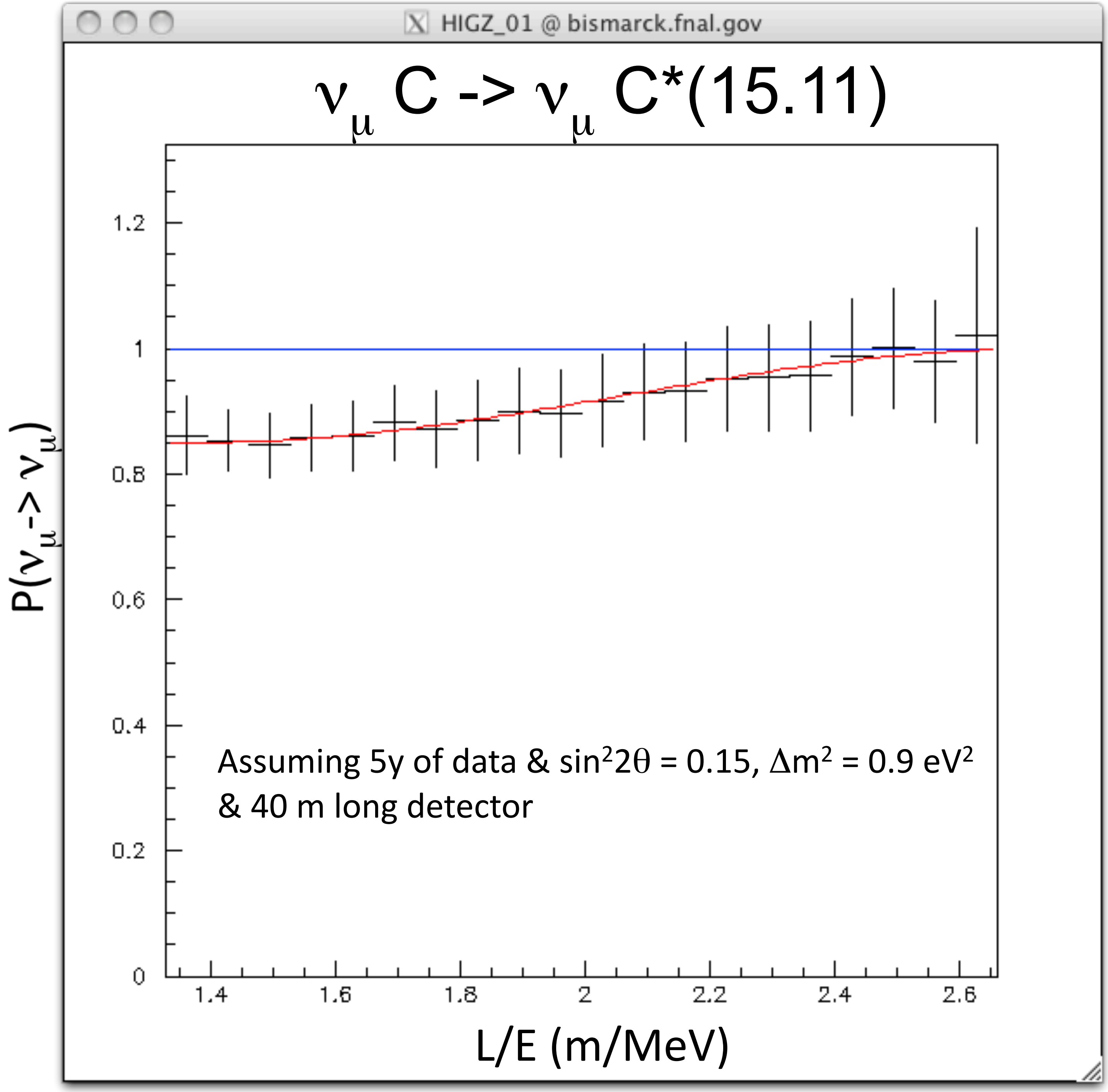
[1] A. Bolshakova *et al.*, arXiv:1110.4265 [hep-ex].
[2] A. Bolshakova *et al.*, arXiv:1112.0907 [hep-ex].
[3] A. Aguilar *et al.*, Phys. Rev. D 64, 112007 (2001).
[4] L. B. Auerbach *et al.*, Phys. Rev. C 66, 015501 (2002).

