Short-Baseline Neutrino Oscillations & Sterile Neutrinos

W.C. Louis

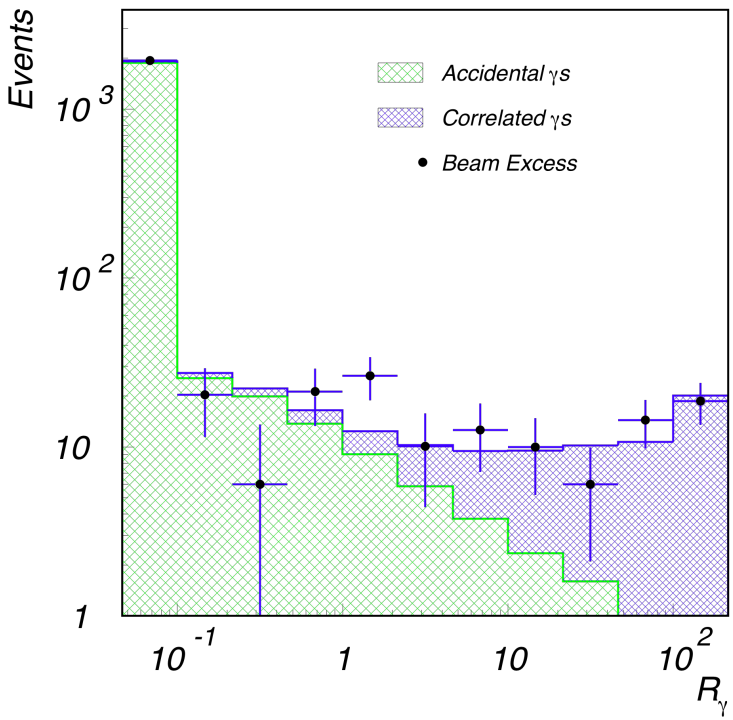
August 26, 2013

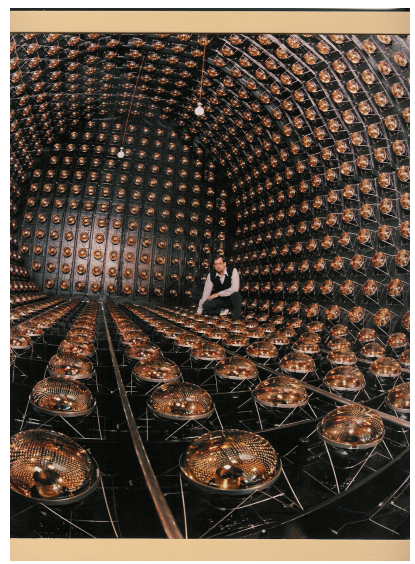
- Motivation from LSND
- MiniBooNE Neutrino & Antineutrino Oscillation Results
- Short-Baseline Neutrino Anomalies
- 3+N Neutrino Oscillation Models
- Next Step: Observe Oscillations in the Detector with OscSNS

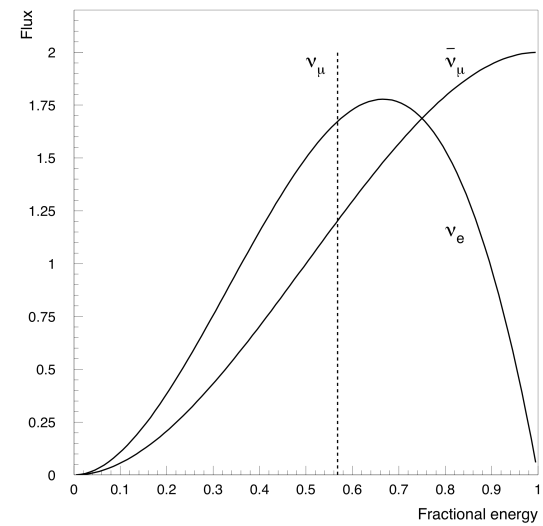
LSND Event Excess

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





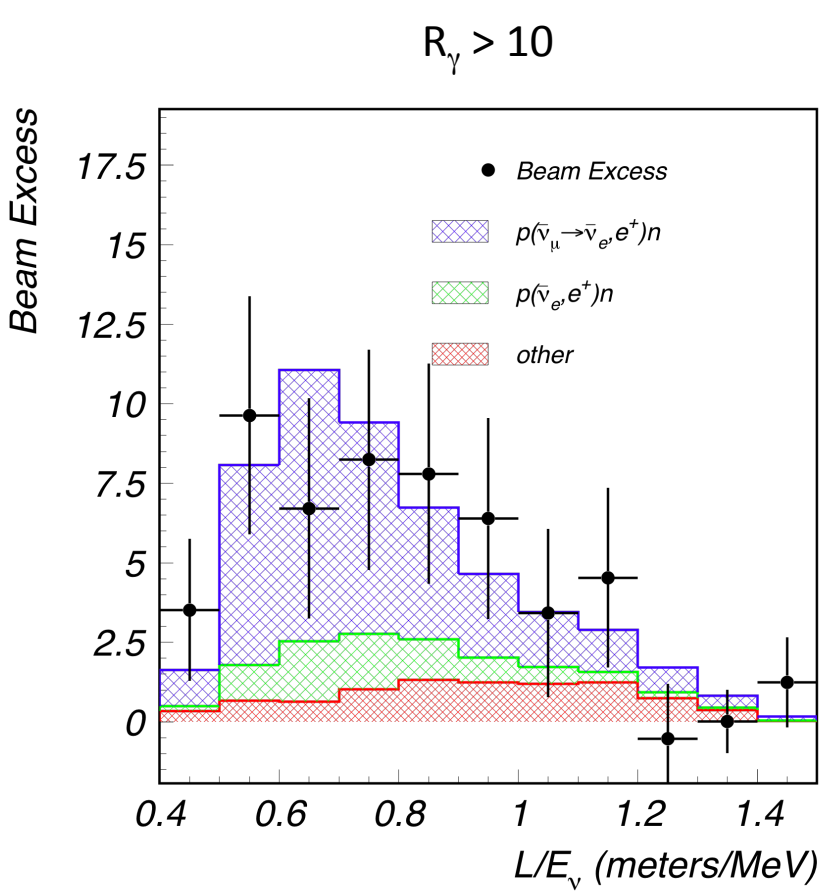


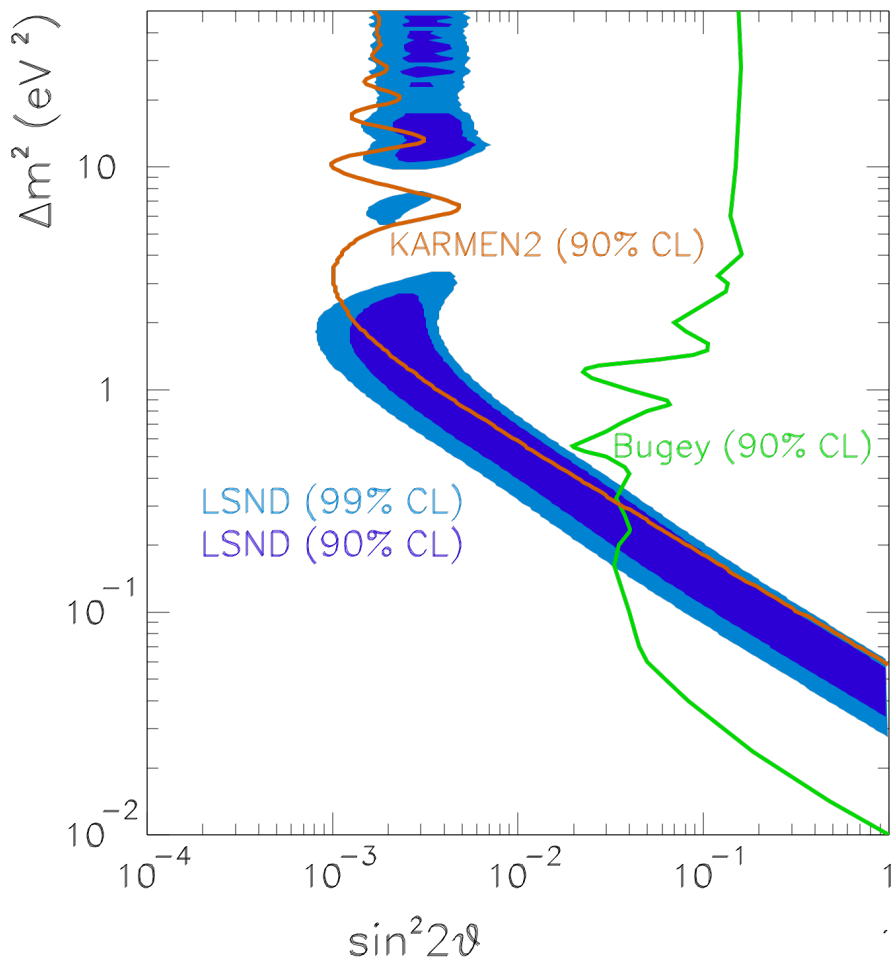
$\bar{\nu}_e$ p -> e^+ n, n p -> d γ(2.2 MeV)

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 Excesses

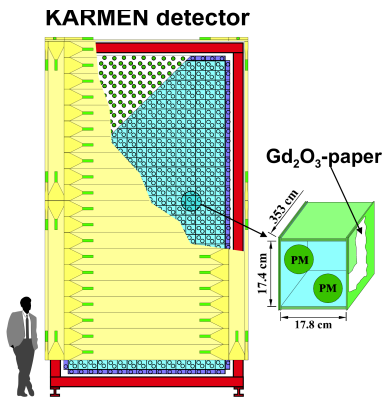
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)





Joint LSND/KARMEN Analysis

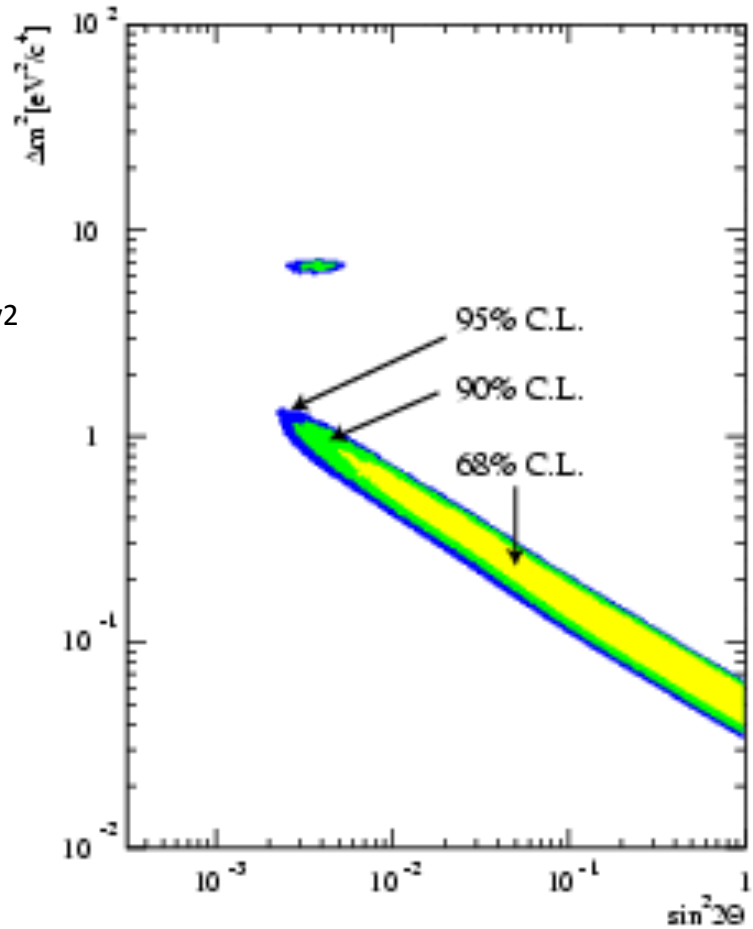
E. D. Church, K. Eitel, G. B. Mills, and M. Steidl, Phys. Rev. D66, 013001, (2002)

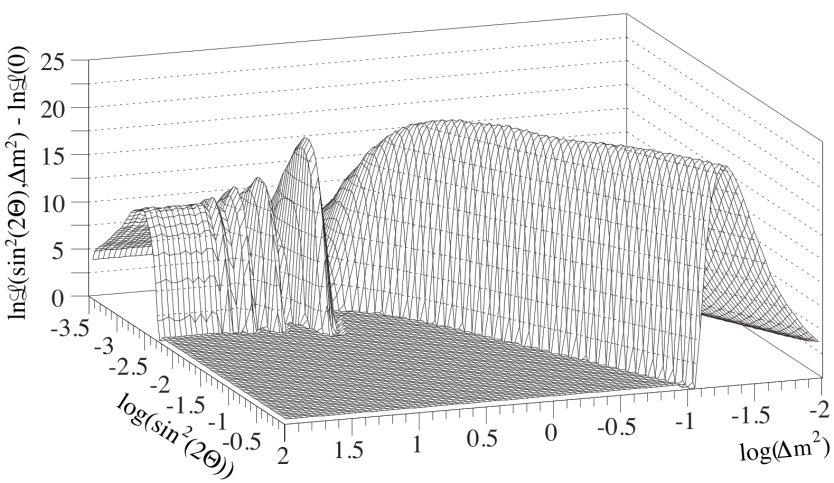


96% active volume of ^{12}C and p

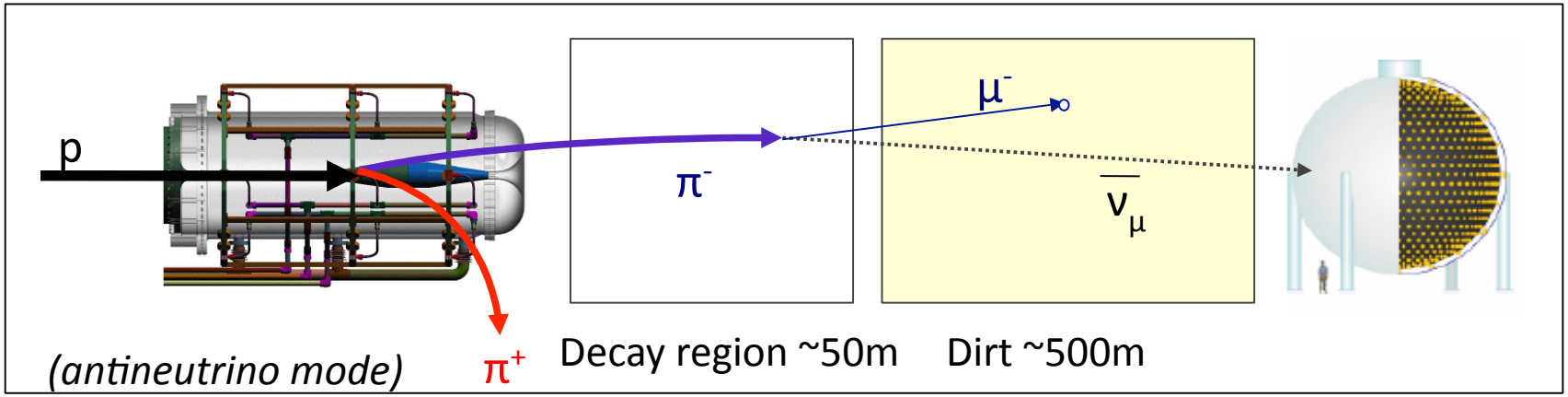
$$\varepsilon \quad \frac{11.5\%}{\sqrt{E[MeV]}} \qquad t_{ISIS} \quad 2ns$$

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



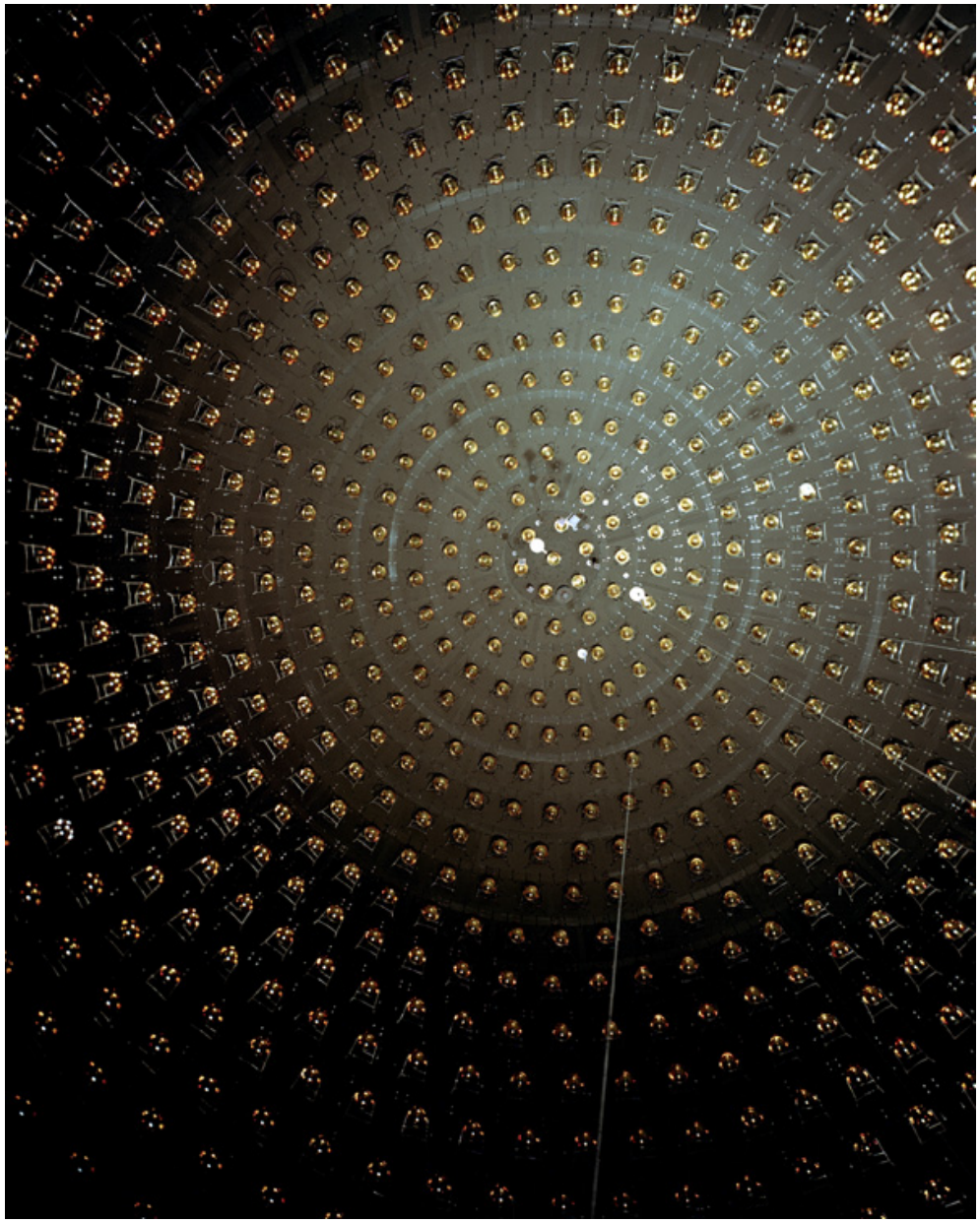


MiniBooNE Experiment



- Similar L/E as LSND for $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ & ν_μ -> ν_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 Detector Tank



800 tons of mineral oil

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

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

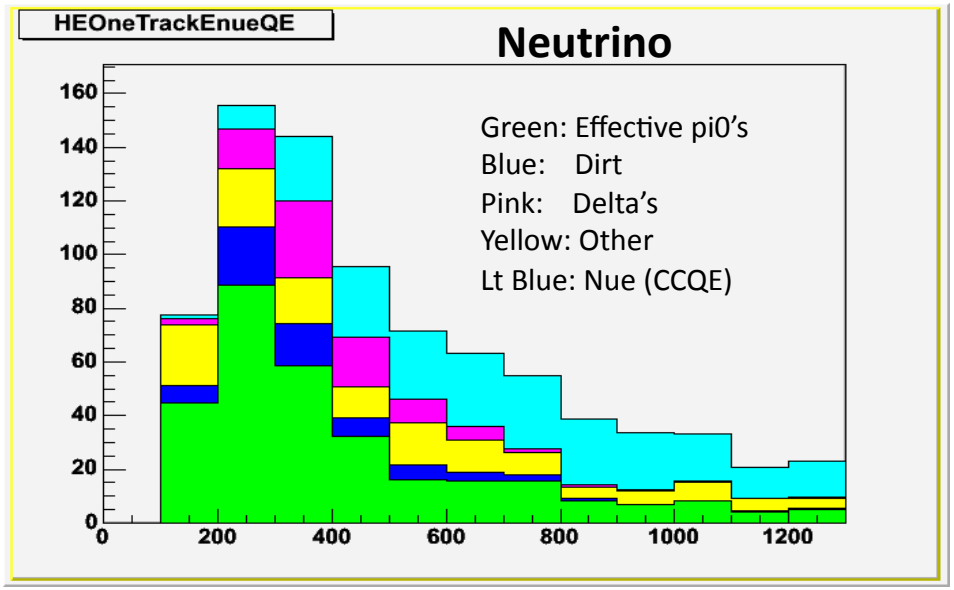
ν_e Background Event Rate Predictions

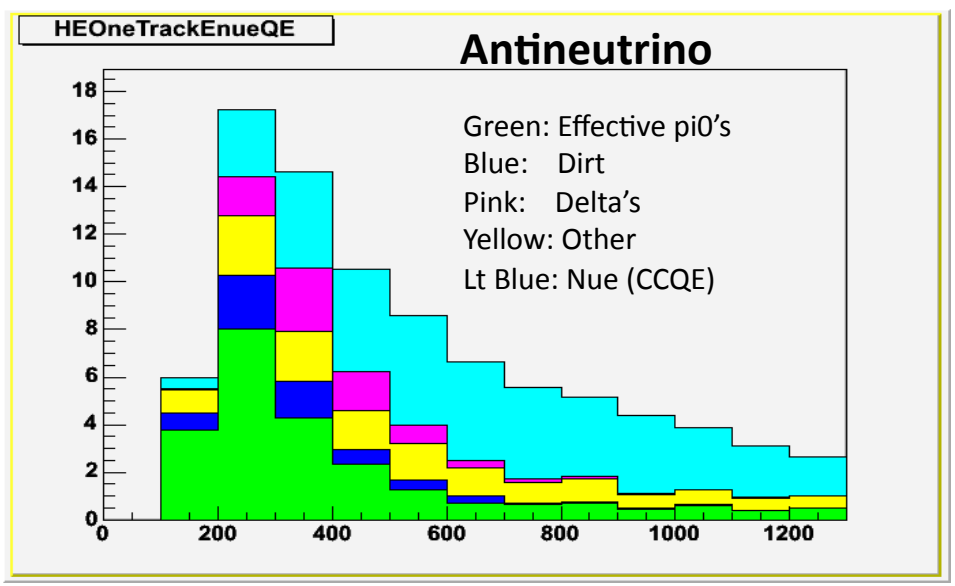
#Events = Flux x Cross-sections x Detector response

External measurements (HARP, etc)
ν_μ rate constrained by neutrino data

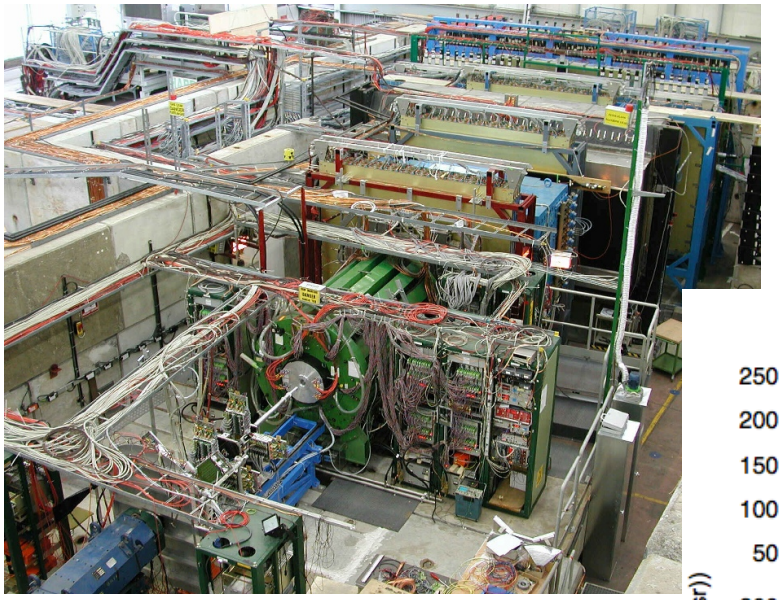
External and MiniBooNE Measurements
π^0, Δ , and dirt backgrounds constrained from data.

Detailed detector simulations checked with neutrino data and calibration sources.

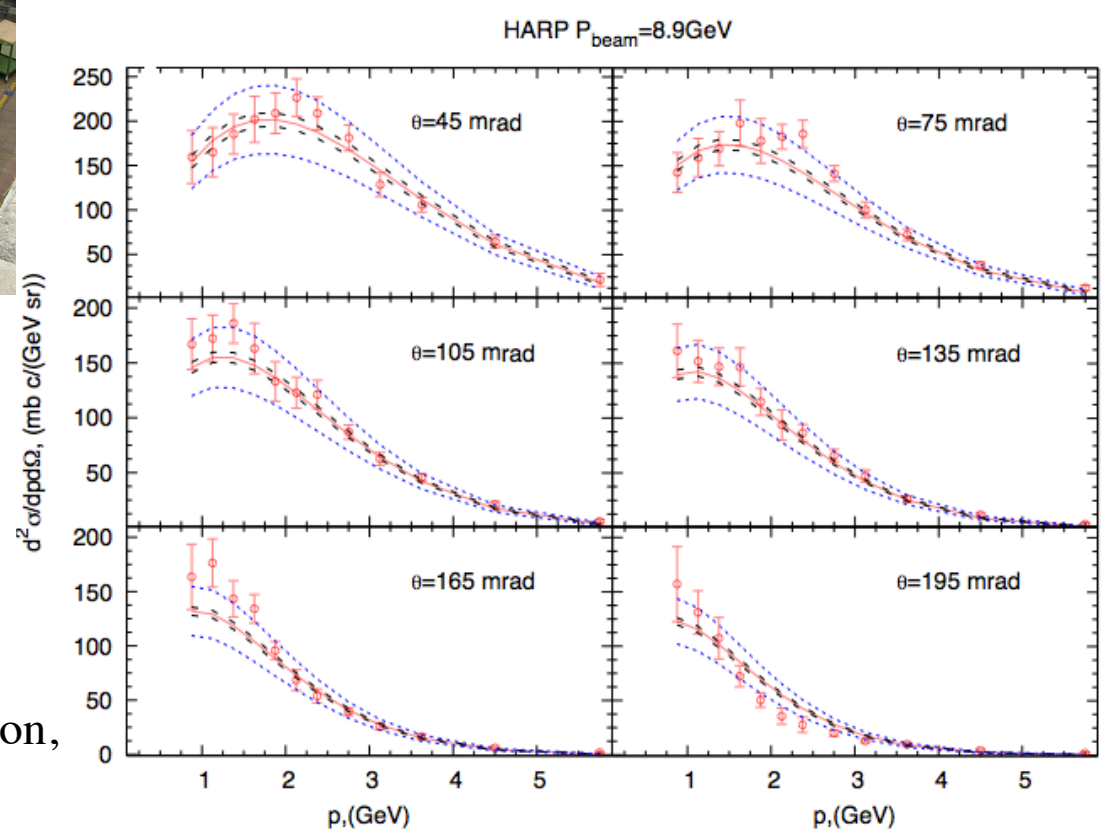




HARP: Measurement of Secondary Pions



- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum
  - π^+ & π^-

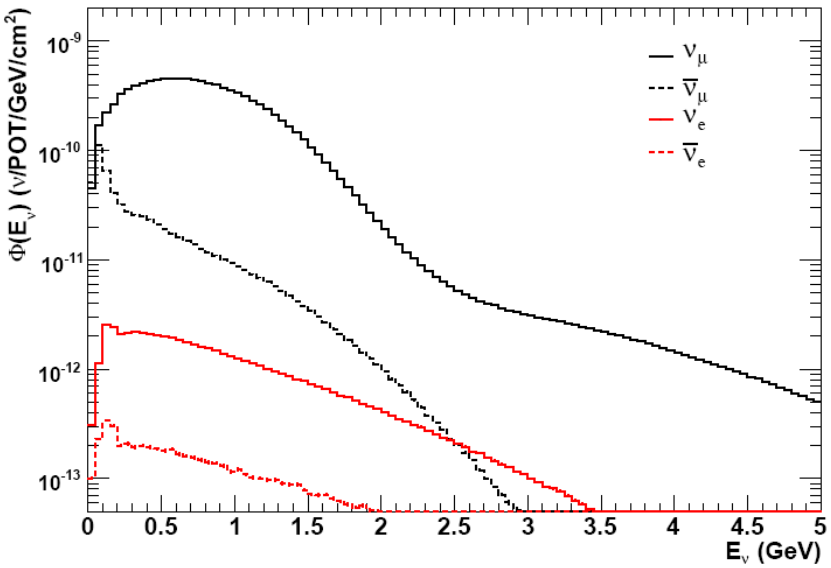


Data are fit to a Sanford-Wang parameterization.

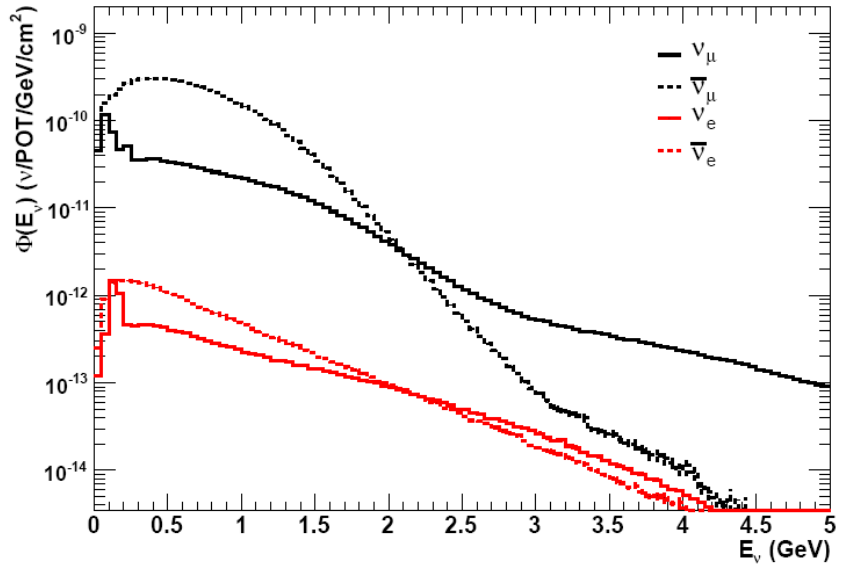
HARP collaboration, hep-ex/0702024

Neutrino Flux from GEANT4 Simulation

Neutrino-Mode Flux

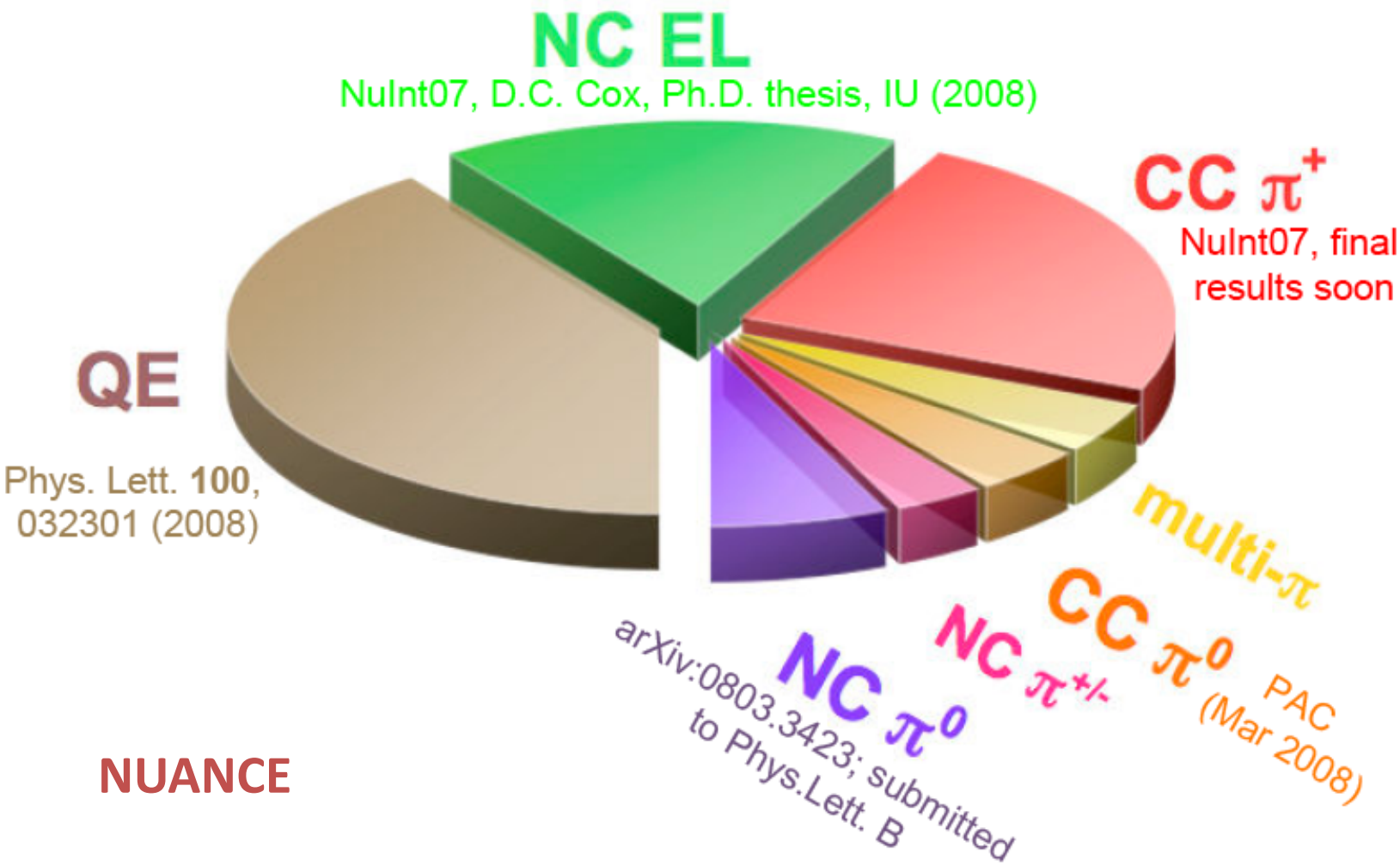


Antineutrino-Mode Flux



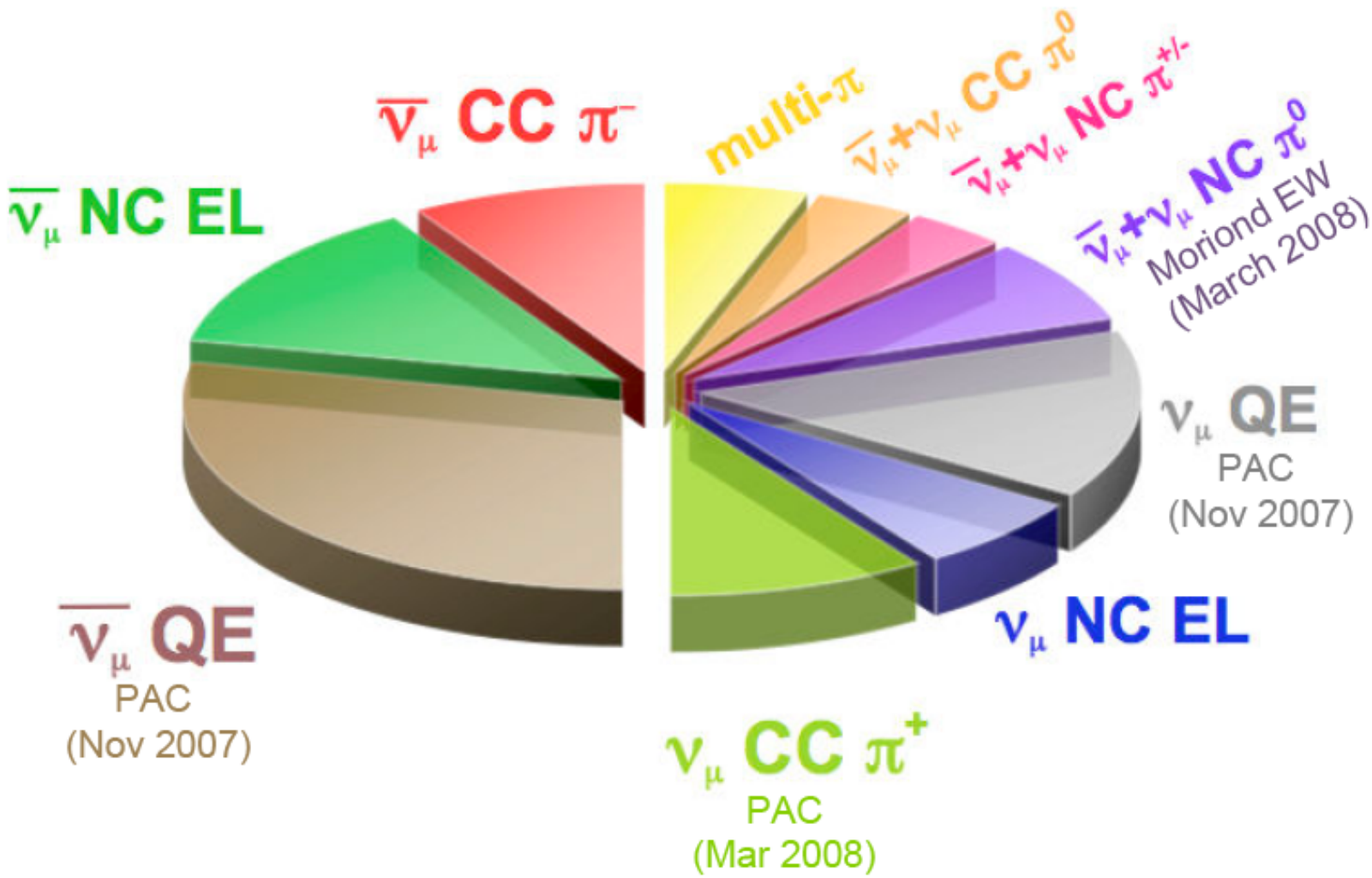
Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode
Instrinsic ν_e background is ~0.6% for both Nu-Mode & Antinu-Mode

Neutrino Cross Sections



NUANCE

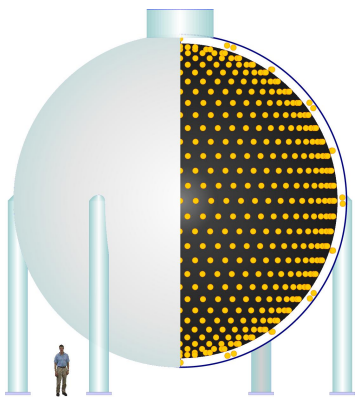
Antineutrino Cross Sections

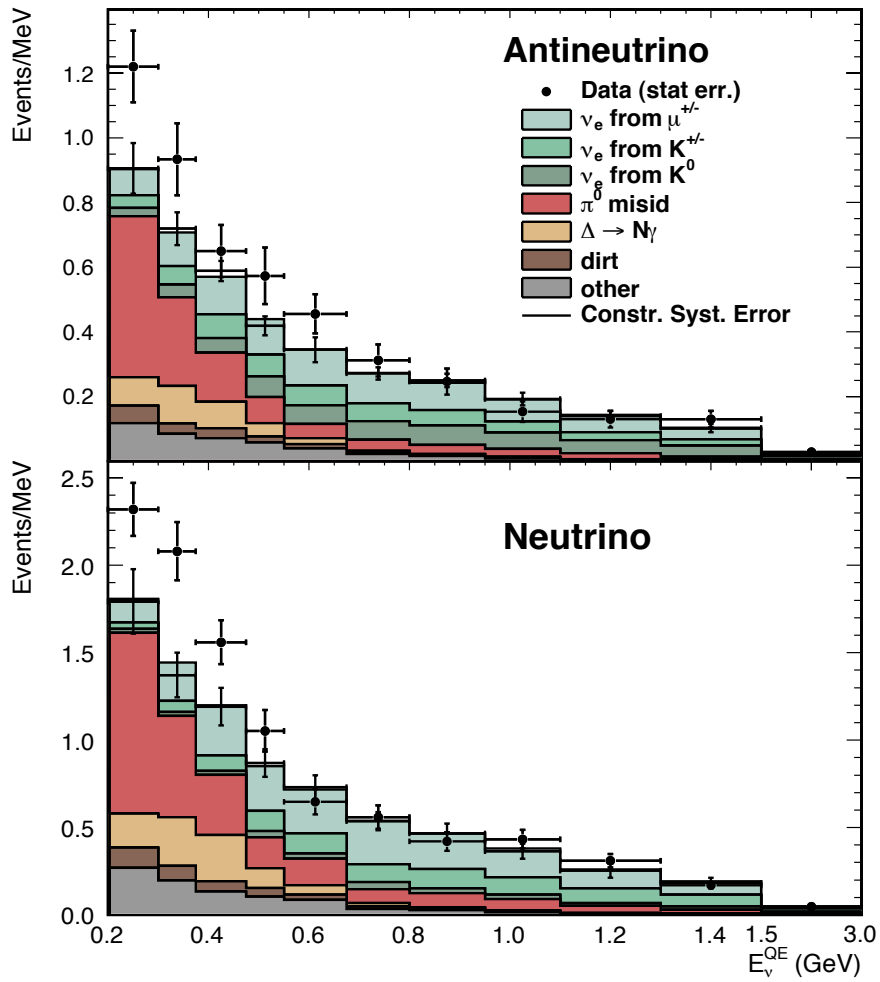


NUANCE

MiniBooNE Neutrino Oscillation Results

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





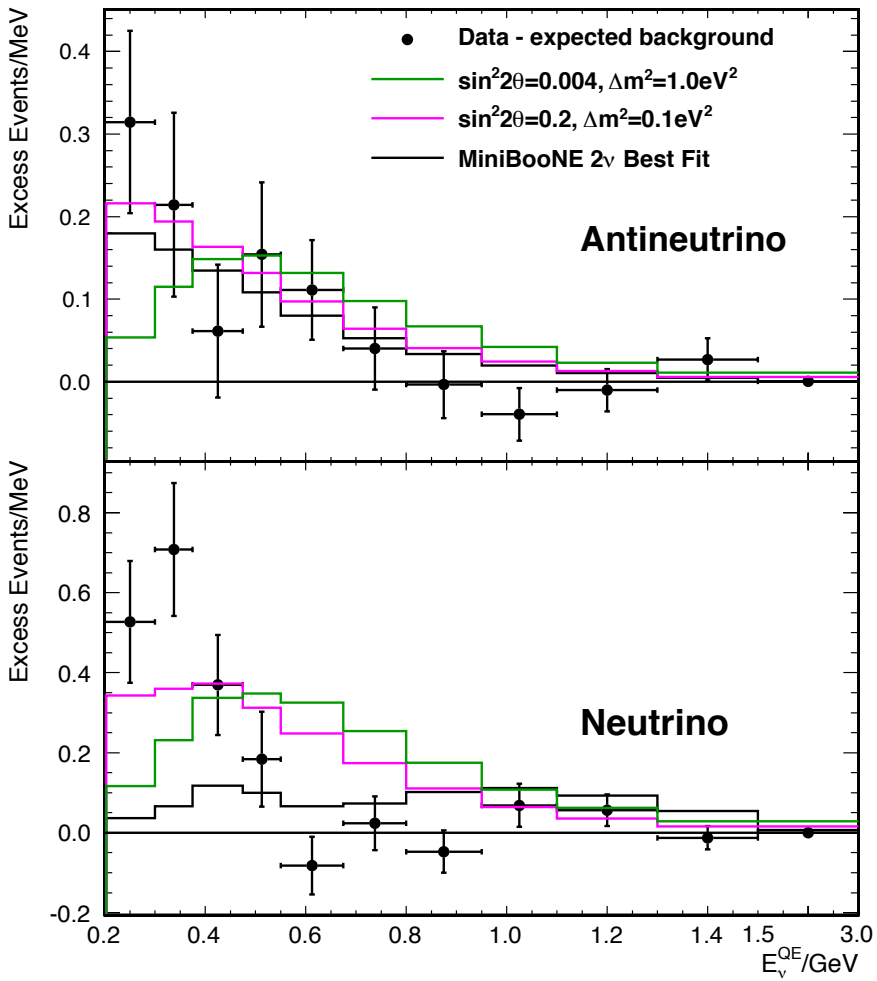
11.27×10^{20} POT

6.46×10^{20} POT

MiniBooNE observes an excess of events consistent with $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

MiniBooNE Neutrino Oscillation Results

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



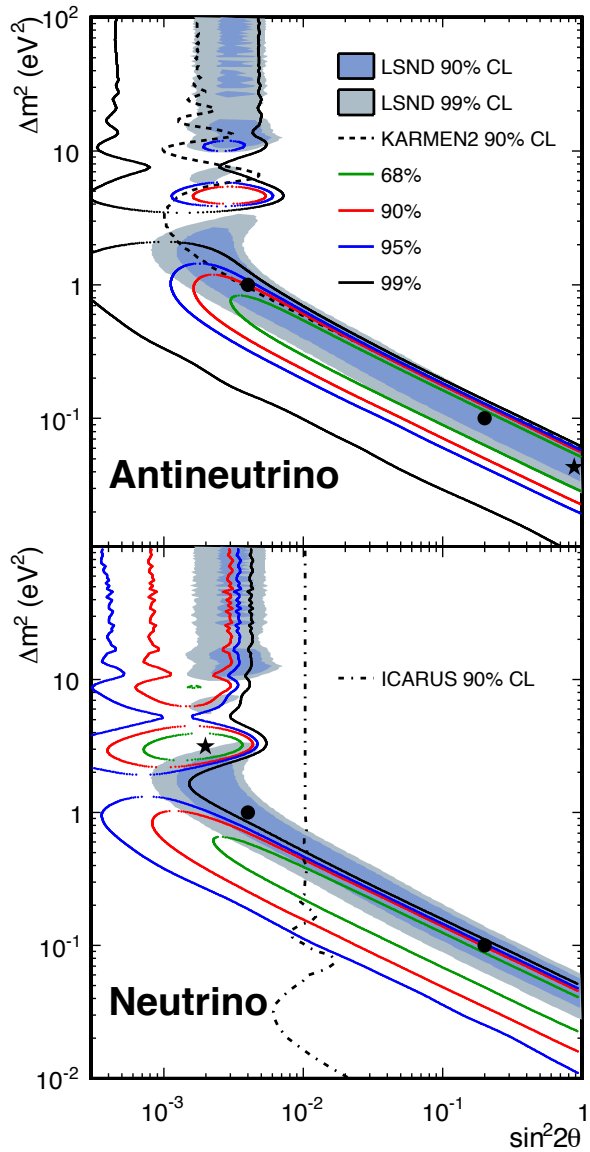
Antineutrino Event Excess from 200-1250 MeV = 78.4+-20.0+-20.3 (2.8σ)

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)