LSND vs HARP-CDP: Number of DIF ν Events

Process	**LSND Data**	**LSND Flux Estimate**	**HARP-CDP Flux Estimate**
ν_μ C -> μ^- N_{gs}	77.8+-8.9	78+-8	184+-18
ν_μ C -> μ^- X	2464+-50	3208+-642	6382+-1276
$\bar{\nu}_\mu$ p -> μ^+ n	286+-27	389+-78	1176+-235

Therefore, the LSND DIF flux estimate agrees well with LSND data; however, HARP-CDP has overestimated the DIF flux by a factor of ~2-3.

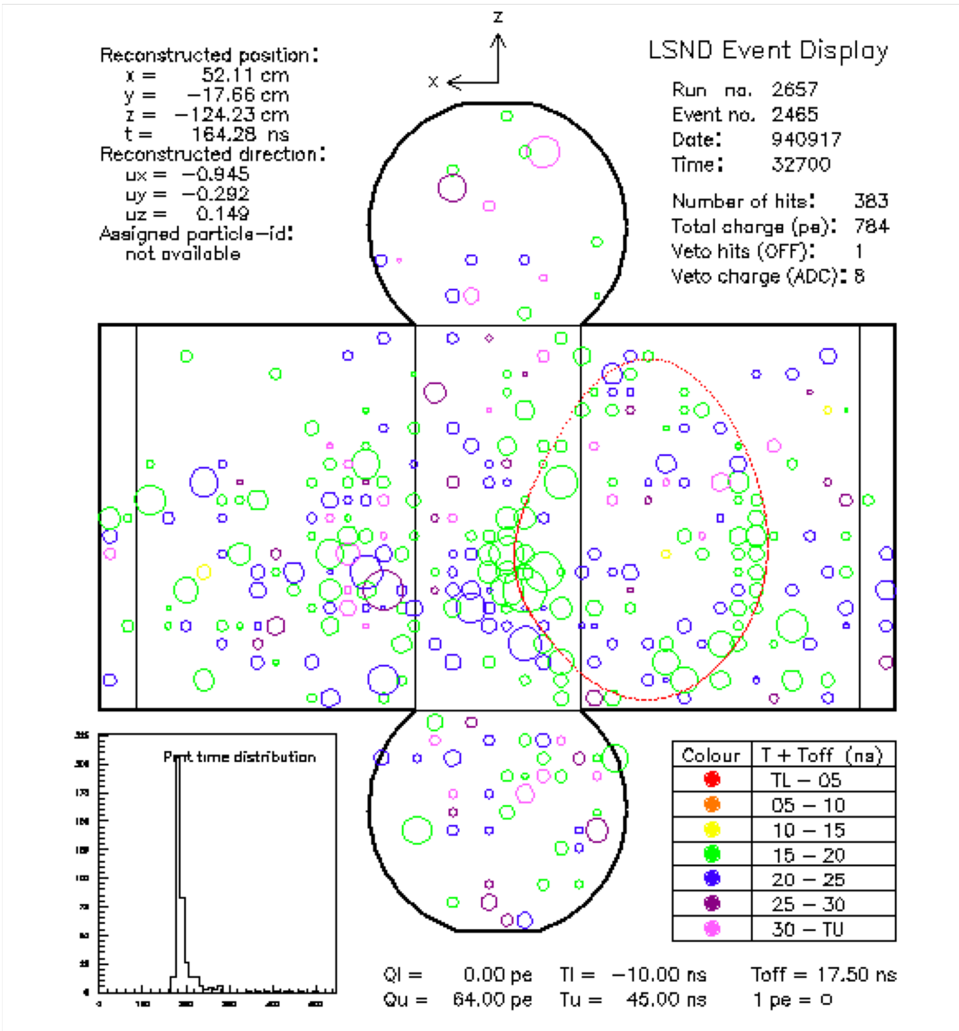
- LSND data from Phys. Rev. C66, 015501 (2002)
- Relative neutrino fluxes from Table 15 of arXiv:1110.4265 [hep-ex]; (HARP-CDP neutrino flux is 2.50 times larger than LSND neutrino flux & HARP-CDP antineutrino flux is 3.27 times larger than LSND antineutrino flux)
- C cross sections from Hayes & Towner, Phys. Rev. C61, 044603 (2000); 10% systematic error for exclusive reactions & 20% systematic error for inclusive reactions


HIGZ_01 @ bismarck.fnal.gov
ν_μ C -> ν_μ C*(15.11)
P(ν_μ -> ν_μ)
L/E (m/MeV)
Assuming 5y of data & $\sin^2 2\theta$ = 0.15, Δm^2 = 0.9 eV^2
& 40 m long detector