MiniBooNE Neutrino Oscillation Results

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



Antineutrino

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

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

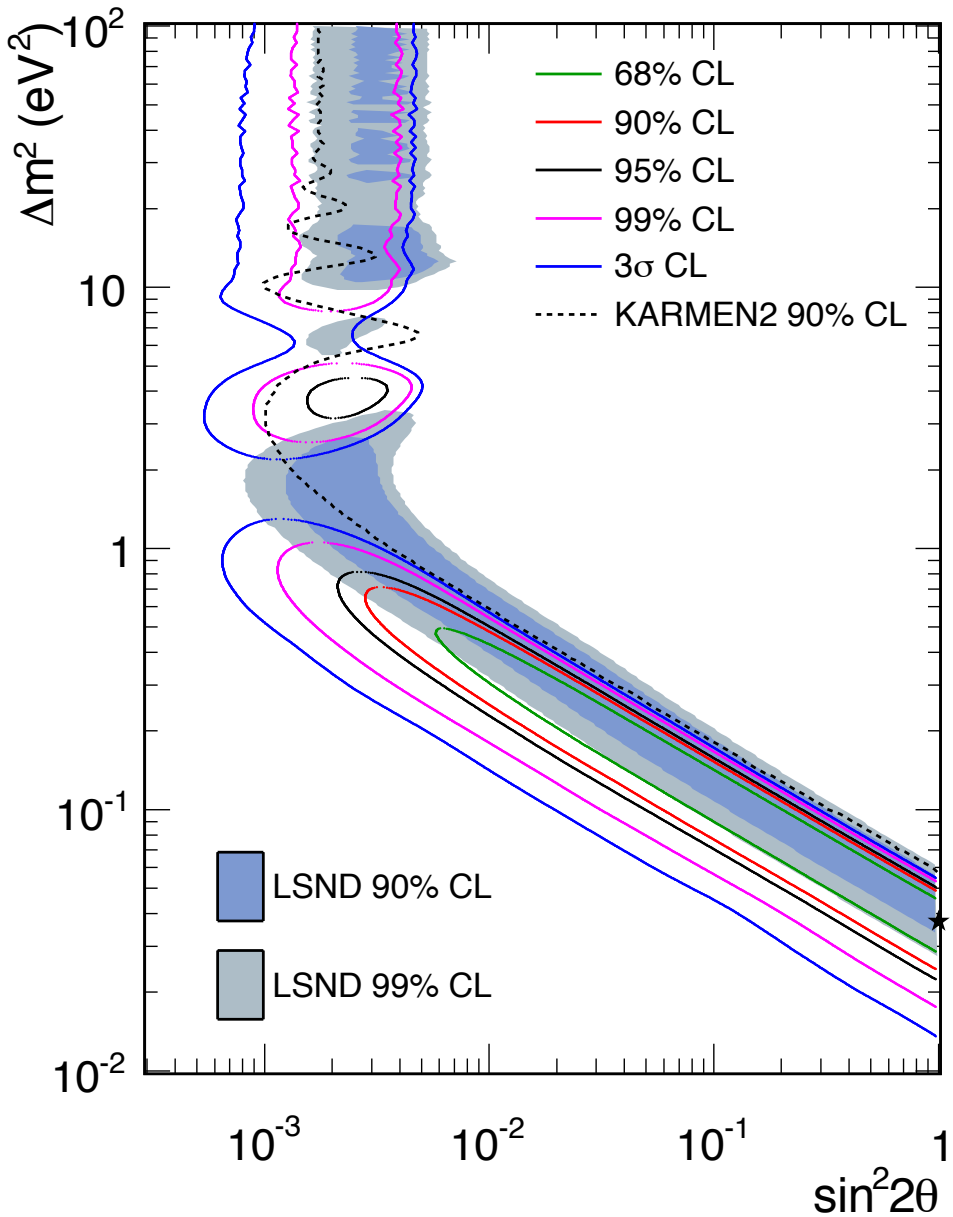
Neutrino

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

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

MiniBooNE Combined Neutrino + Antineutrino 3+1 Fit

arXiv:1207.4809

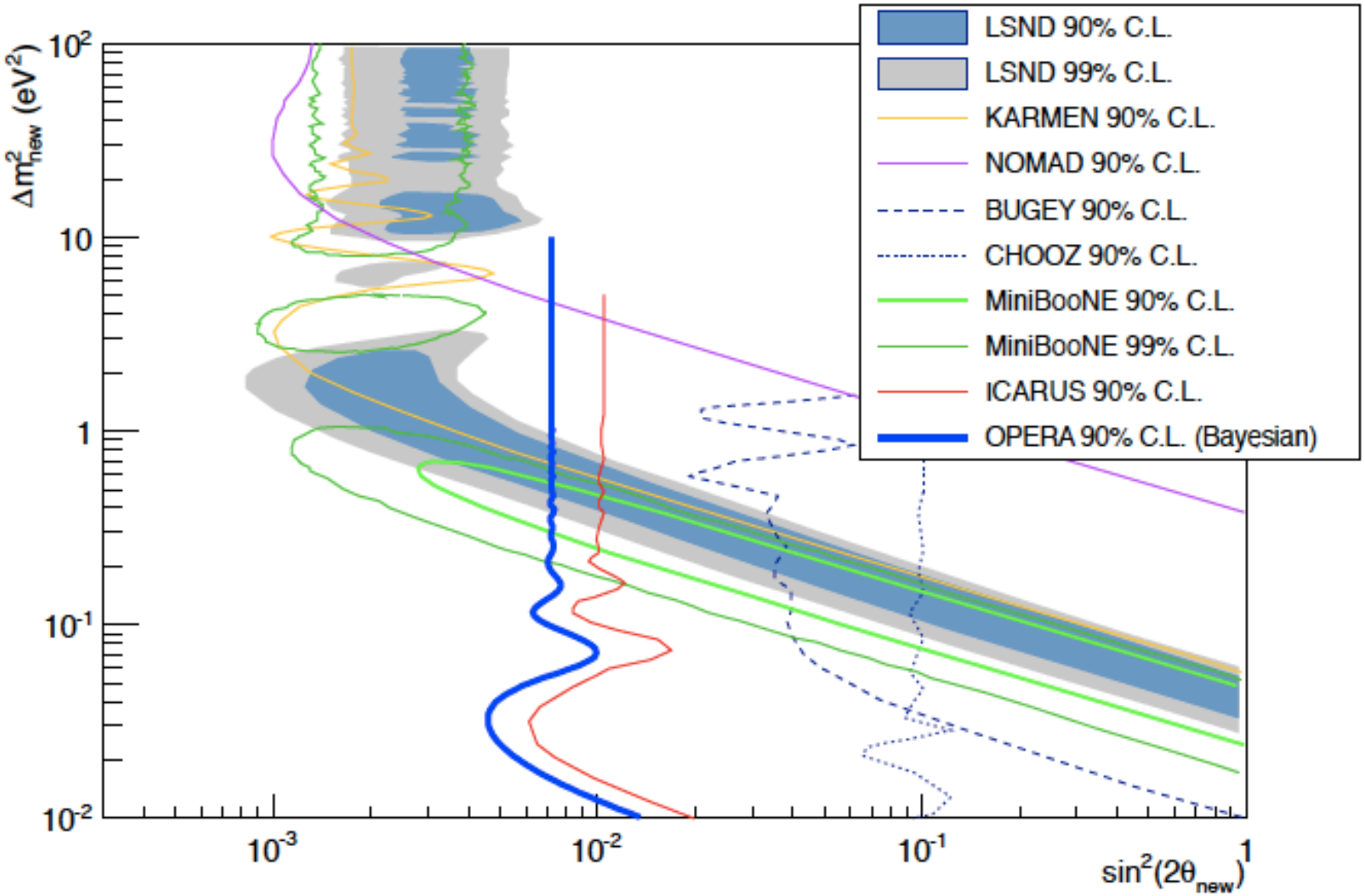


P_{bf} = 6.7%, P_{null} = 0.1%

P_{null} relative to P_{bf} = 0.03%

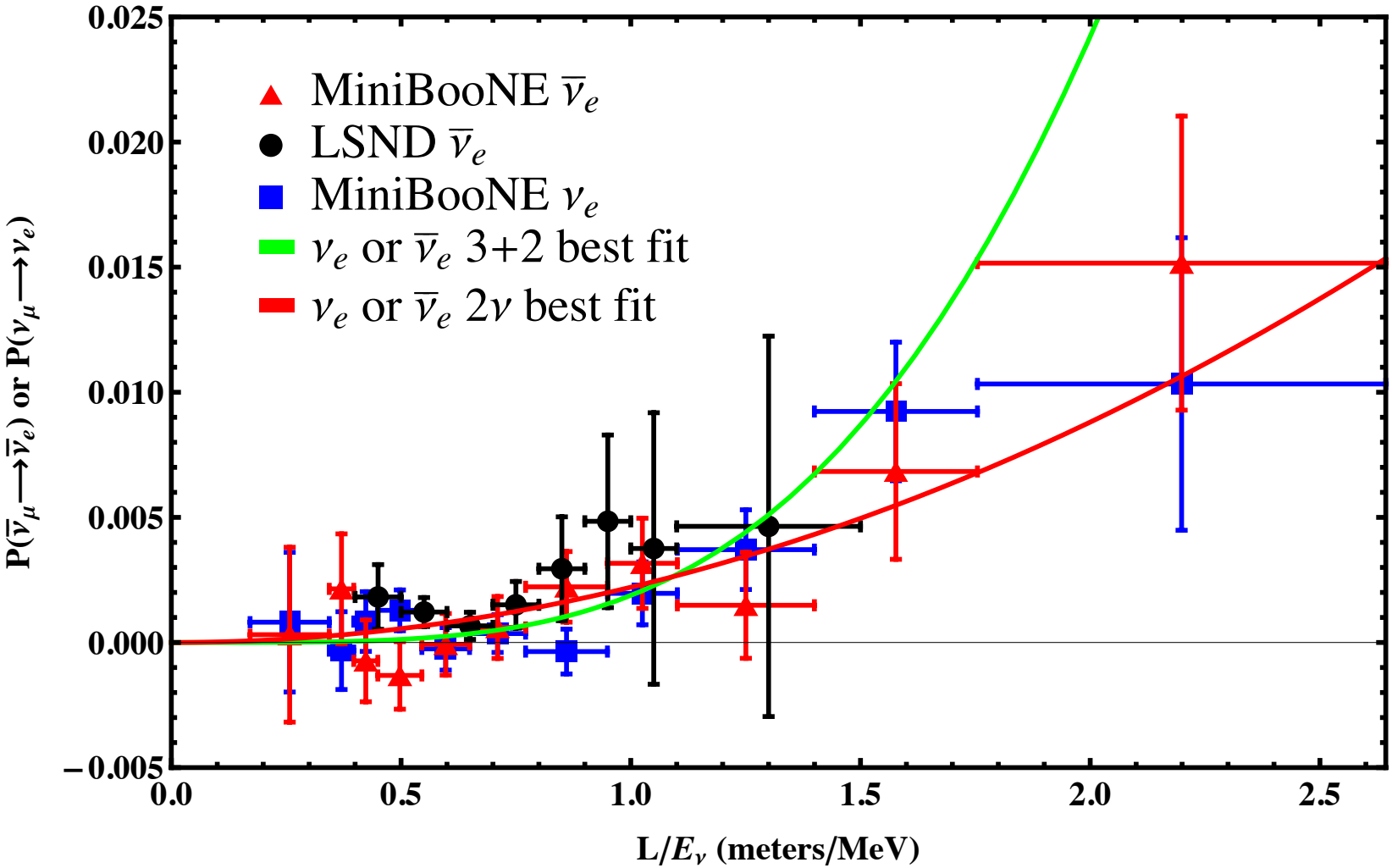
MiniBooNE Combined Neutrino + Antineutrino 3+1 Fit

OPERA: arXiv:1303.3953



MiniBooNE L/E Distributions

arXiv:1207.4809

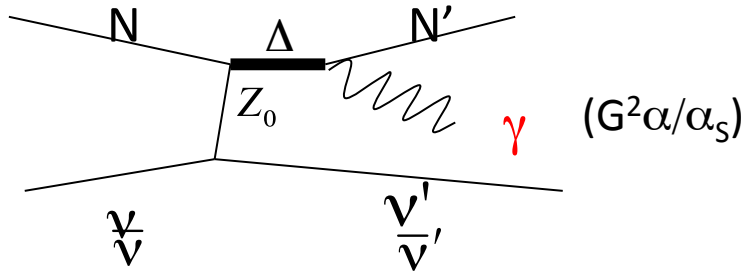


Questions/Caveats

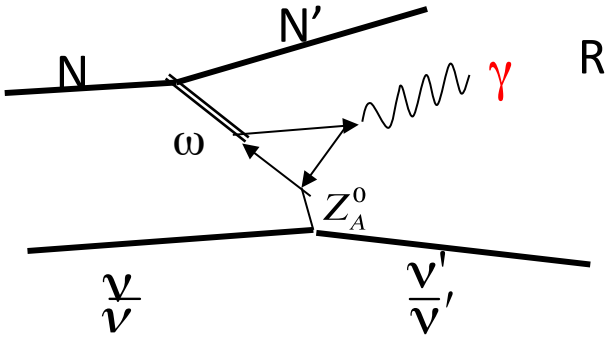
- NC γ background?
- Multi-nucleon nuclear effects & neutrino energy?
- ν_μ & ν_e disappearance & oscillation parameters?

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

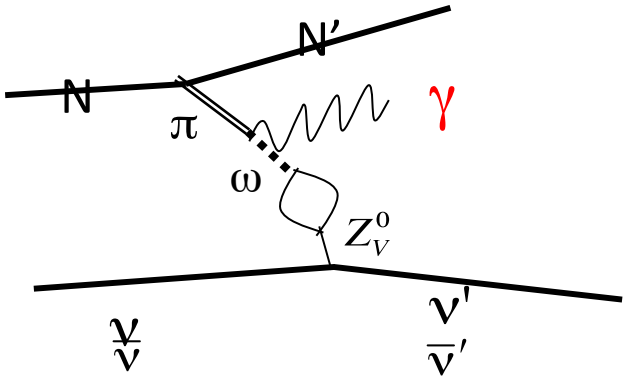
Dominant processes accounted for in MC!



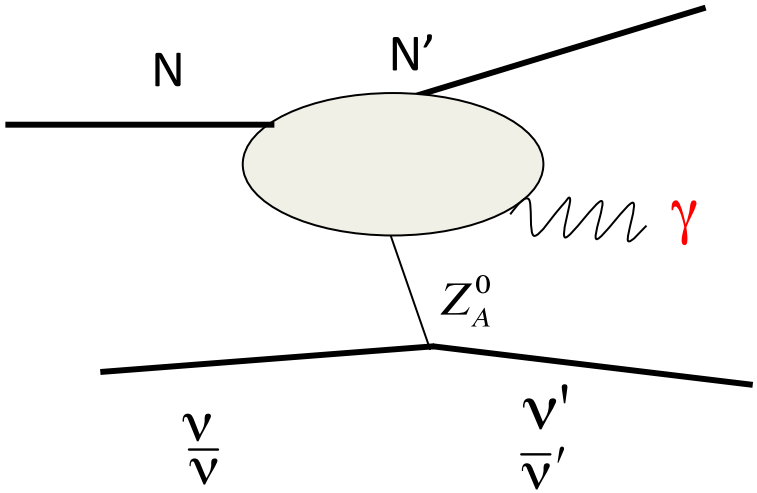
Radiative Delta Decay



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

Multi-Nucleon Nuclear Effects & Neutrino Energy

Martini, Ericson, & Chanfray, arXiv:1211.1523

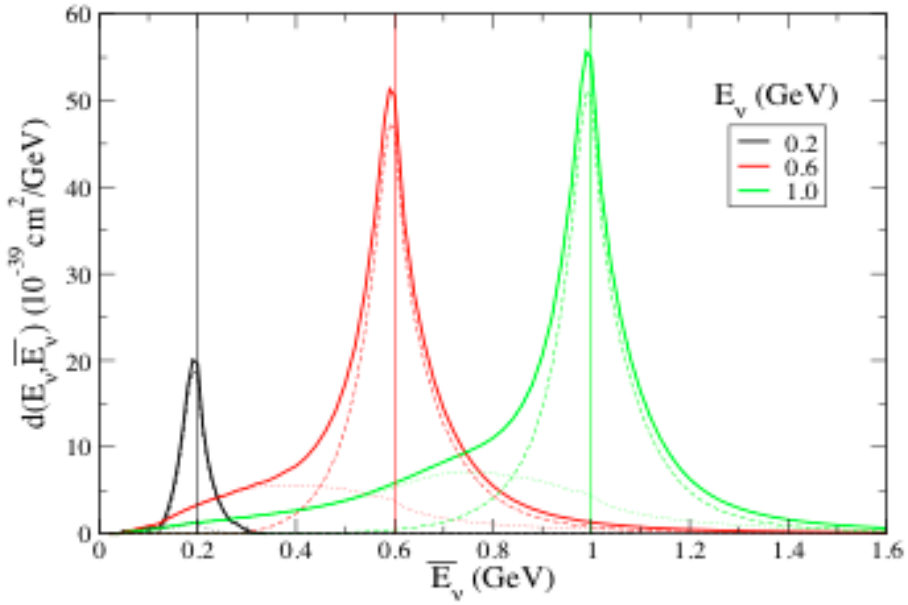


FIG. 1: (Color online) The spreading function $d(E_\nu, \overline{E_\nu})$ of Eq. (4) per neutron of ^{12}C in the case of electrons evaluated for three E_ν values. The genuine quasielastic (dashed lines) and the multinucleon (dotted lines) contributions are also shown separately.

Multi-Nucleon Nuclear Effects cause MiniBooNE to underestimate E_ν!

Nominal best antineutrino fit: Δm^2=0.043 eV^2, $\sin^2 2\theta$=0.88

Martini Inspired Model: Δm^2=0.059 eV^2, $\sin^2 2\theta$=0.64

ν_μ & ν_e Disappearance & Oscillation Parameters

- MB fits performed to date assume small ν_e & ν_μ disappearance
- However, ν_e (ν_μ) disappearance in 3+N models will cause the intrinsic ν_e background to be overestimated (underestimated)
- Therefore, MB is now working on fitting Δm^2 & both U_{e4} & $U_{\mu 4}$:

$$\sin^2 2\theta_{\mu e} = 4(U_{e4}U_{\mu 4})^2$$

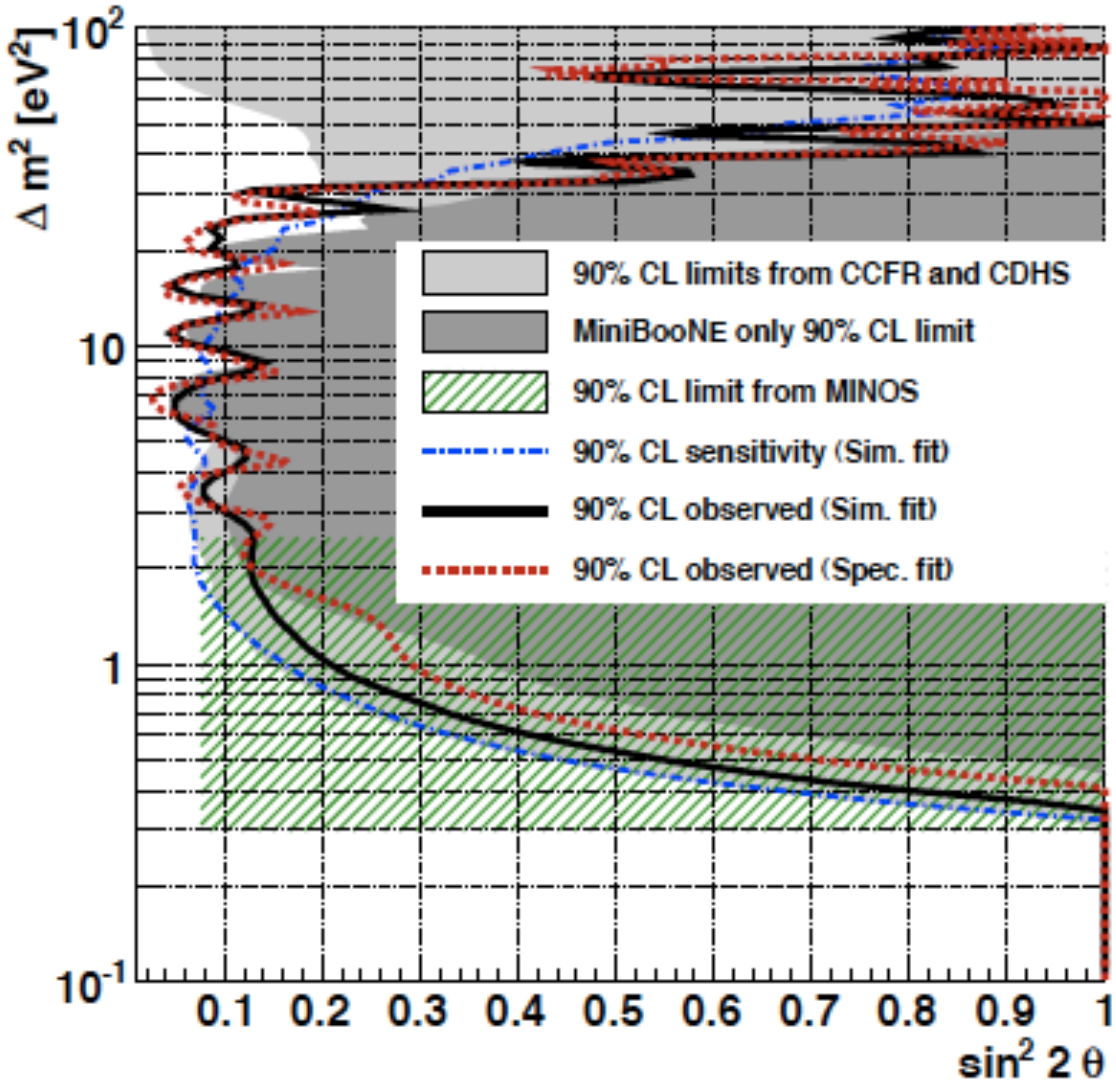
$$\sin^2 2\theta_{\mu\mu} = 4(U_{\mu 4})^2(1-(U_{\mu 4})^2)$$

$$\sin^2 2\theta_{\mu e} = 4(U_{e4})^2(1-(U_{e4})^2)$$

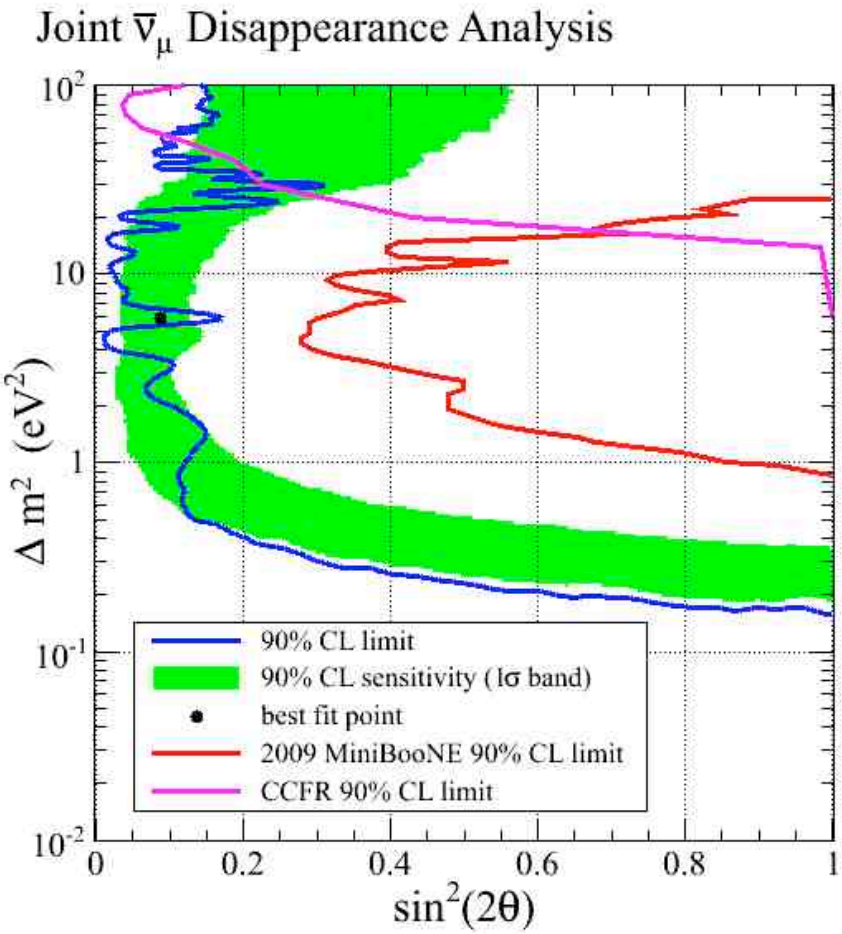
Nominal best antineutrino fit: Δm^2=0.043 eV^2, $\sin^2 2\theta$=0.88
Model with $U_{e4} = U_{\mu 4}$ Disappearance: Δm^2=0.177 eV^2, $\sin^2 2\theta$=0.07

SciBooNE/MiniBooNE Neutrino Disappearance Limits

arXiv:1106.5685



$\bar{\nu}_\mu$ Disappearance Results

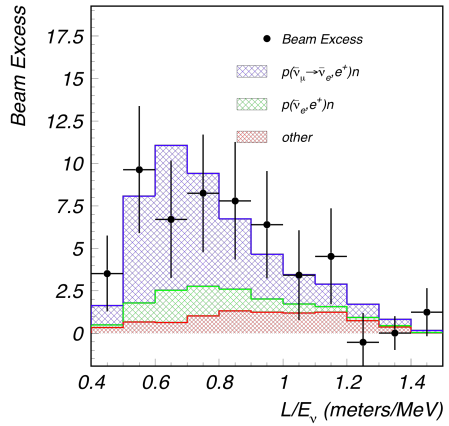


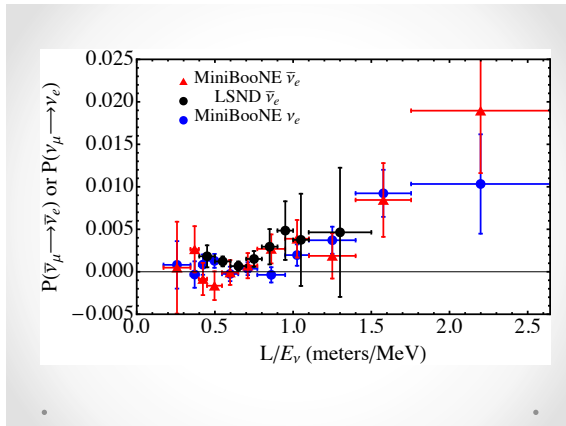
MiniBooNE + SciBooNE

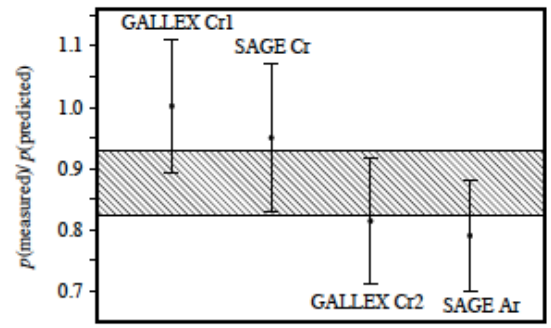
- Consistent with no disappearance
- Best fit point: $\Delta m^2 = 5.9$ eV^2, $\sin^2 2\theta = 0.086$
- $\chi^2 = 40.0$ (probability 47.1%) at the best fit point
- $\chi^2 = 43.5$ (probability 41.2%) for the null hypothesis
- With $\Delta\chi^2 = 3.5$, null is excluded at 81.9% confidence level
- Probabilities are based on fake data studies

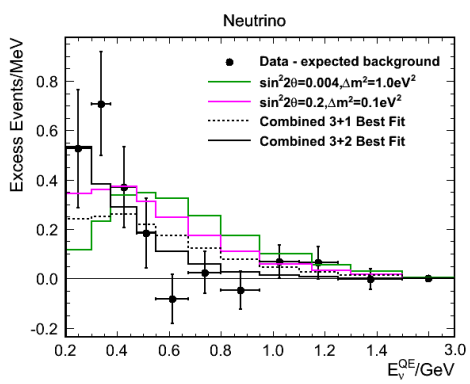
arXiv:1208.0322 (submitted to Phys. Rev. D)

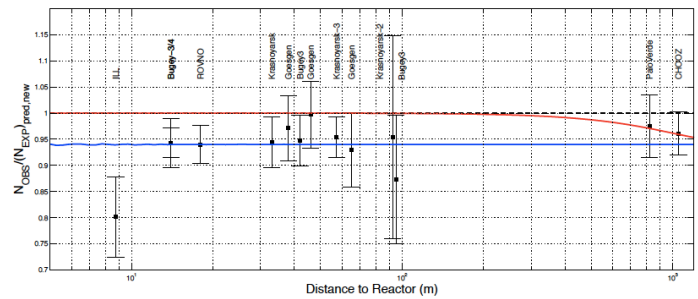
Short-Baseline Neutrino Anomalies

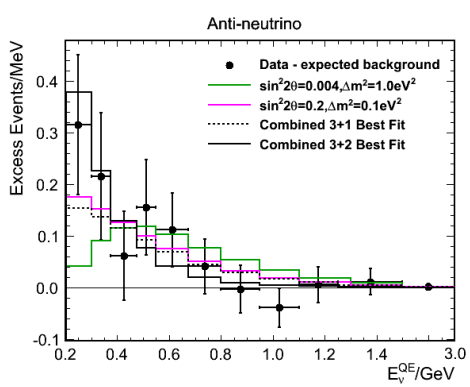


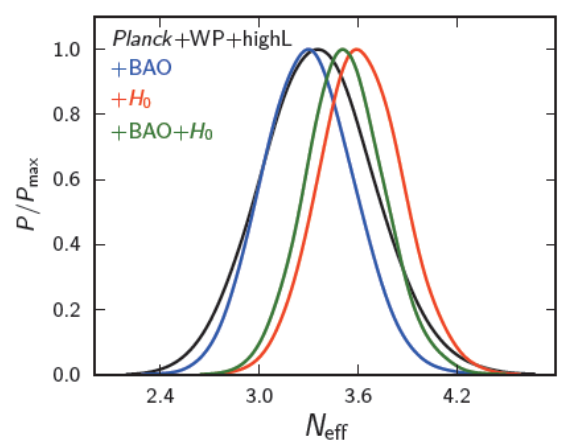






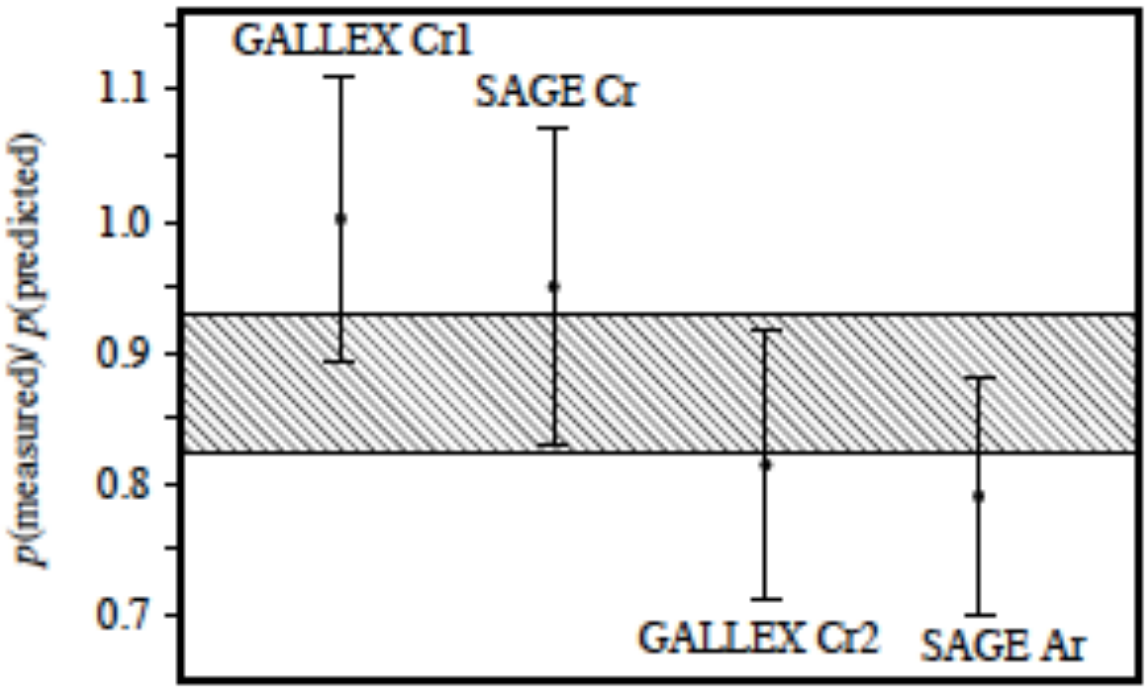






Radioactive Neutrino Source Anomaly

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



R=0.86+-0.05

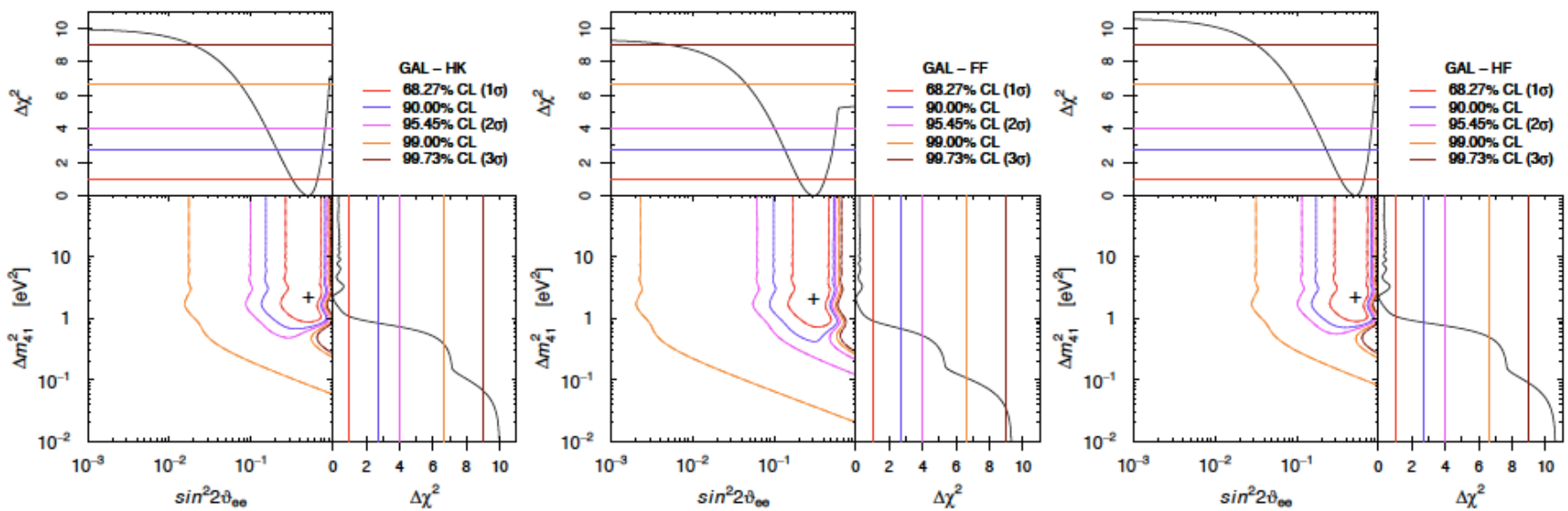
GALLEX & SAGE observe fewer events than expected from their calibration measurements, consistent with ν_e disappearance to sterile neutrinos

Radioactive Neutrino Source Anomaly

Giunti et al.; arXiv:1210.5715

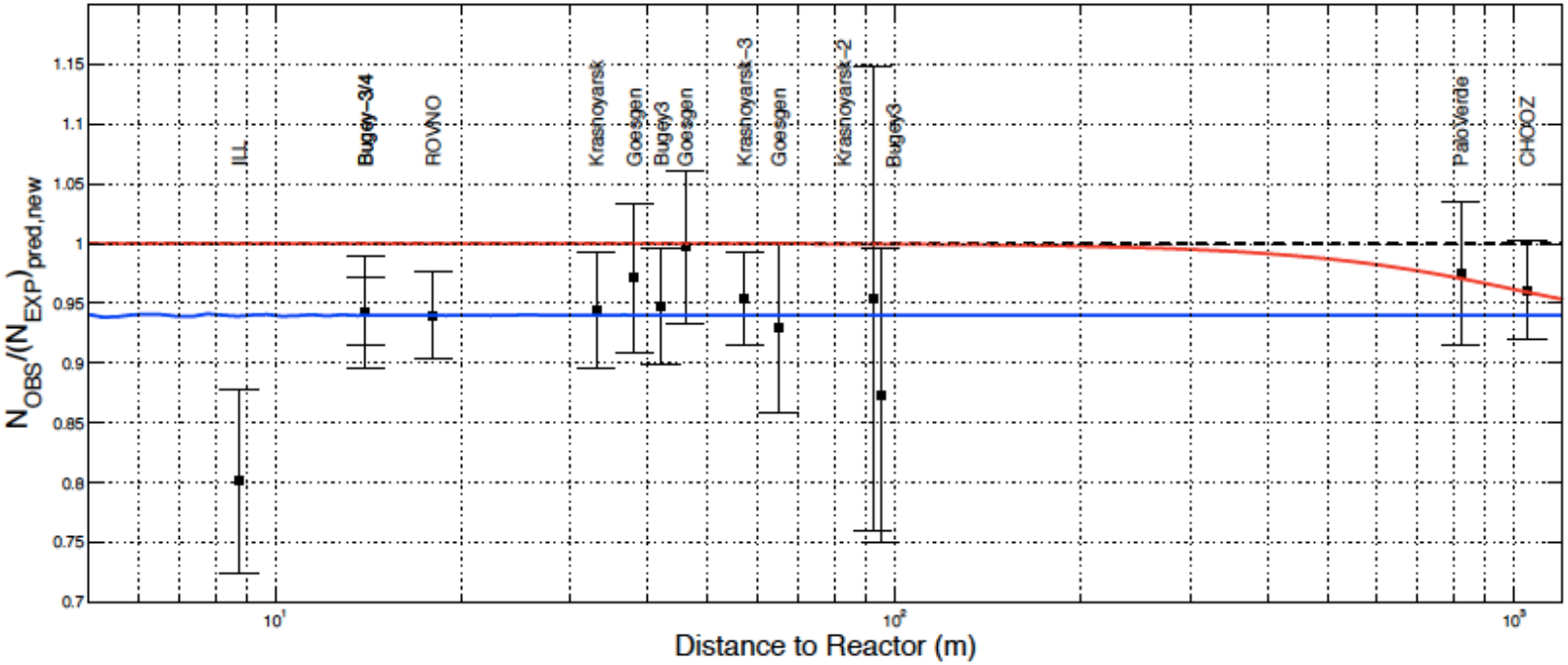
TABLE II. Ratios of measured and expected ^{71}Ge event rates in the four radioactive source experiments. G1 and G2 denote the two GALLEX experiments with ^{51}Cr sources [30–32], S1 denotes the SAGE experiment with a ^{51}Cr source, and S2 denotes the SAGE experiment with a ^{37}Ar source [33–36]. AVE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

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



Reactor Neutrino Anomaly

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

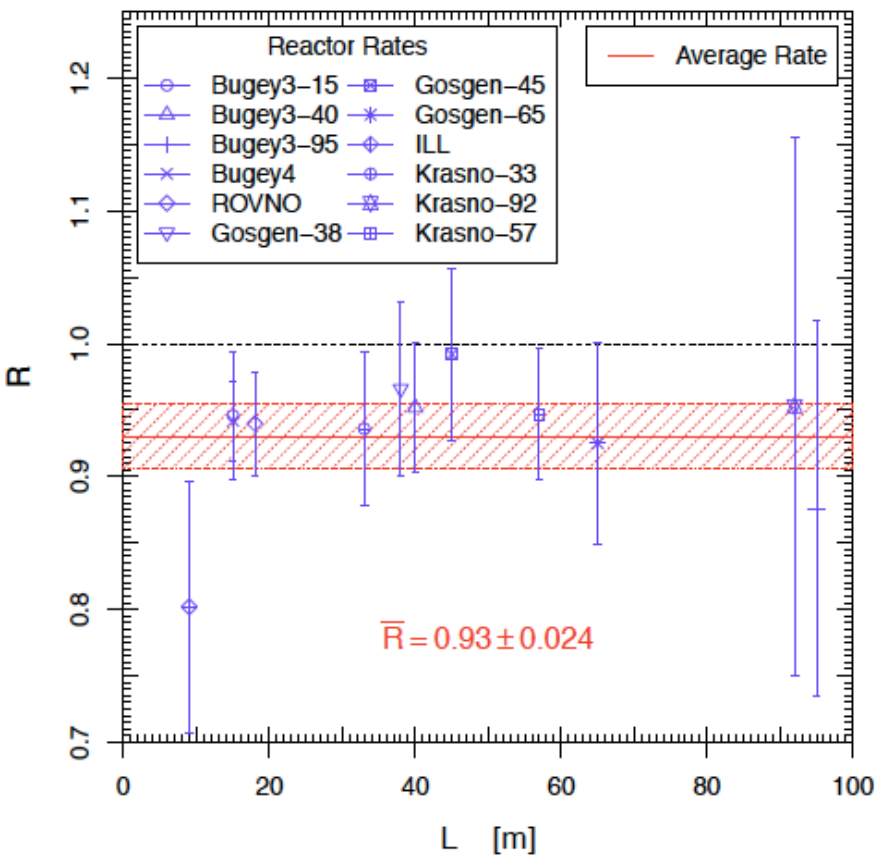


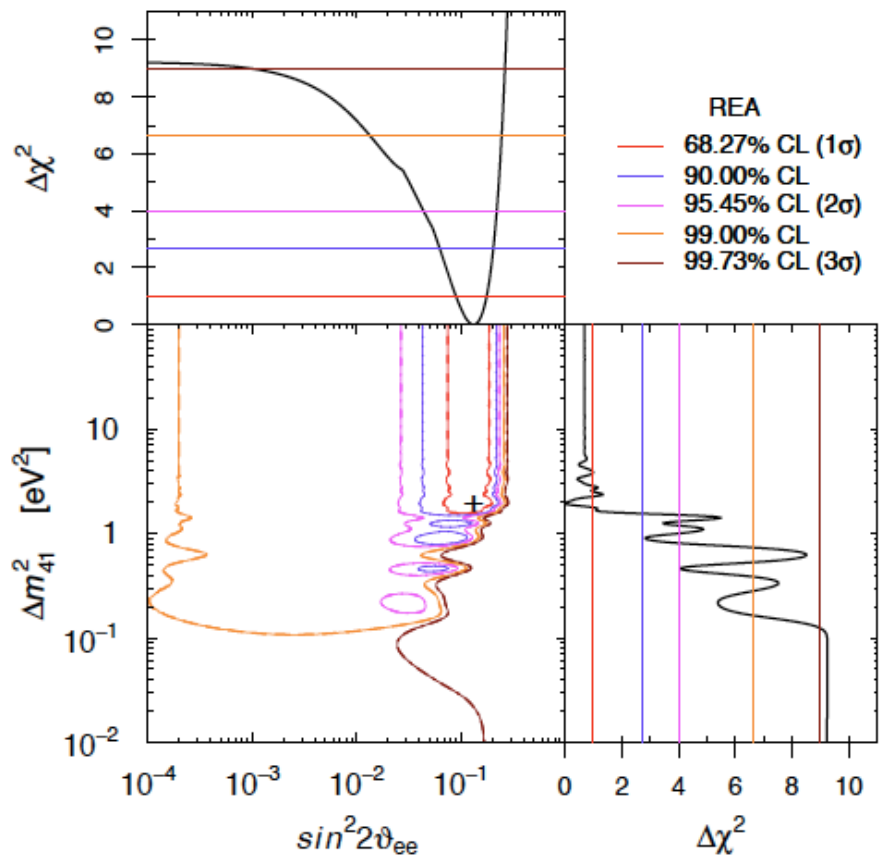
R=0.937+-0.027

Reactor Neutrino experiments observe fewer events than expected, consistent with $\bar{\nu}_e$ disappearance to sterile neutrinos. However, what is systematic uncertainty in neutrino flux?

Reactor Neutrino Anomaly

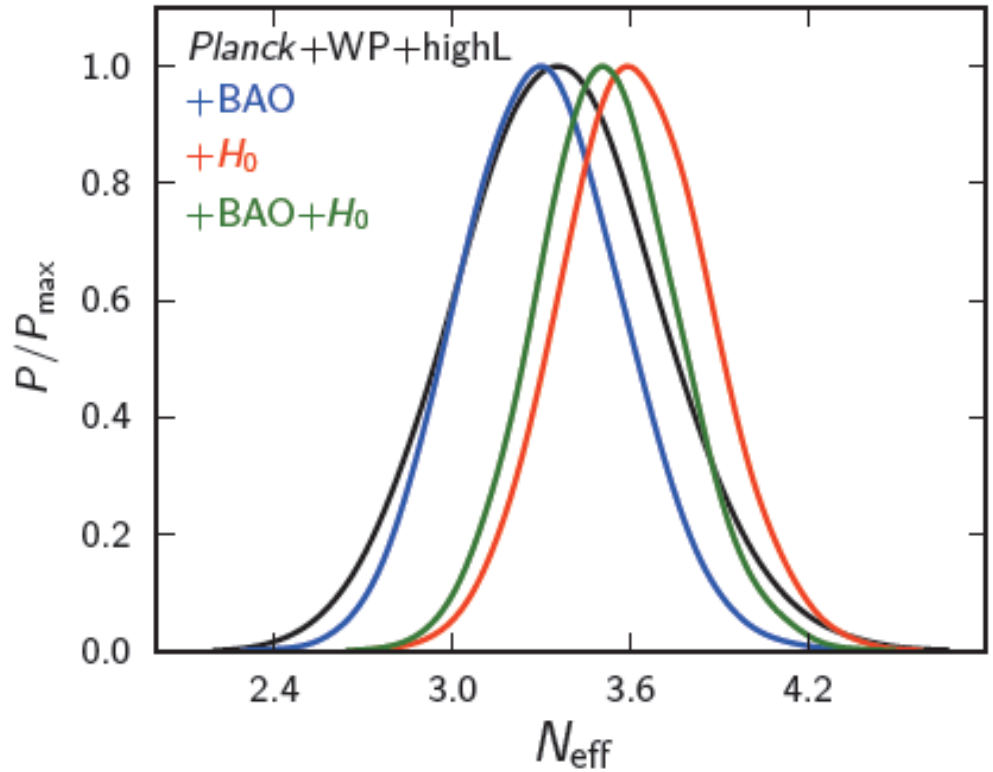
Giunti et al.; arXiv:1210.5715





SPT & Planck Results

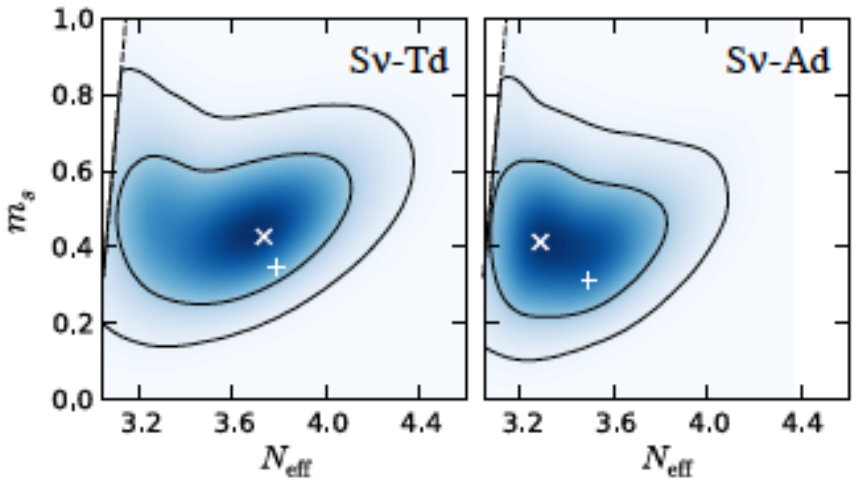
arXiv:1212.6267 & arXiv:1303.5076 & arXiv:1304.5981



Neff =	3.36+-0.34	CMB(Planck+ACT)
	3.30+-0.27	CMB(Planck+ACT)+BAO
	3.62+-0.25	CMB(Planck+ACT)+H_0
	3.52+-0.24	CMB(Planck+ACT)+BAO+H_0
	3.71+-0.35	CMB(SPT)+BAO+H_0
	3.62+-0.24	CMB(Planck+SPT+ACT)+BAO+H_0