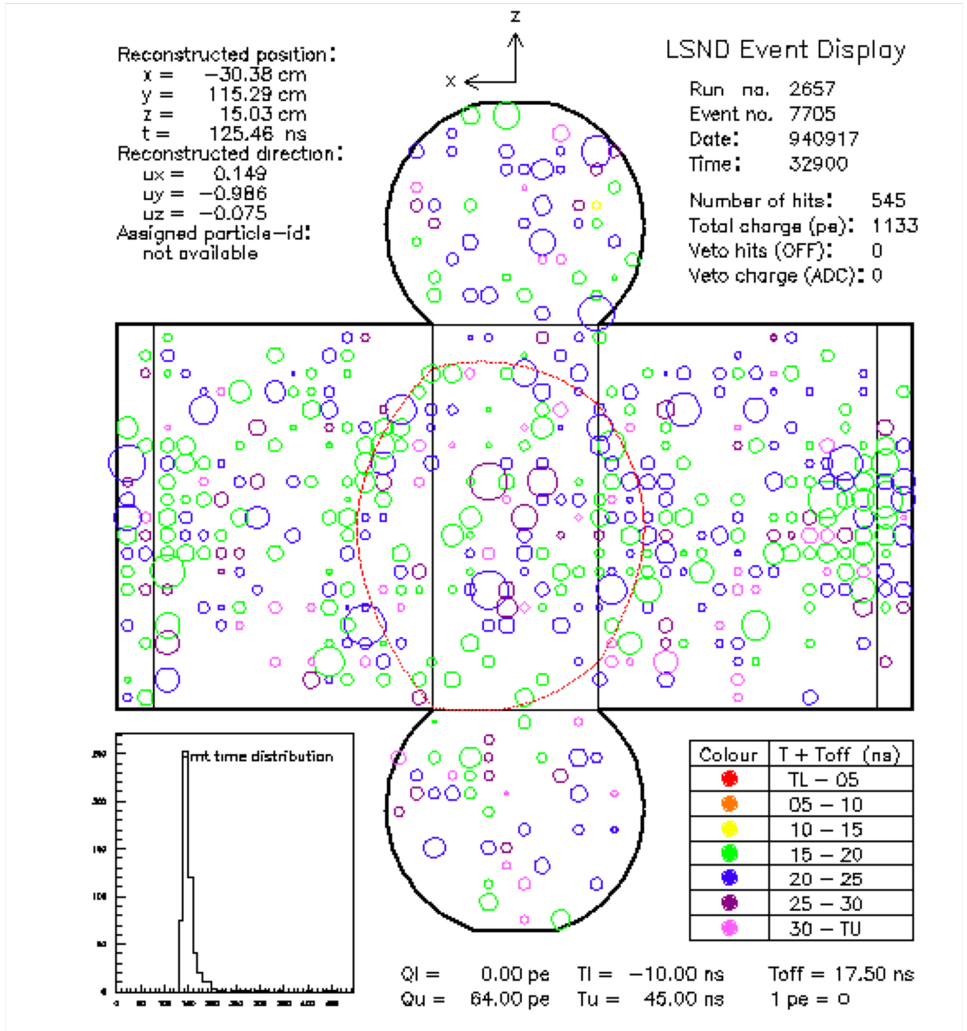
OscSNS Design Considerations

- Add Gd to oil?
- Size of detector
- Cylindrical or spherical detector
- b-PBD concentration
- PMT coverage
- Add near detector?