Global Cosmology Fits

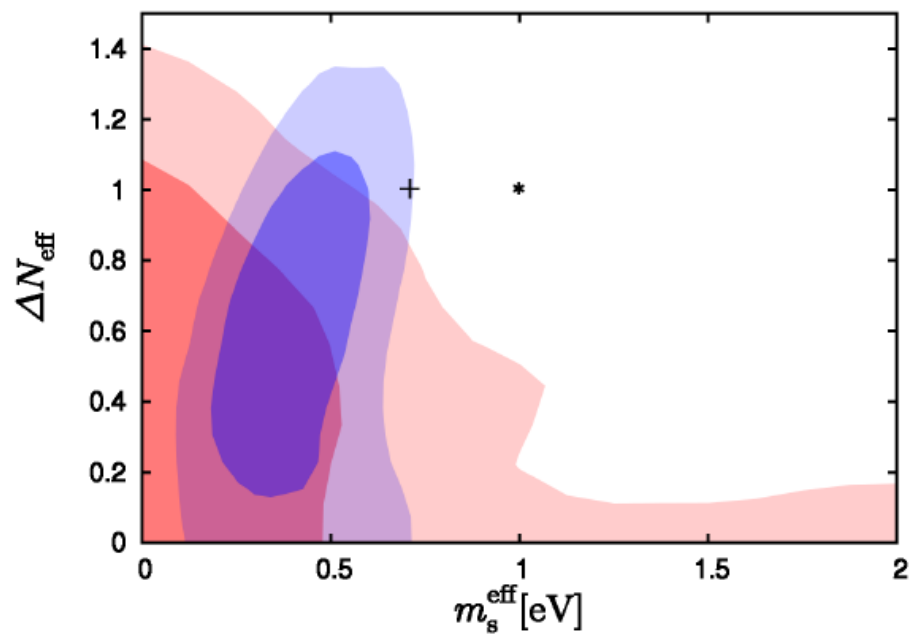
Wyman, Rudd, Vanderveld, & Hu
arXiv:1307.7715



N_{eff} = 3.72+-0.29
m_s = 0.46+-0.12

N_{eff} = 3.51+-0.26
m_s = 0.39+-0.11

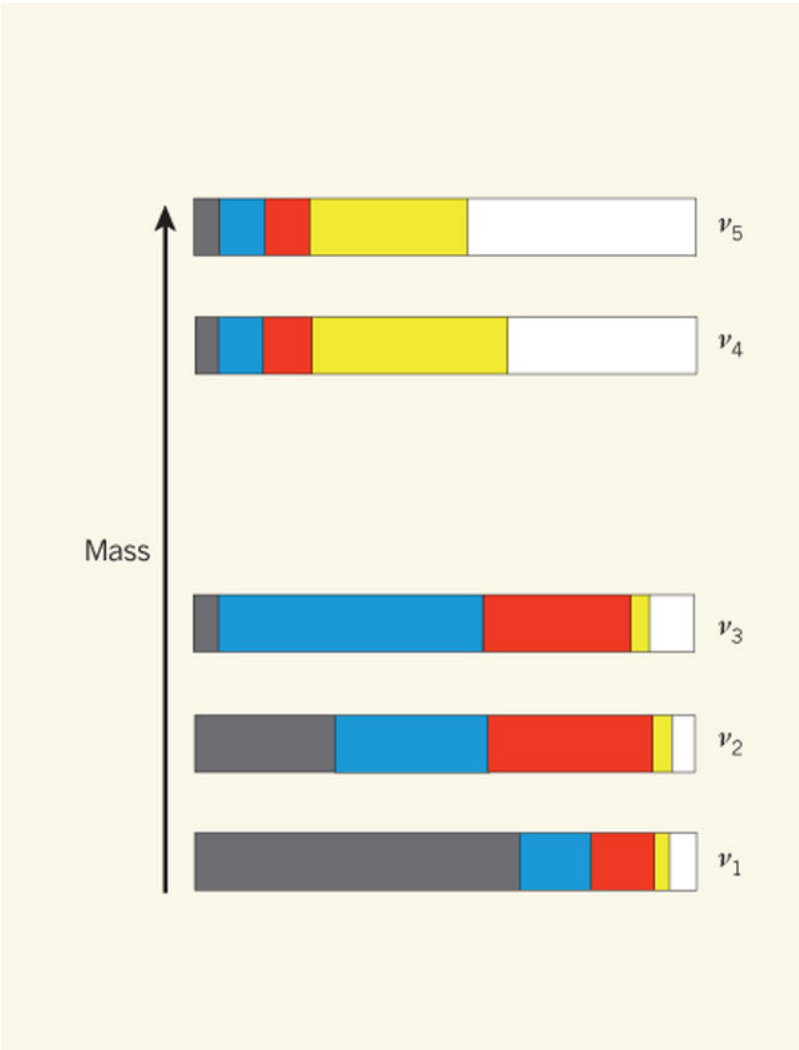
Hamann & Hasenkamp, arXiv:1308.3255



ΔN_{eff} = 0.61+-0.30, m^{eff}_s = 0.41+-0.13

By including HST H_0 measurement & cluster data, the data favor a non-zero ΔN_{eff} & m^{eff}_s

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 Models Require Large ν_e & 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: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

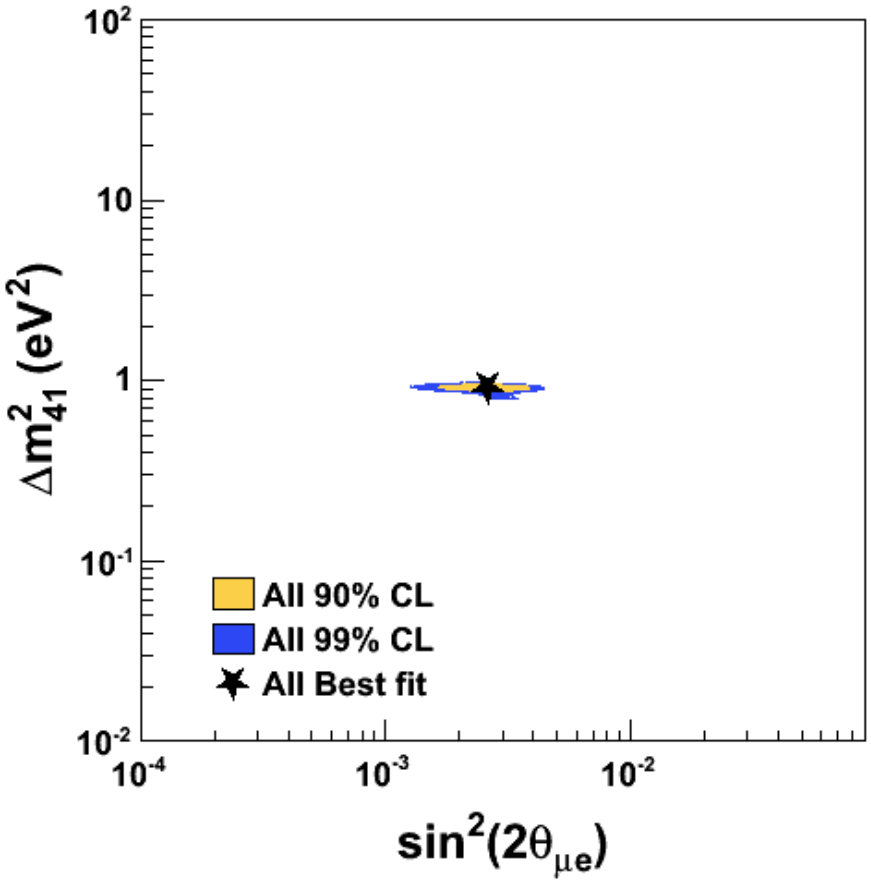
Therefore: **$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 7\%$**

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

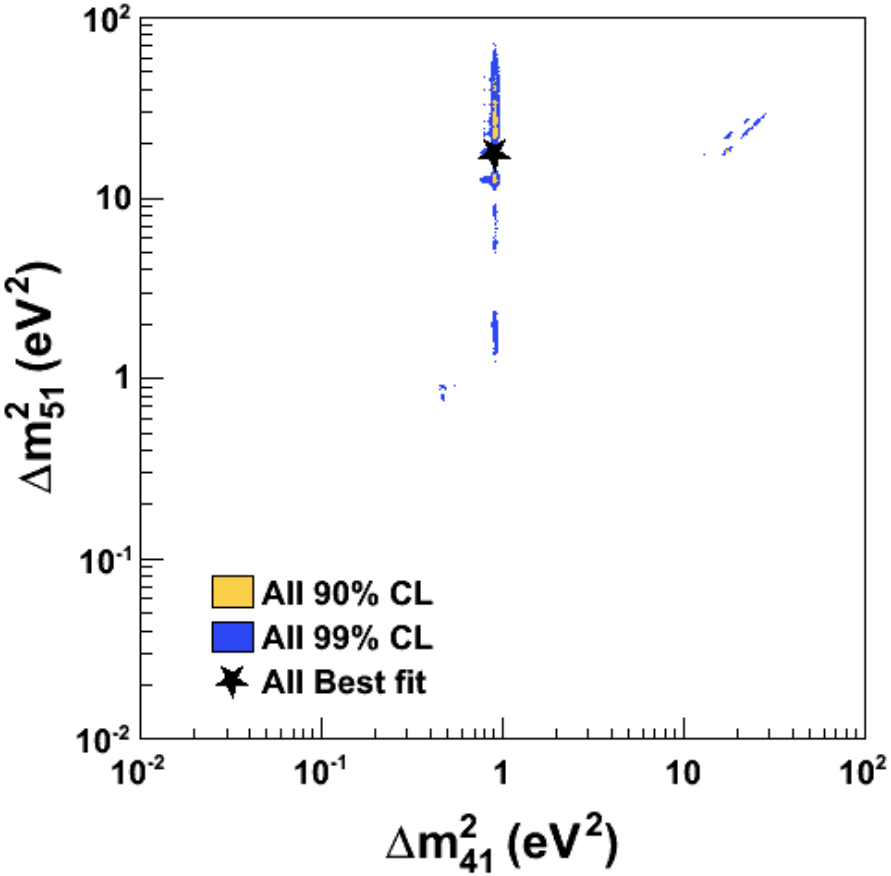
Global 3+N Fits to World Data

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

3+1

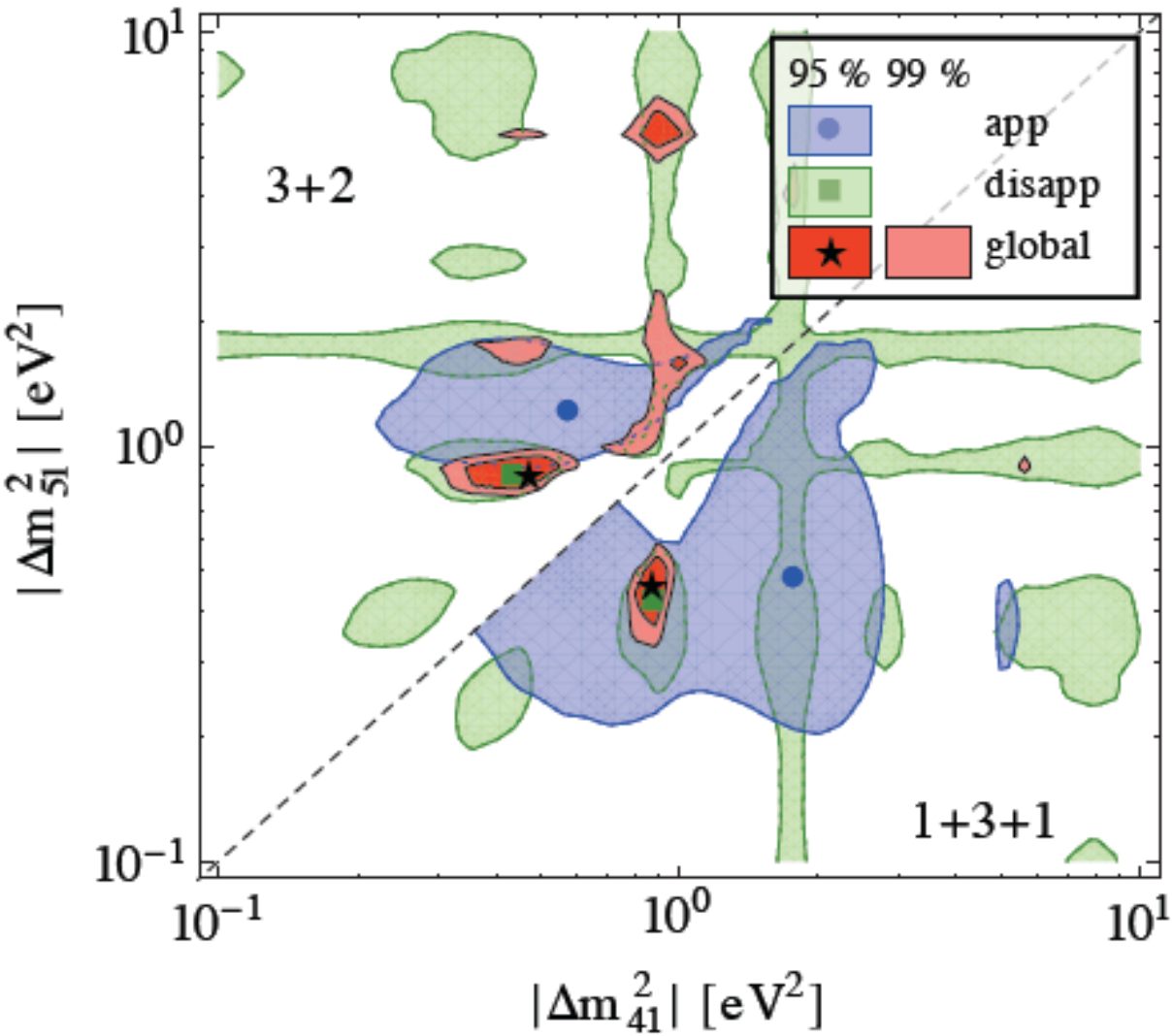


3+2



Global 3+2 & 1+3+1 Fits

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



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:

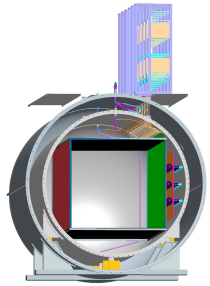
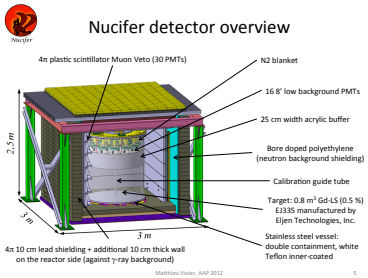


Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

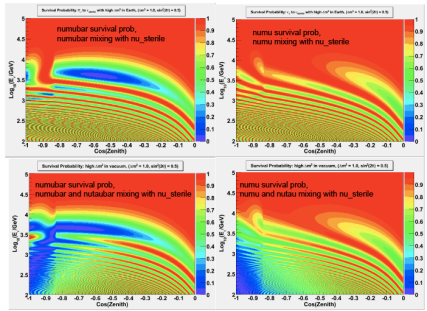
- Accelerator ν Experiments: MicroBooNE, MINOS+, NuStorm at FNAL, ICARUS at CERN, OscSNS at ORNL or J-PARC, IsoDAR

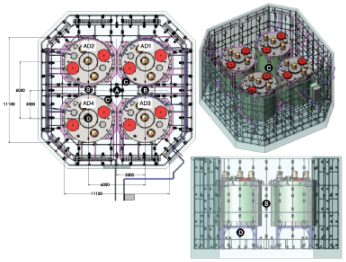
- Reactor ν Experiments: SCRAAM, NUCIFER, Stereo



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

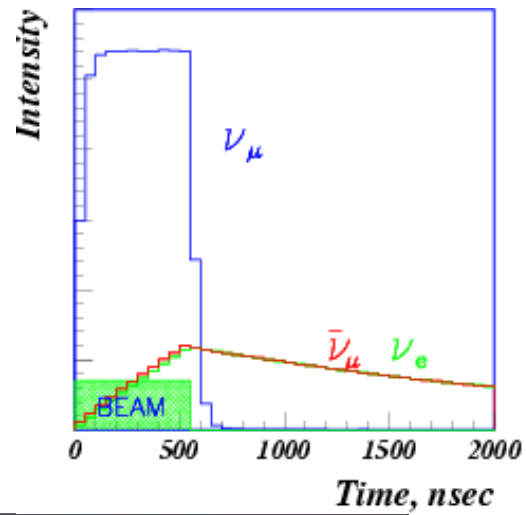
- Atmospheric ν Experiments: IceCube

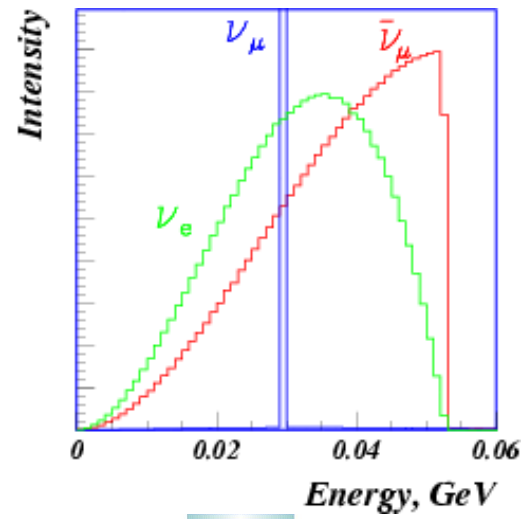


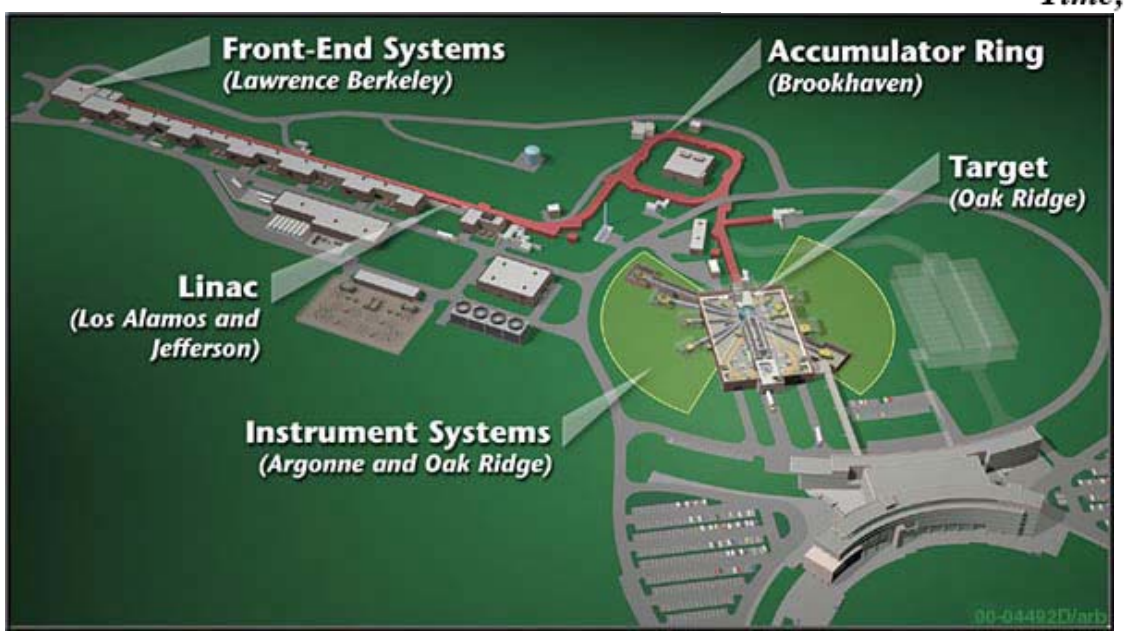


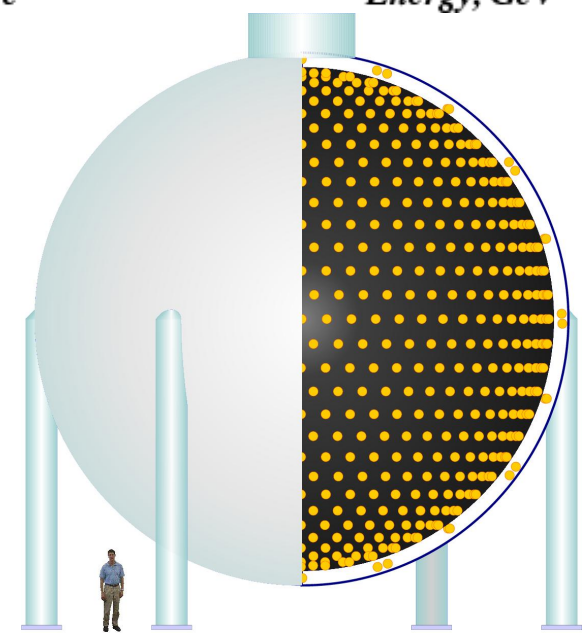
OscSNS

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

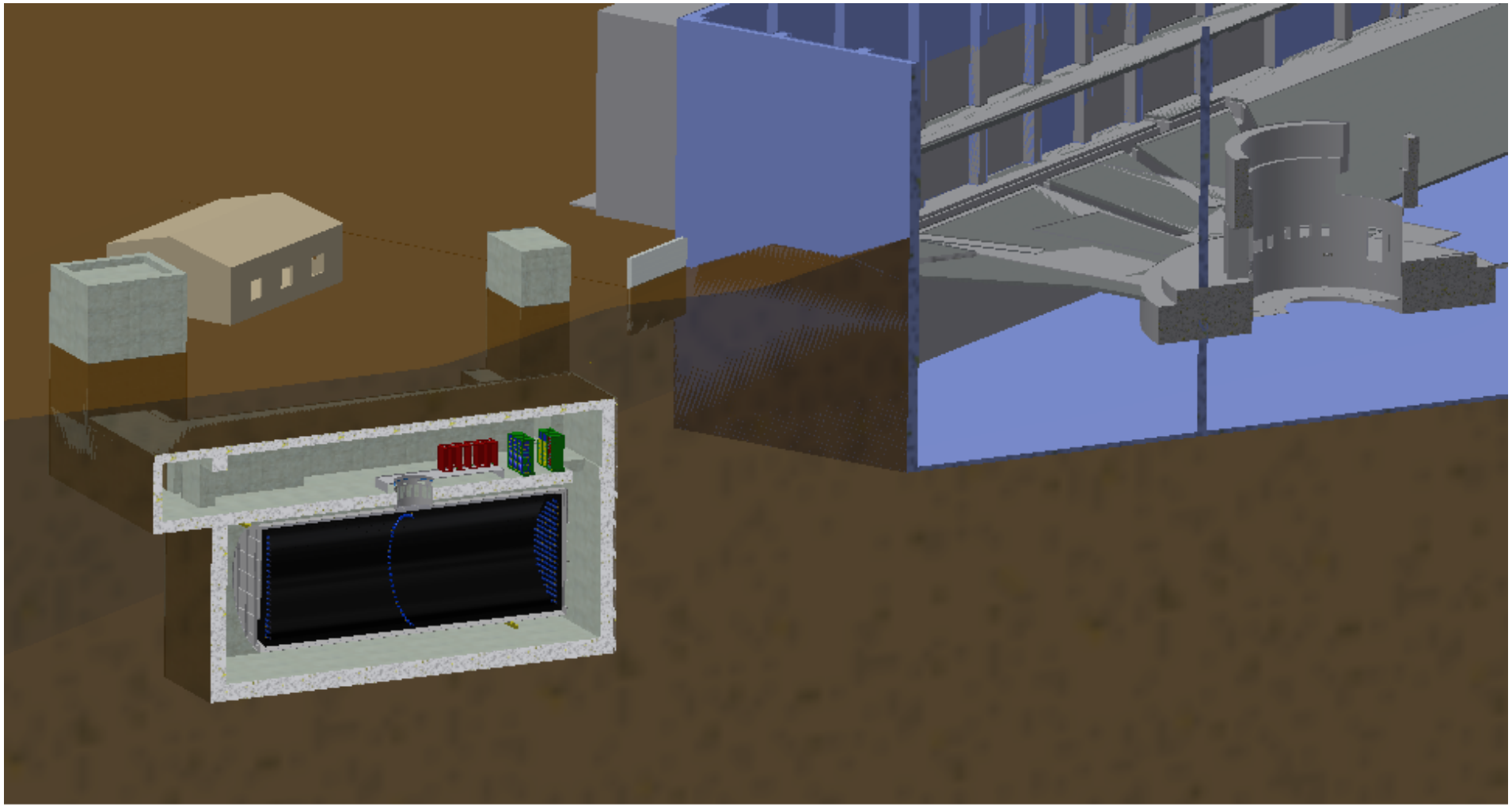


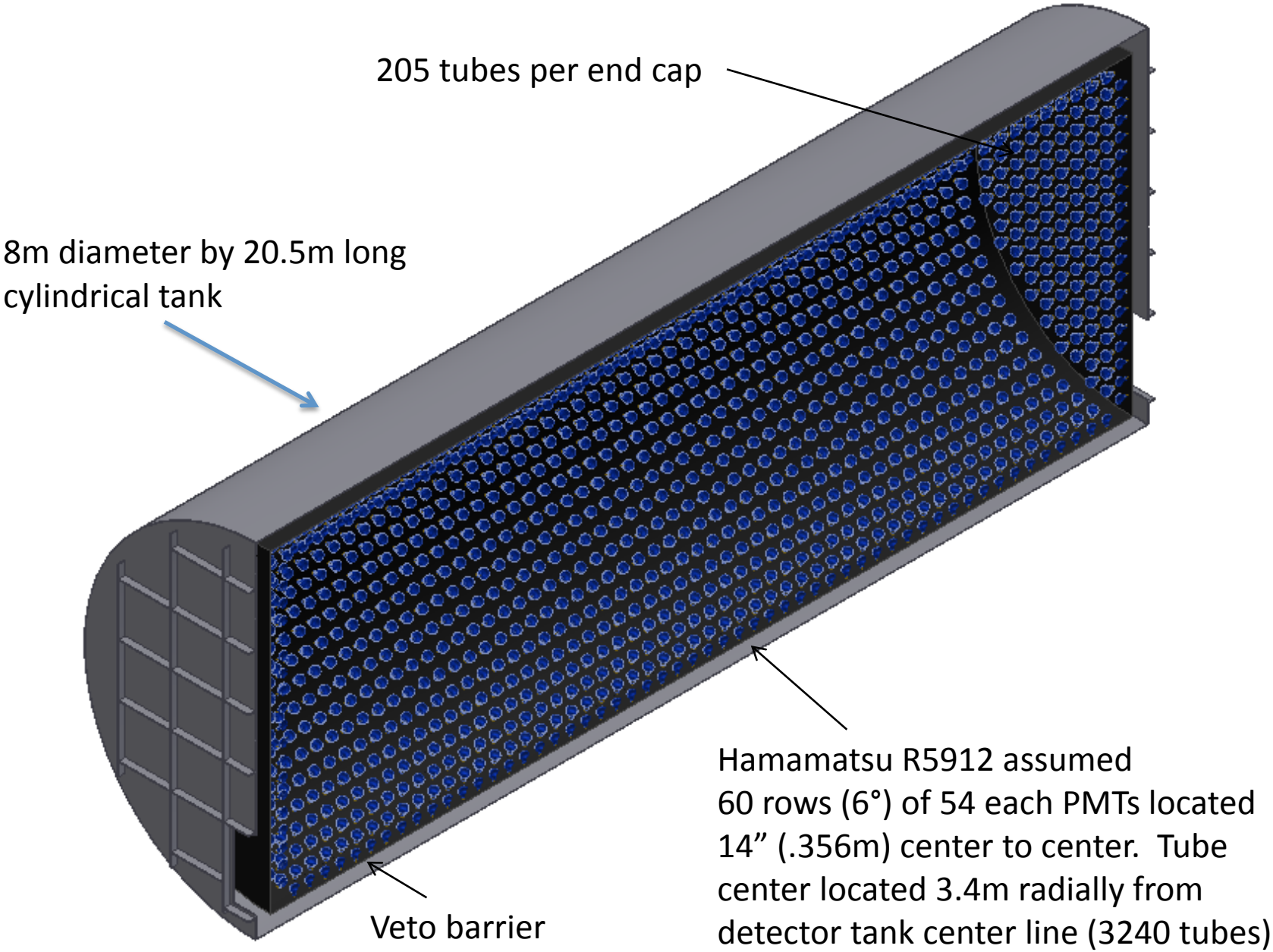






Spallation Neutron Source at ORNL




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

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!

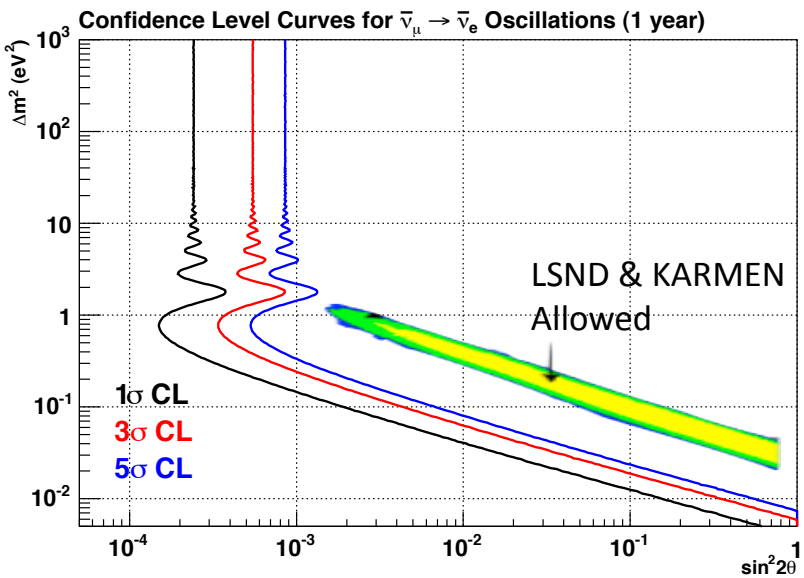
Major Goals of the OscSNS Experiment

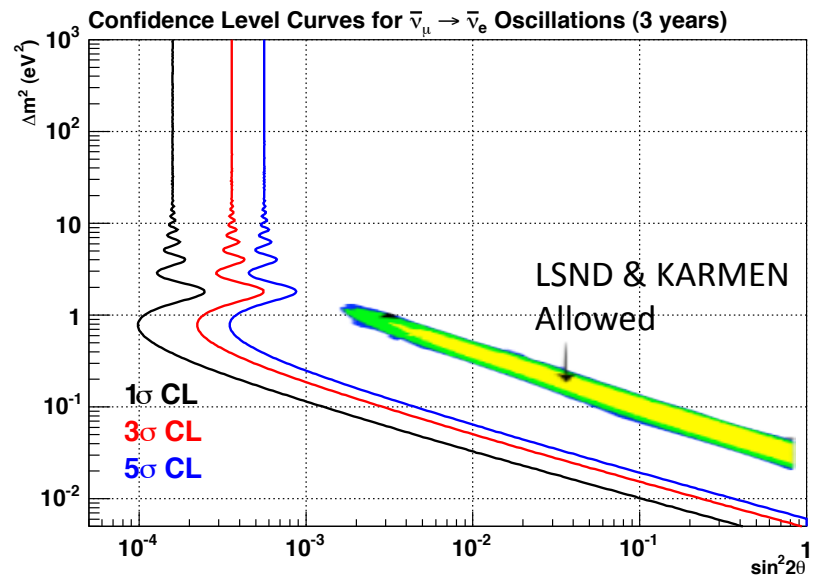
- $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ appearance
- ν_e -> ν_s disappearance
- ν_μ -> ν_s disappearance
- ν e -> ν e cross section measurements

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

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

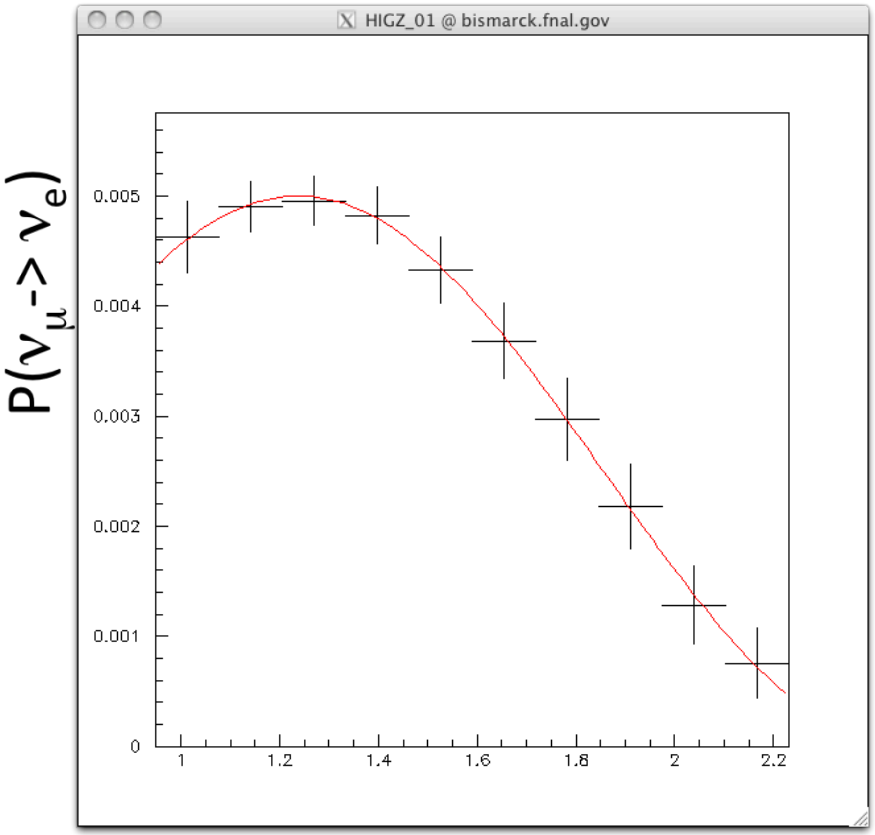
$\bar{\nu}_e$ p -> e^+ n; n p -> d γ (2.2 MeV)



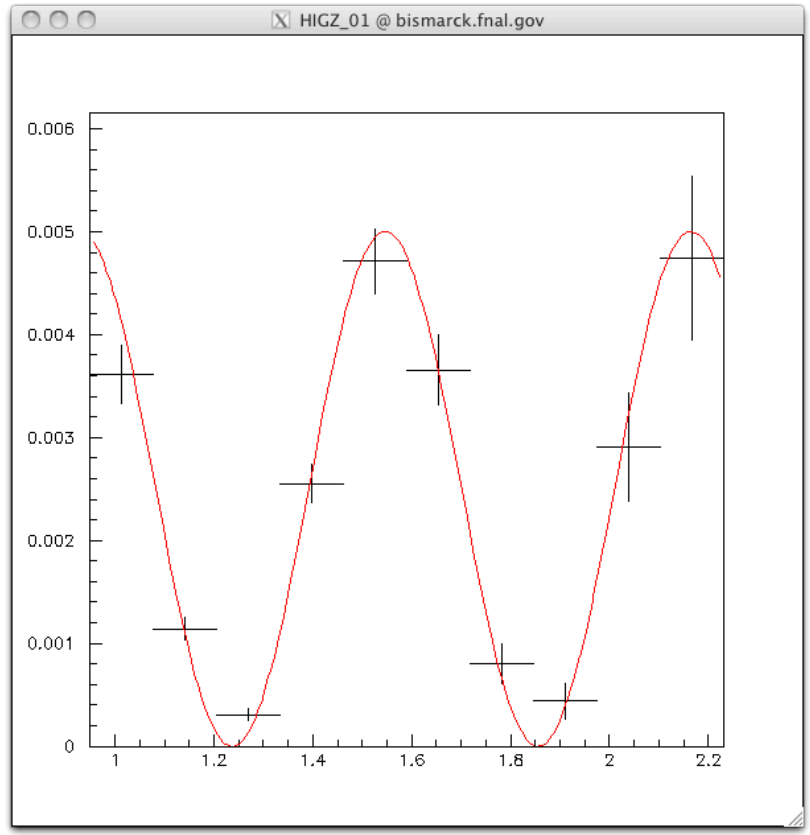


$\bar{\nu}_e\ p \rightarrow e^+\ n$

Assuming 10y of data & $\sin^2 2\theta = 0.005$, $\Delta m^2 = 1\ eV^2$



Assuming 10y of data & $\sin^2 2\theta = 0.005$, $\Delta m^2 = 4\ eV^2$

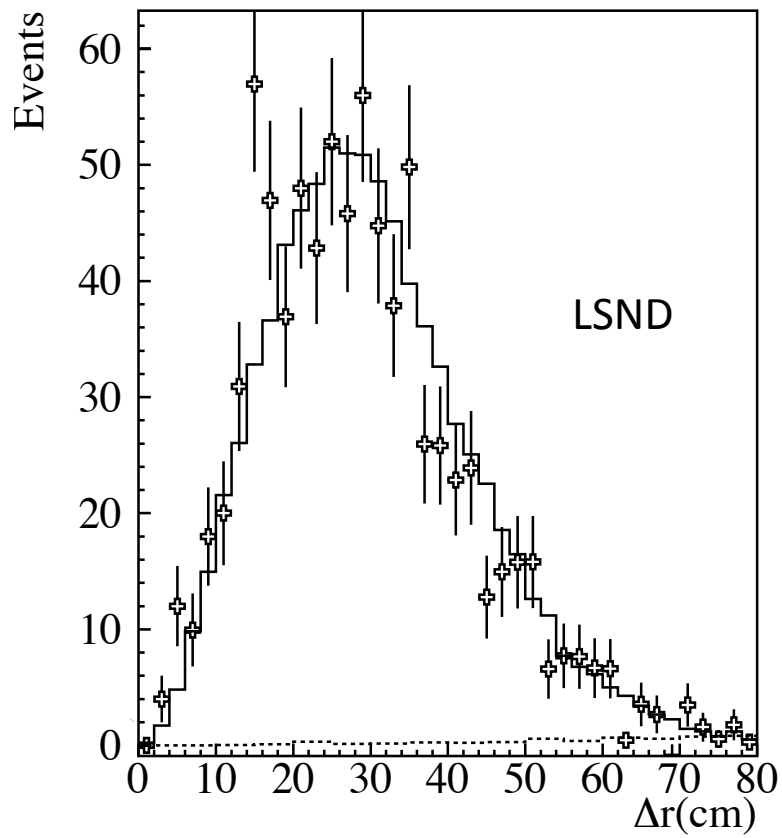


$P(\nu_\mu \rightarrow \nu_e)$

L/E (m/MeV)

ν_e Disappearance of a CC Reaction

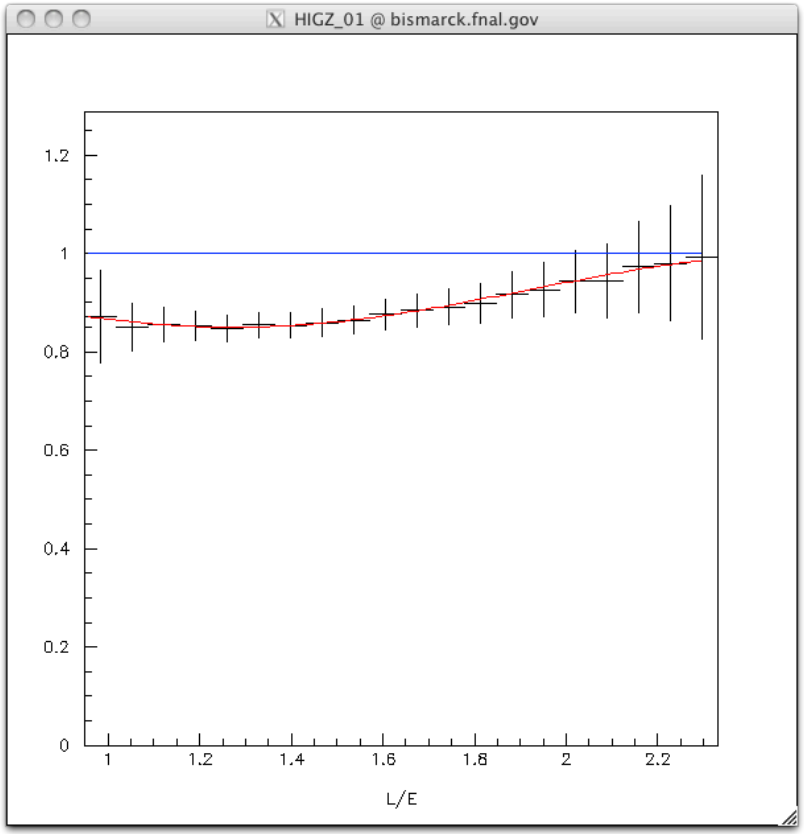
ν_e C -> e^- N_{gs} , N_{gs} -> C_{gs} e^+ ν_e



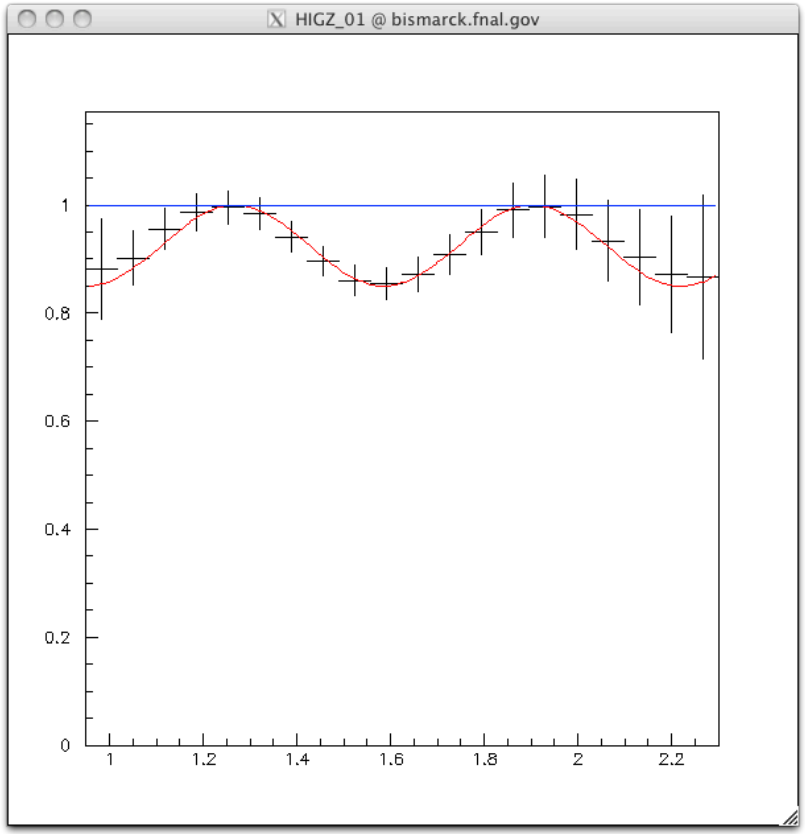
σ_{CC} = (8.9+-0.3+-0.9)x10^{-42} cm^2 (L. B. Auerbach et al., Phys. Rev. C64, 065501 (2001))

ν_e C -> e^- N_{gs} , N_{gs} -> C_{gs} e^+ ν_e

Assuming 10y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 1$ eV^2



Assuming 10y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 4$ eV^2

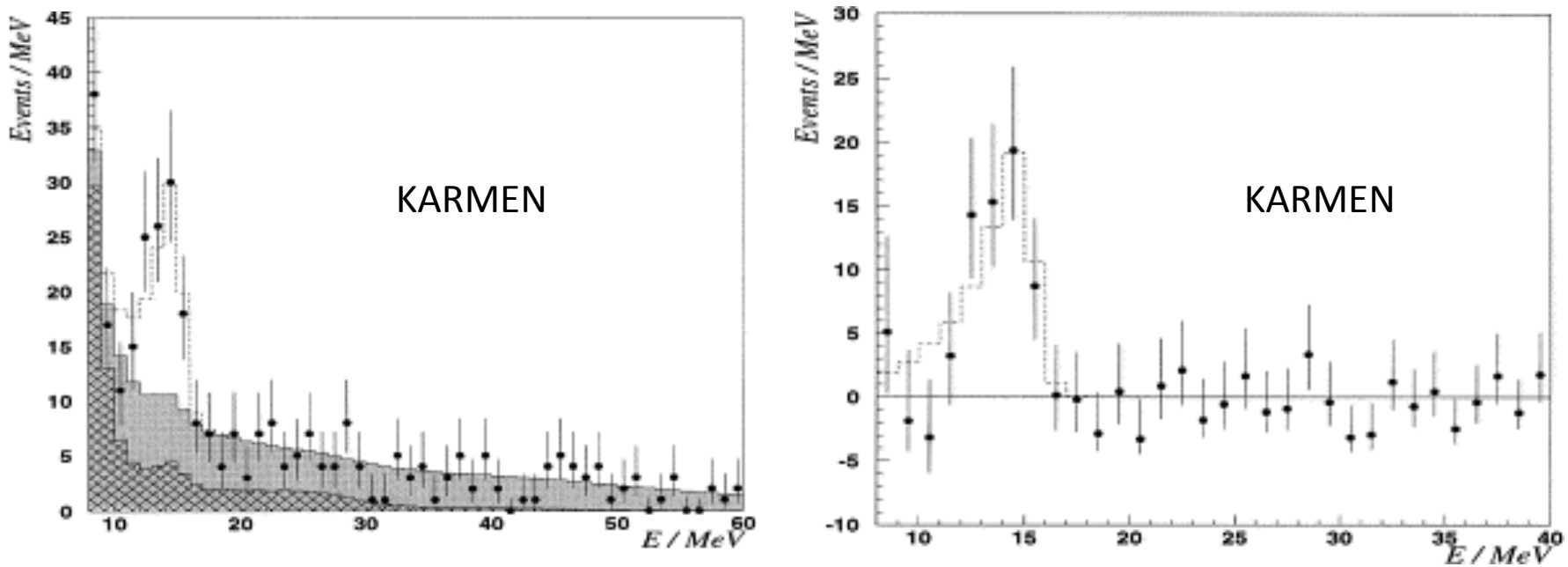


$P(\nu_e \to \nu_e)$

L/E (m/MeV)

ν_μ Disappearance of a NC Reaction

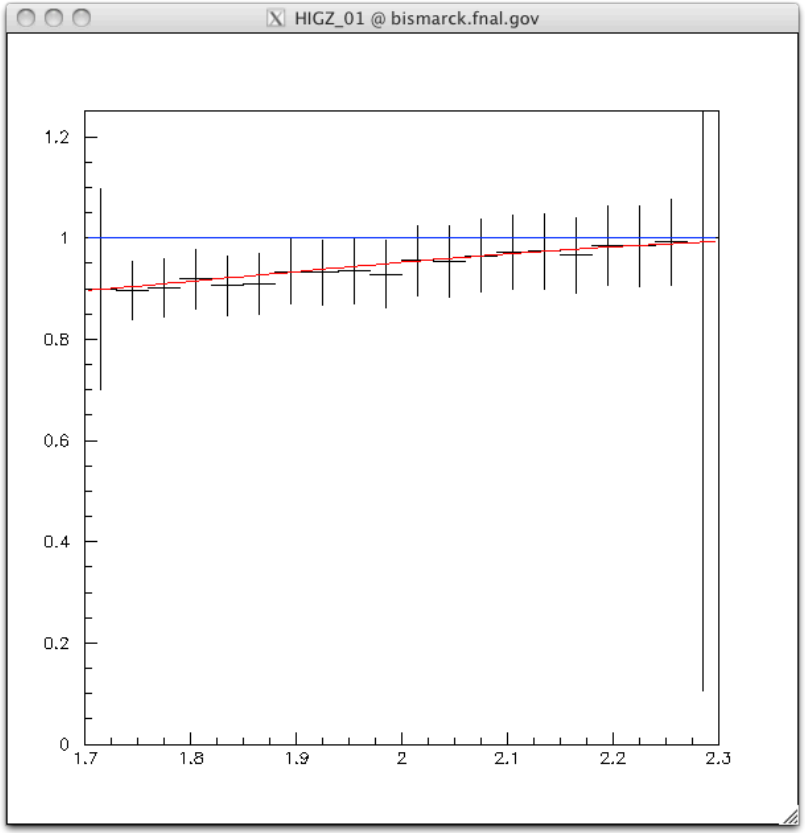
ν_μ C -> ν_μ C*(15.11)



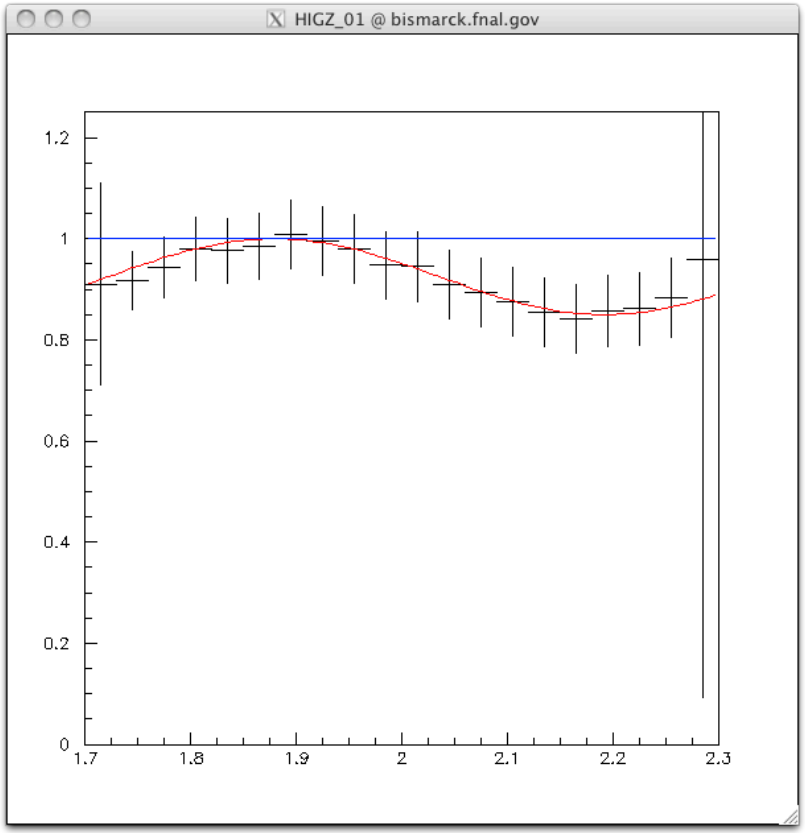
σ_{NC} = (3.2+-0.5+-0.4)x10^{-42} cm^2 (B. Armbruster et al., Phys. Lett. B423 (1998) 15)

ν_μ C -> ν_μ C*(15.11)

Assuming 10y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 1$ eV^2



Assuming 10y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 4$ eV^2



$P(\nu_\mu \to \nu_\mu)$

L/E (m/MeV)

Conclusion

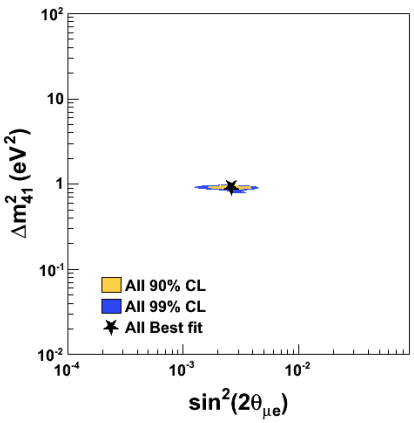
- The results from LSND & MiniBooNE and the anomalies in short baseline ν experiments cannot be explained by the 3 ν paradigm and suggest the existence of sterile ν.
- Sterile ν would contribute to the dark matter of the universe and would have a big impact on particle physics, nuclear physics, astrophysics 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.
- OscSNS has the golden opportunity of proving whether short-baseline oscillations and light, sterile neutrinos exist!