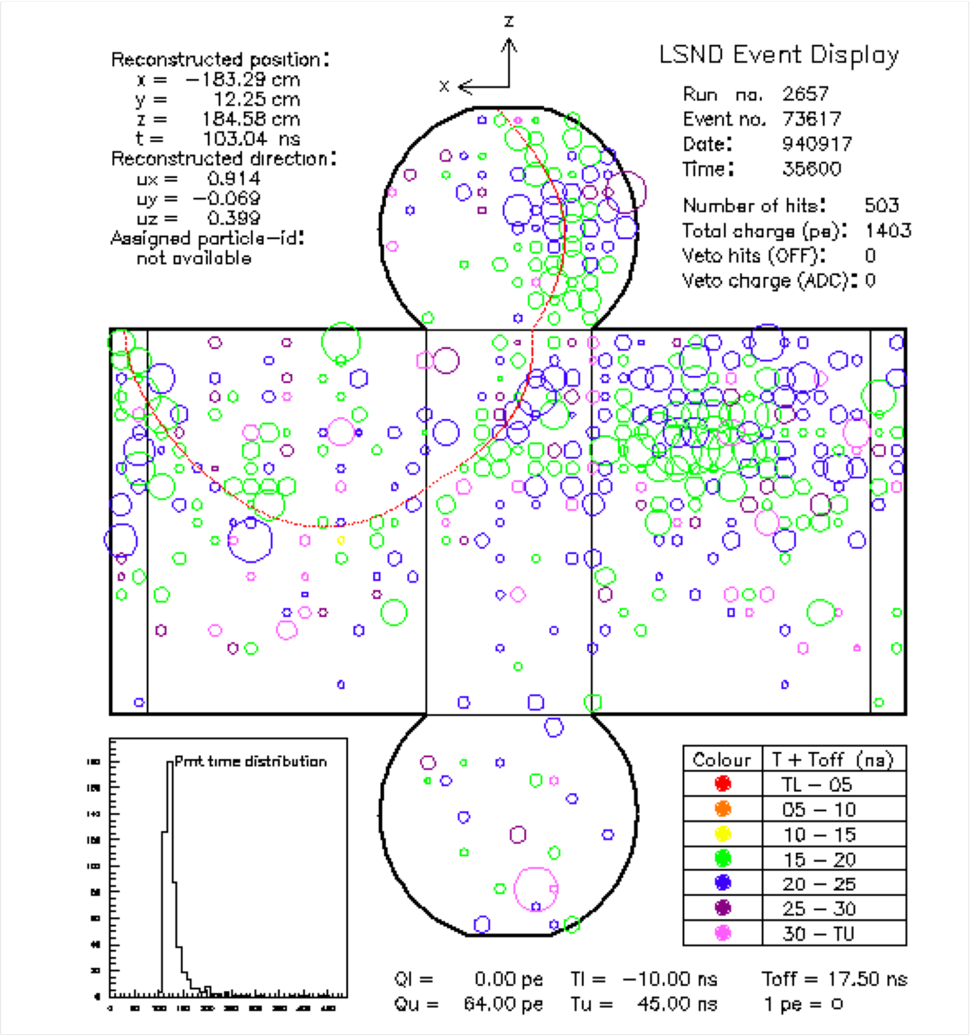
Typical Michel Electron Event Display



Typical Michel Electron Event Display



Typical Michel Electron Event Display



3+N Models Require Large ν_μ Disappearance!

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

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

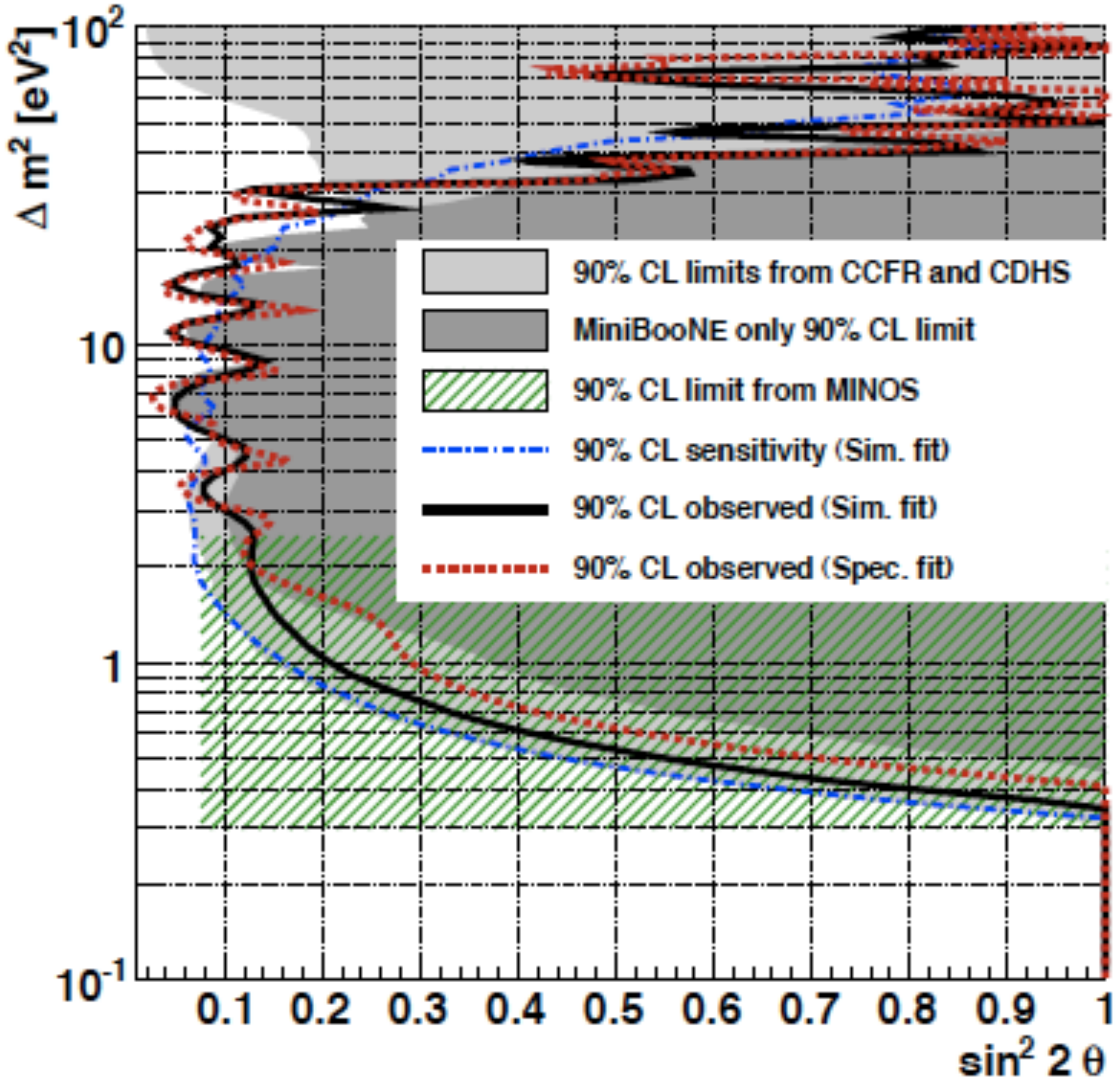
LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