Backup

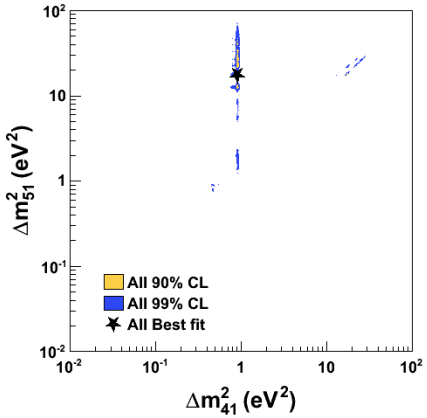
Global 3+N Fits

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

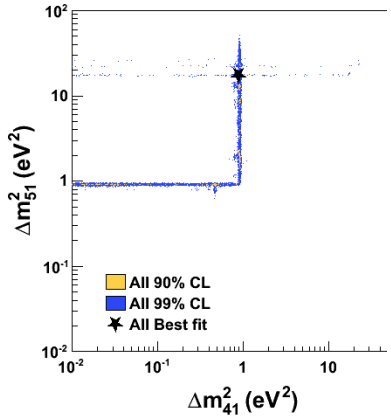
3+1

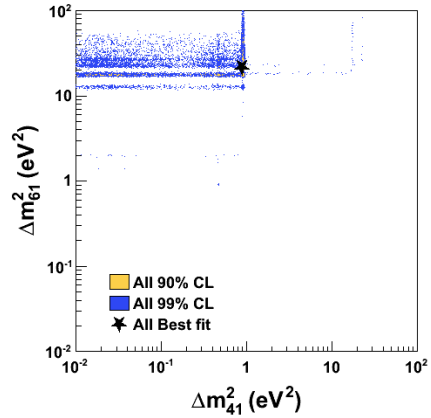


3+2



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

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 Advantages Over Other Neutrino Oscillation Experiments

- Well understood ν fluxes: ν_μ, ν_e, $\overline{\nu}_\mu$
- Well understood ν cross sections
- Low duty factor (4×10^{-5})
- Nuclear effects are not a problem
- 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 $\Delta m^2 > 0.5\ eV^2$!

OscSNS Event Rates at 60m

Channel	Events/2 years
ν_e C -> e^- N_{gs}	4705
ν_e C -> e^- N^*	2247
ν_μ C -> ν_μ C^*(15.11)	1490
ν C -> ν C^*(15.11)	7070
ν_e e^- -> ν_e e^-	1353
ν_μ e^- -> ν_μ e^-	450
100% $\overline{\nu}_\mu$ -> $\overline{\nu}_e$, $\overline{\nu}_e$ p -> e^+ n	92,308
0.26% $\overline{\nu}_\mu$ -> $\overline{\nu}_e$, $\overline{\nu}_e$ p -> e^+ n	240

The OscSNS White Paper

February 4, 2013

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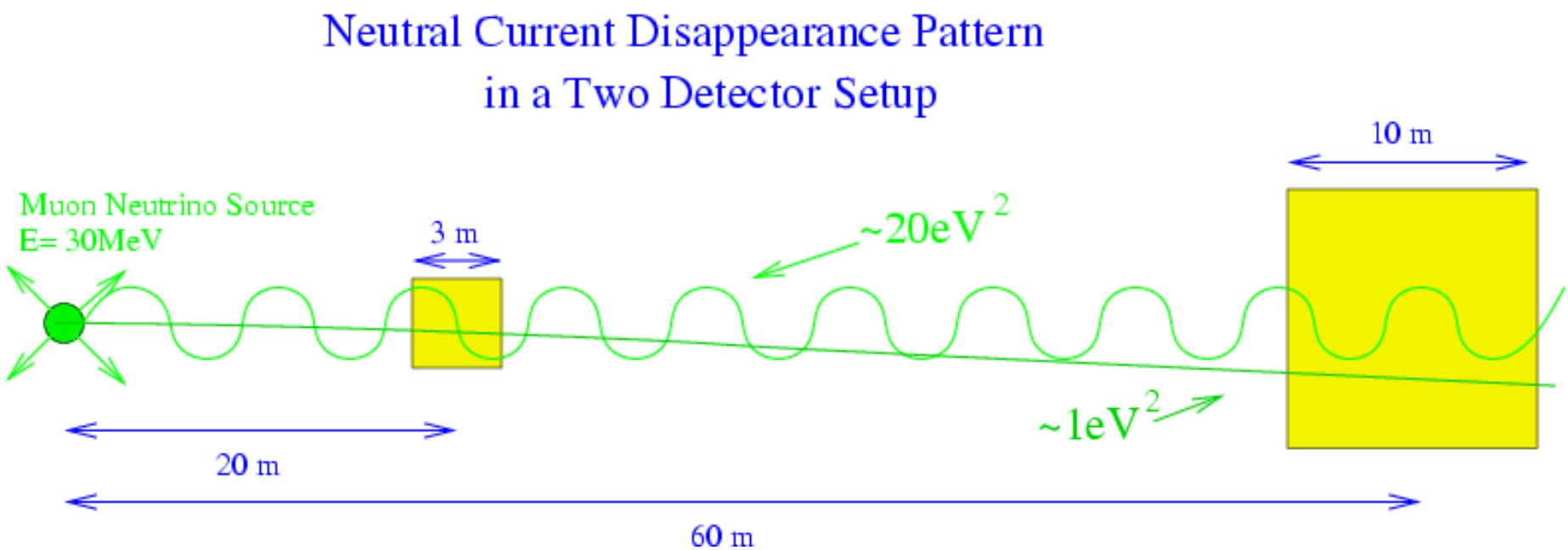
LSND vs OscSNS vs OscJPARC

Parameter	**LSND**	**OscSNS**	**OscJPARC**
Baseline	30 m	60 m	Under consideration
Orientation	Downstream	Upstream	Upstream
Beam Power	0.8 MW	1.4 MW	1.0 MW
Beam Pulse Width	600 μs x 120 Hz	700 ns x 60 Hz	2x80 ns x 25 Hz
Proton Energy	798 MeV	1300 MeV	3000 MeV
Detector Mass	167 tons	886 tons	Under consideration

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

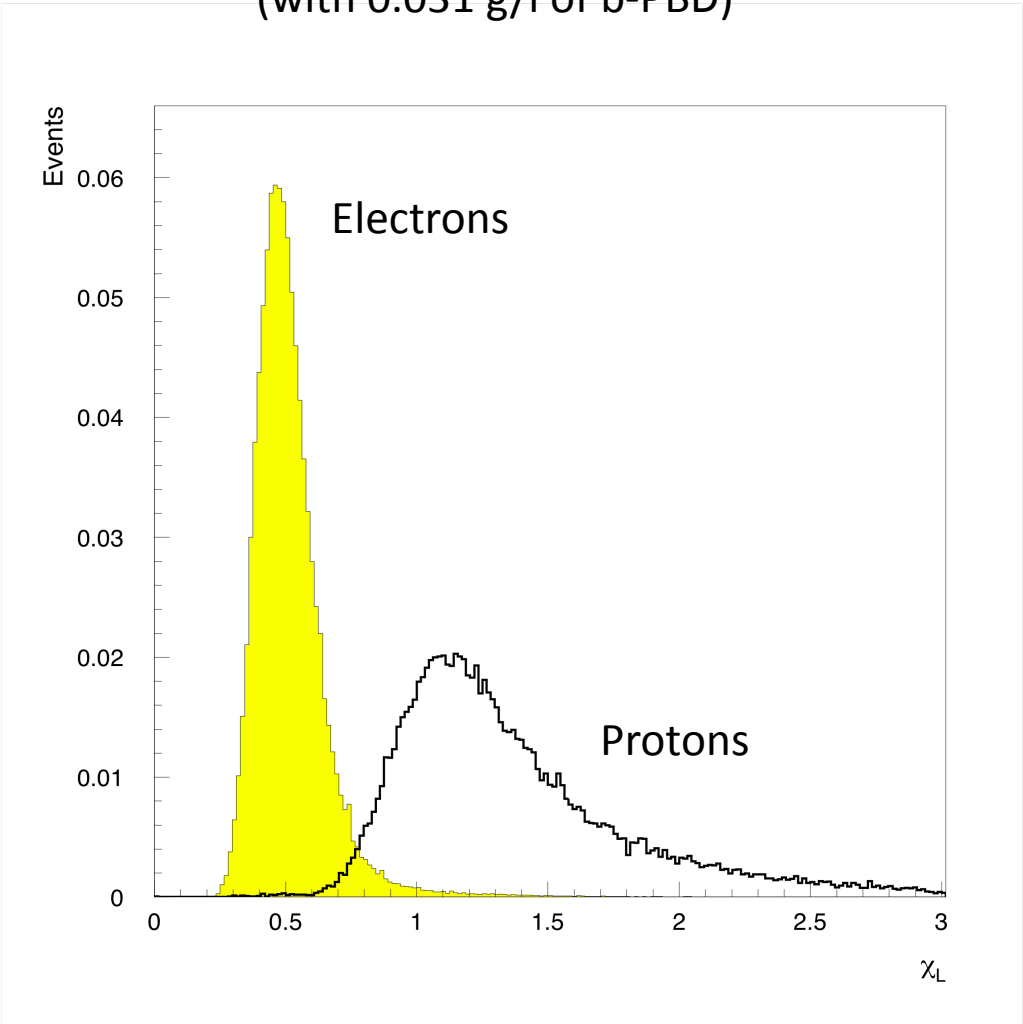
ν_μ C -> ν_μ C*(15.11)

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



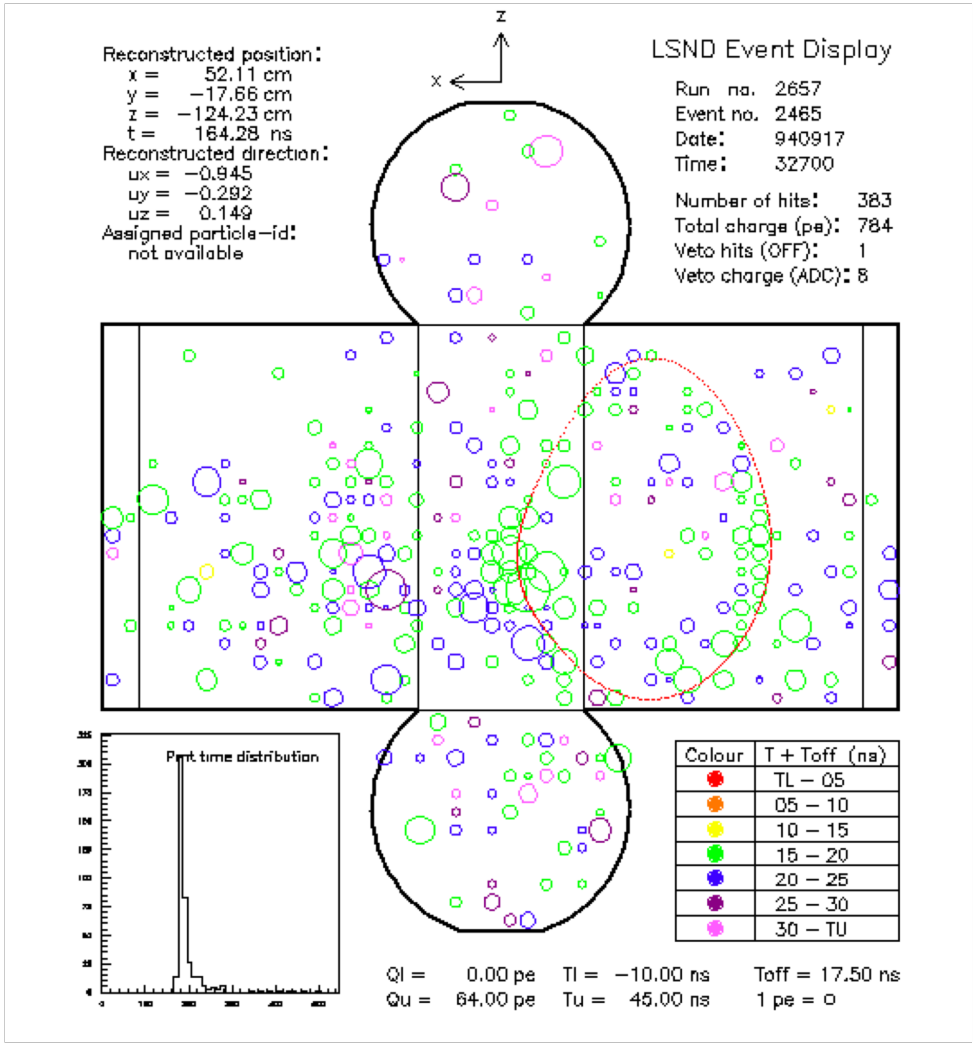
Particle Identification

(with 0.031 g/l of b-PBD)

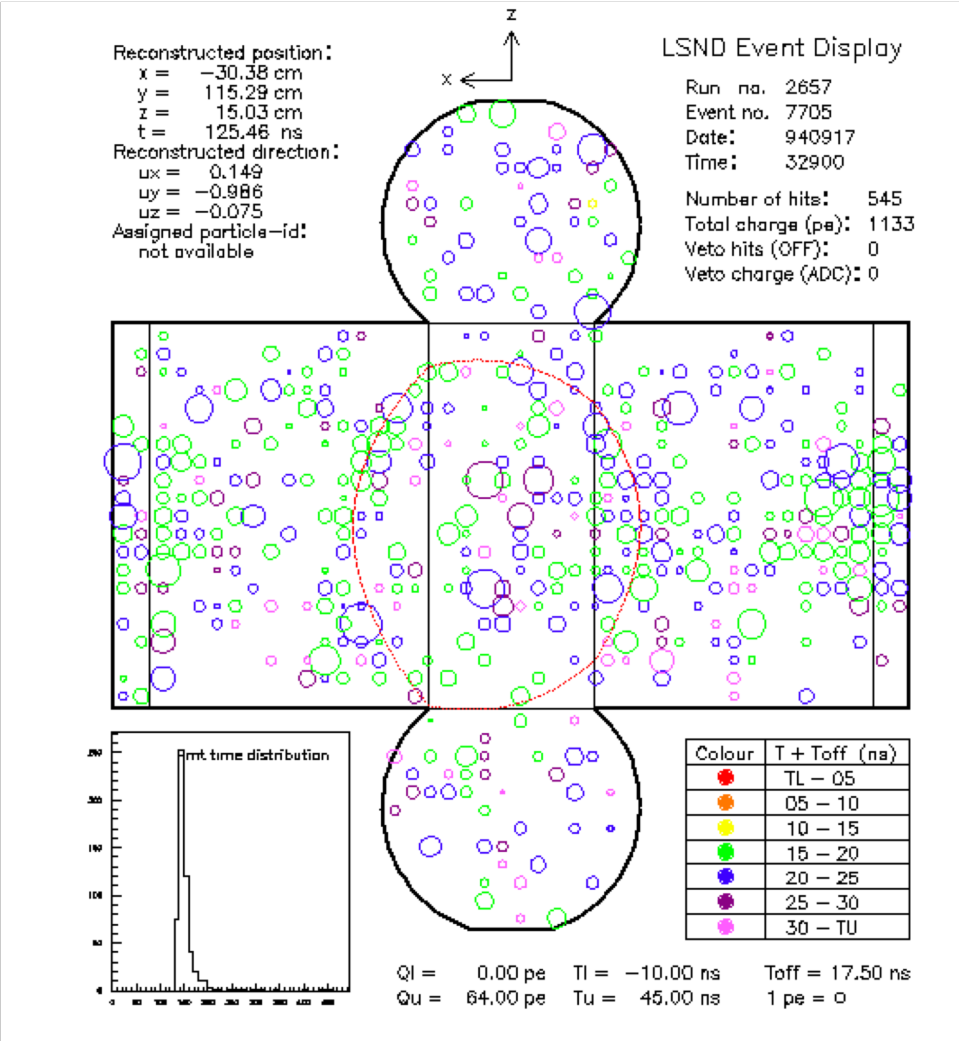


Particle Identification depends on Cherenkov cone fit, position fit, and fraction of late light

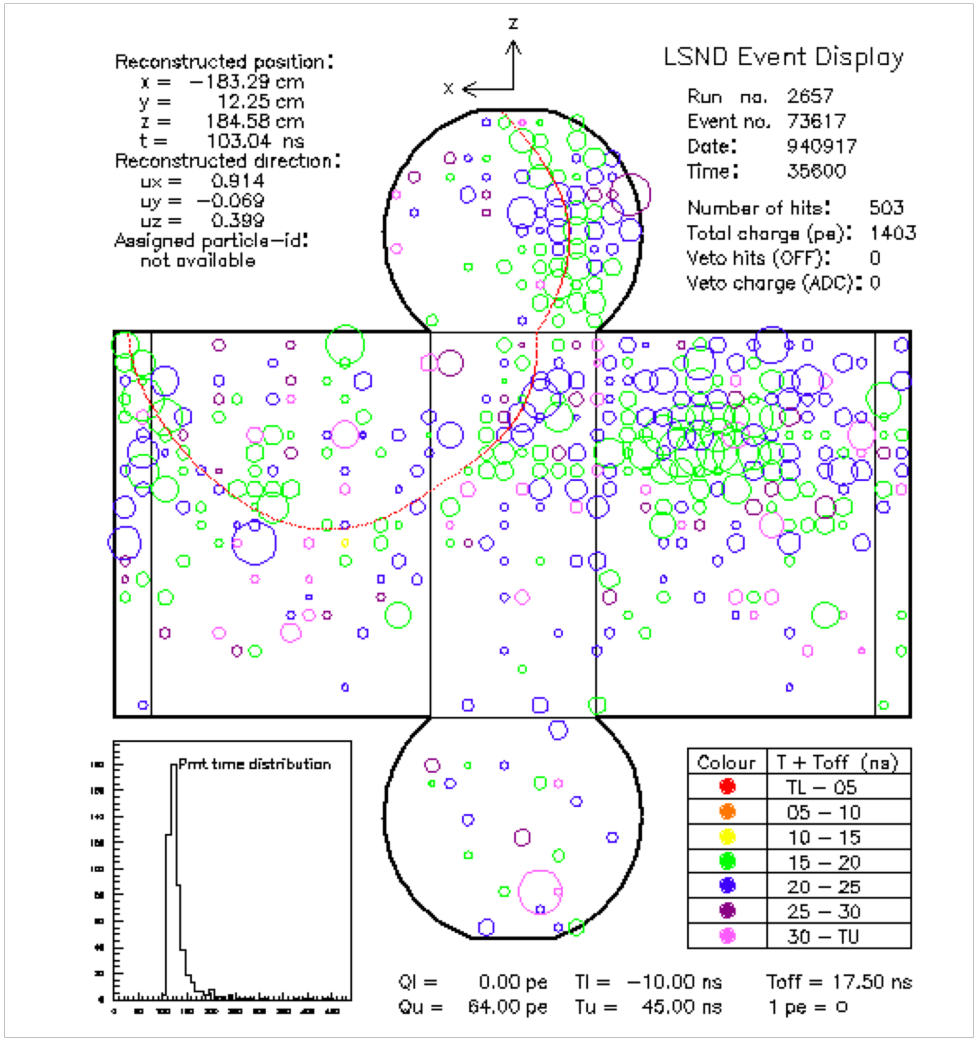
Typical Michel Electron Event Display



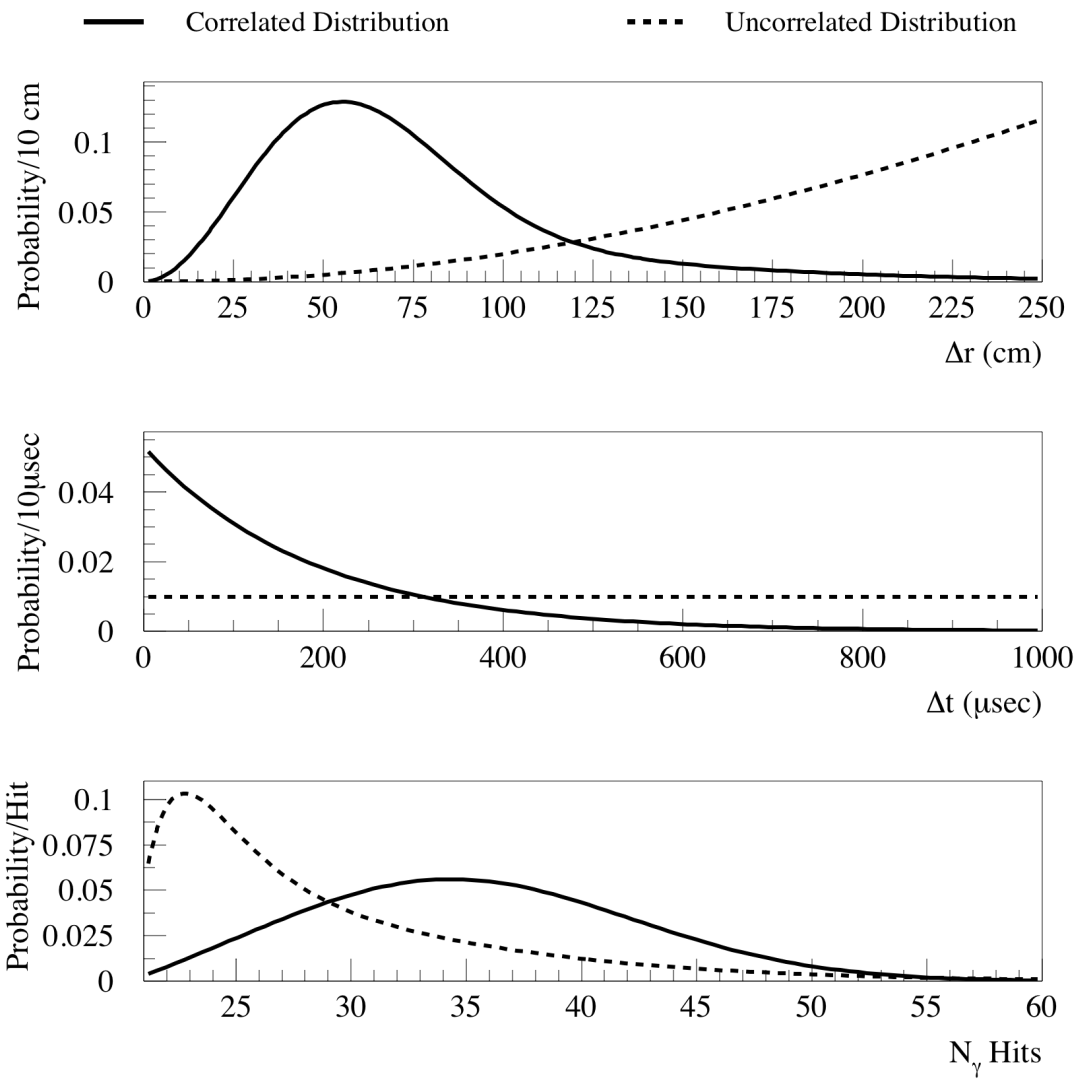
Typical Michel Electron Event Display

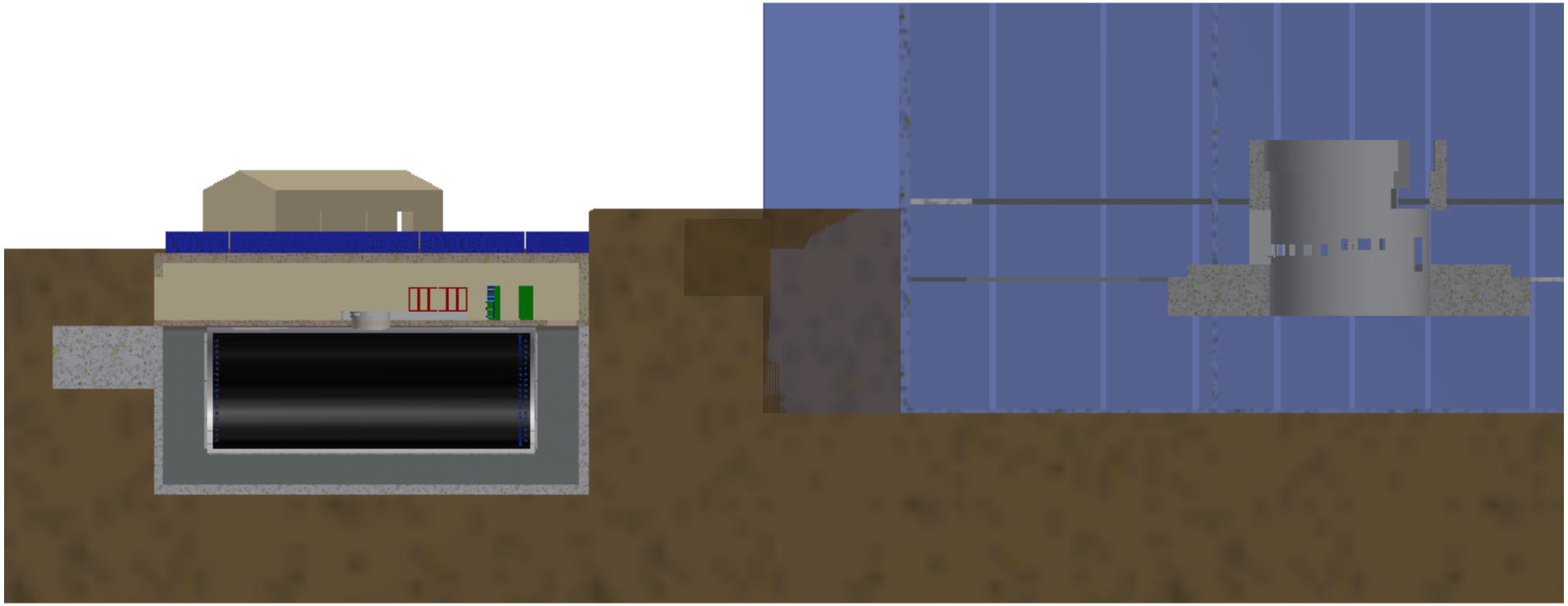


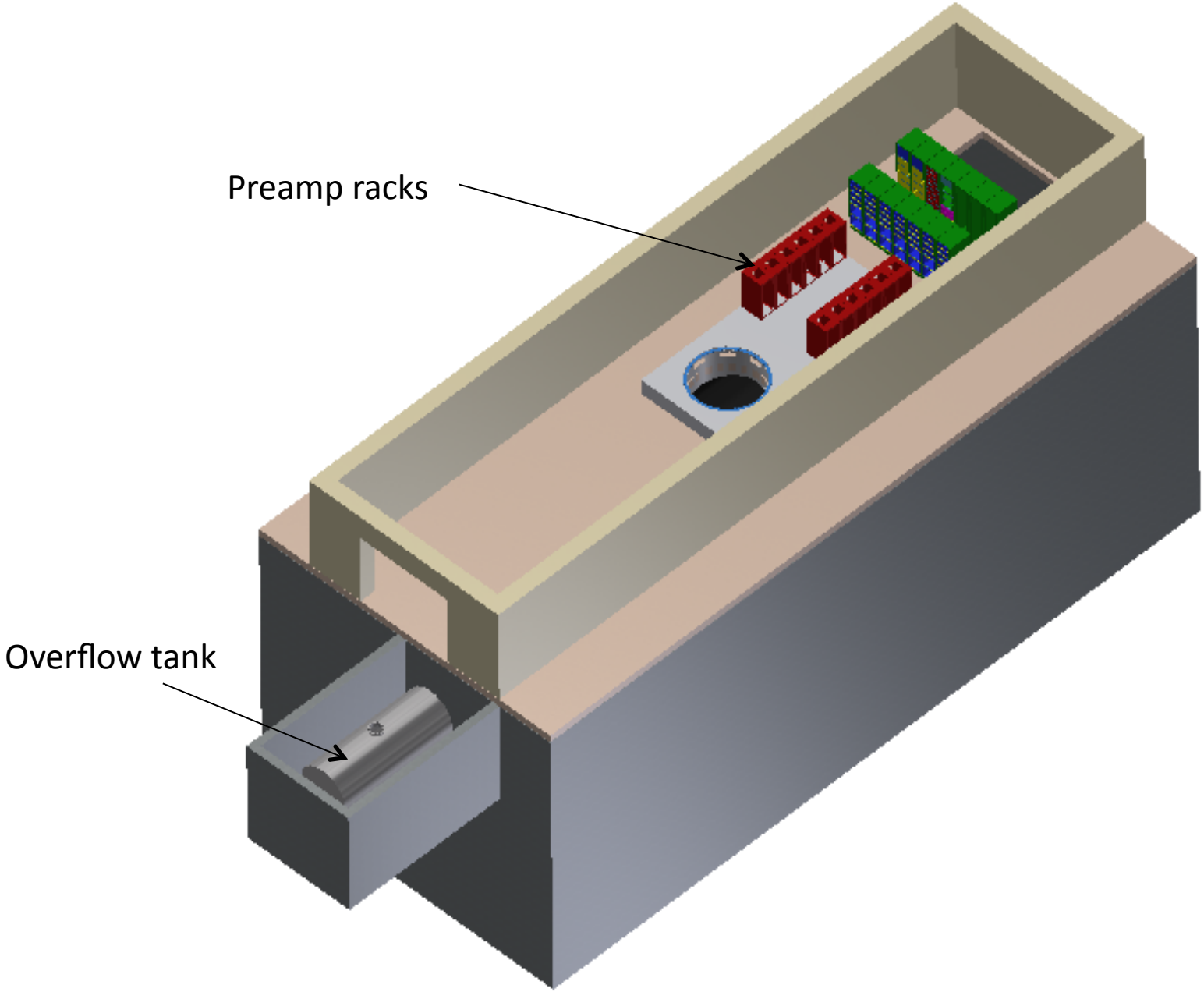
Typical Michel Electron Event Display

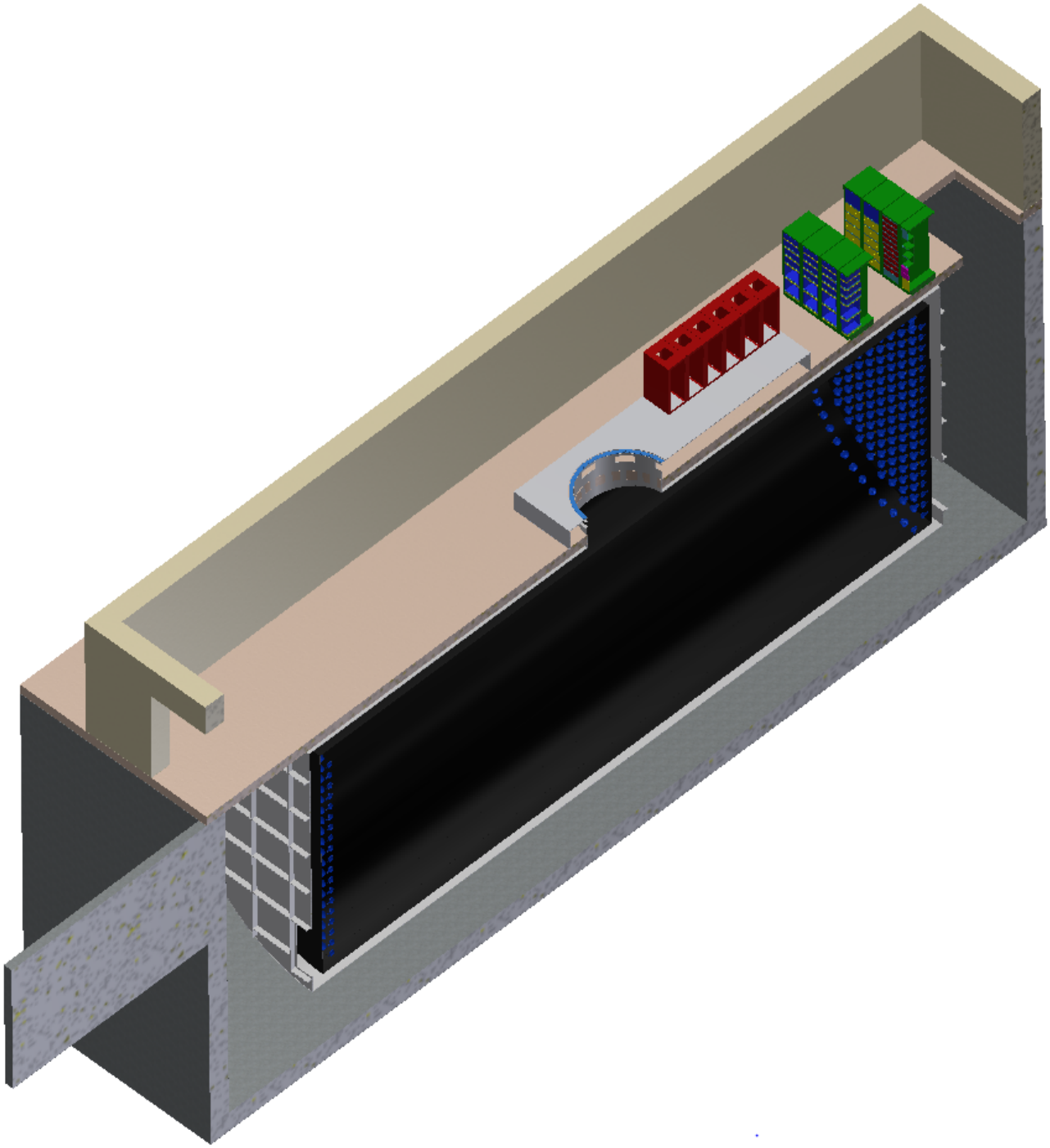


2.2 MeV γ Identification



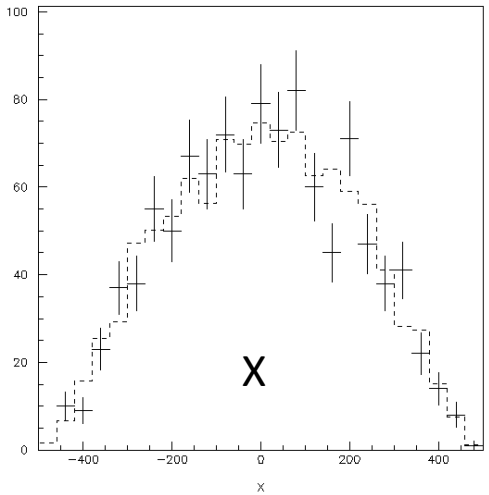



Preamp racks
Overflow tank



MB Spatial Distributions

Neutrino



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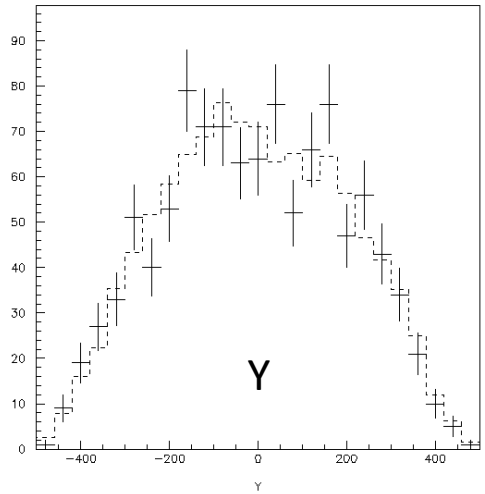
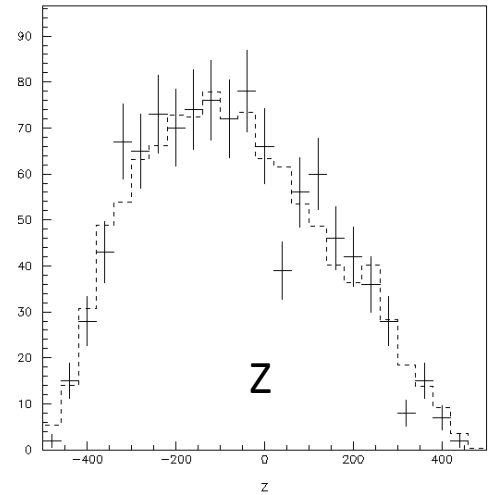
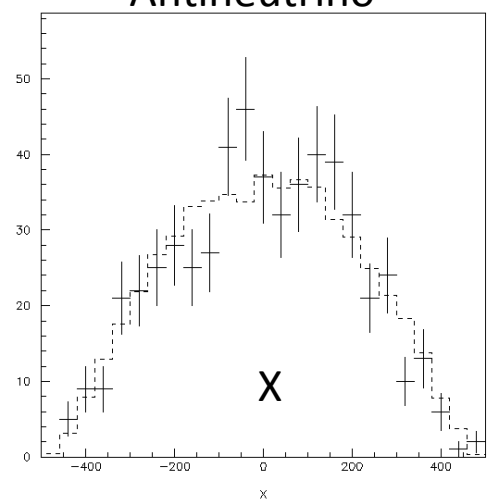


Neutrino



Antineutrino



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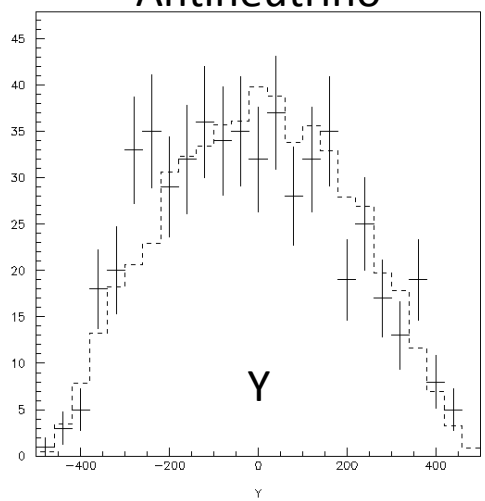

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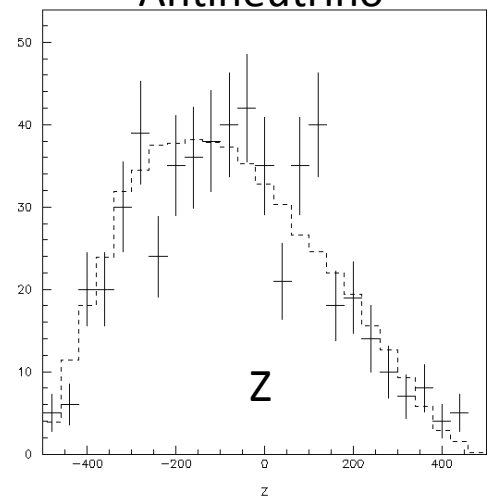
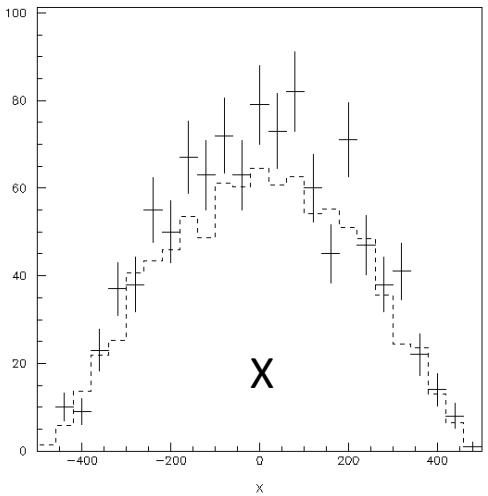


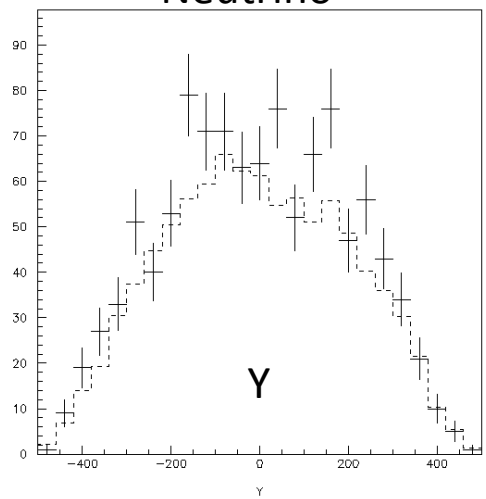
Relative Normalization

MB Spatial Distributions

Neutrino



Neutrino



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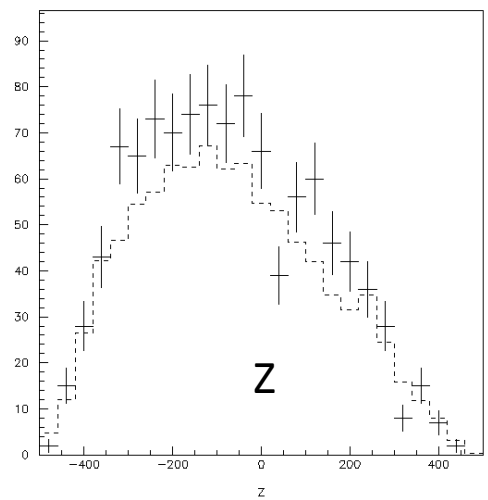

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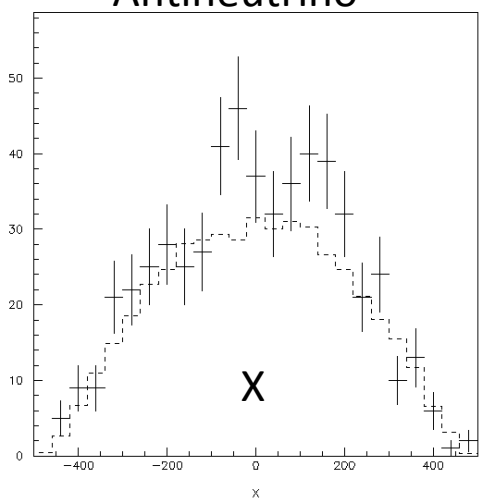

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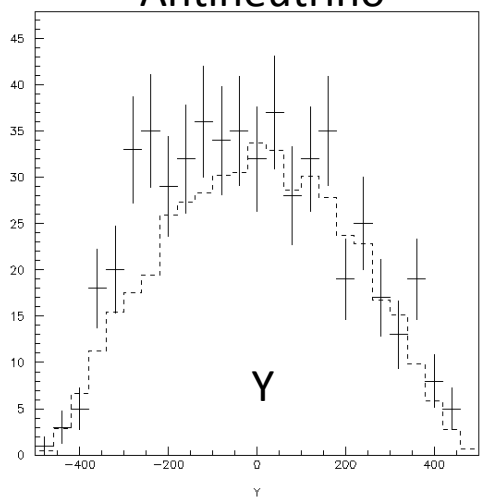

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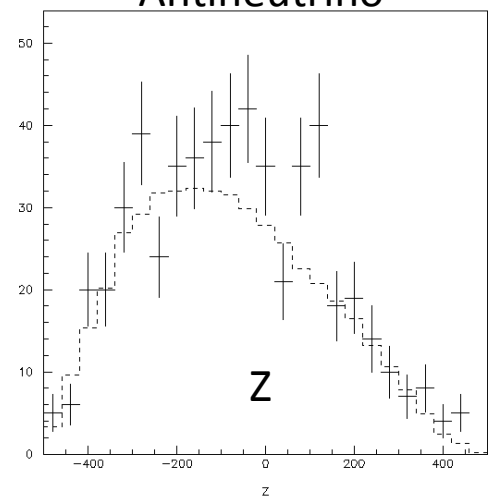

Absolute Normalization

MB Spatial Distributions
(Statistical Errors Only)

Neutrino

$\langle X_{Data}\rangle - \langle X_{MC}\rangle = -0.2 +- 6.8$

$\langle Y_{Data}\rangle - \langle Y_{MC}\rangle = -2.2 +- 6.9$

$\langle Z_{Data}\rangle - \langle Z_{MC}\rangle = -4.4 +- 6.7$

Antineutrino

$\langle X_{Data}\rangle - \langle X_{MC}\rangle = -2.1 +- 8.7$

$\langle Y_{Data}\rangle - \langle Y_{MC}\rangle = -16.4 +- 9.2$

$\langle Z_{Data}\rangle - \langle Z_{MC}\rangle = 14.0 +- 8.9$

χ^2 = 6.2/6 DF (Prob = 40%)

NCγ Background Estimates

- $<E_\nu>$ ~ 800 MeV for π^0 production in MB
- MB: $<\sigma_{\pi 0}>$ ~ 5×10^{-40} cm^2/N
- MB: $<\sigma_\gamma>$ ~ 5×10^{-42} cm^2/N
- Richard Hill: $<\sigma_\gamma>$ ~ 6.7×10^{-42} cm^2/N (Δ: 5.0; Compton: 0.9; ω: 0.1; Coh: 0.7)
- Xilin Zhang: $<\sigma_\gamma>$ ~ 3.7×10^{-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

arXiv:1112.2181v1 [hep-ex] 9 Dec 2011

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

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(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