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

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

SciBooNE/MiniBooNE Neutrino Disappearance Limits

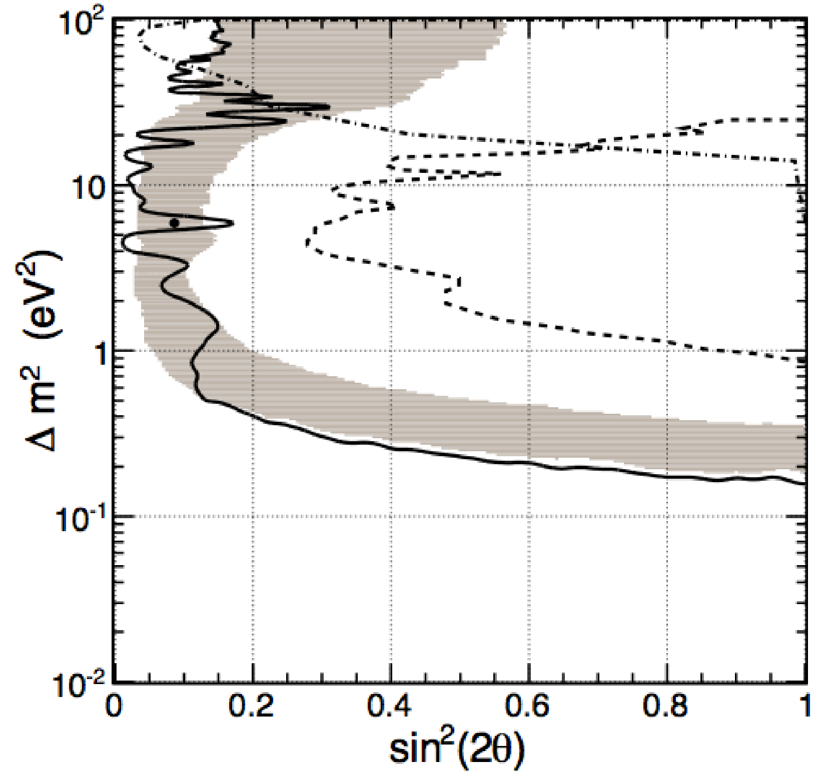
arXiv:1106.5685



Combined disappearance result

- Joint analysis:
- BF point $\Delta m^2 = 5.9$ eV^2, $\sin^2 2\theta = 0.086$
- $\chi^2 = 40.0$ (probability 47.1%) at the best fit point
- $\chi^2 = 43.5$ (probability 41.2%) for the null hypothesis
- With $\Delta\chi^2 = 3.5$, null is excluded at 81.9% CL

- Probabilities are based on fake data studies



G. Cheng, W. Huelsnitz