Terrestrial Hints/Evidence for Sterile Neutrinos: Short-Baseline Anomalies

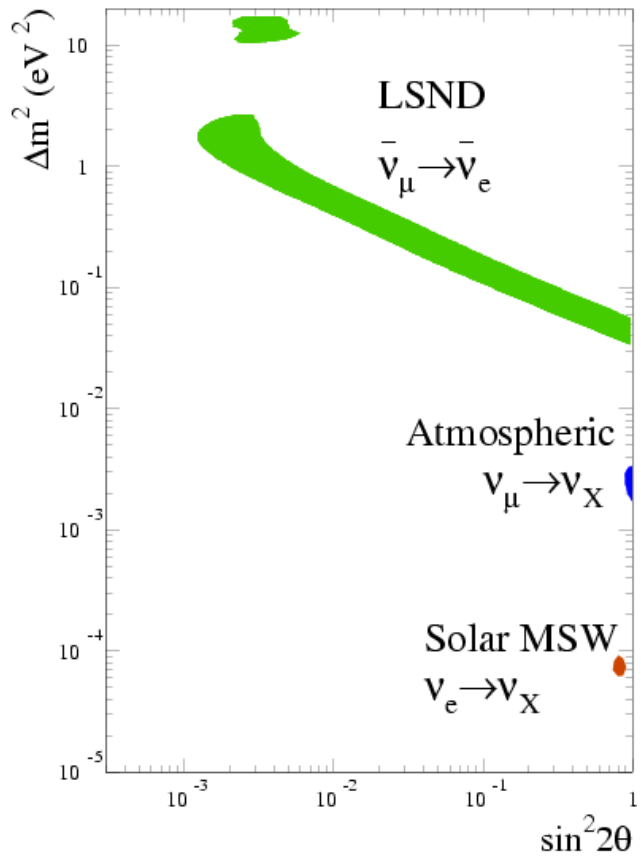
W. C. Louis, LANL

May 18, 2012

- Short-Baseline Anomalies: LSND, MiniBooNE, reactor ν experiments, radioactive ν source experiments
- 3+N Models & Sterile Neutrinos
- Proving the Existence of Sterile Neutrinos: OscSNS
- Conclusions

Anomalous Results from Short-Baseline ν Experiments Not Explained by 3 ν

- LSND $\bar{\nu}_e$ Excess
- MiniBooNE ν_e Excess
- MiniBooNE $\bar{\nu}_e$ Excess
- Reactor $\bar{\nu}_e$ Anomaly
- Radioactive ν_e Source Anomaly

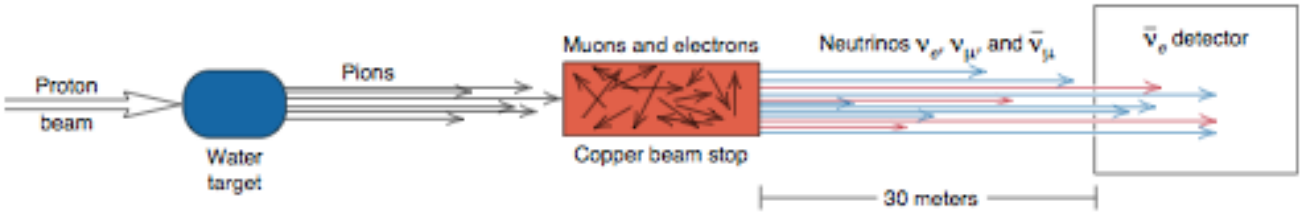


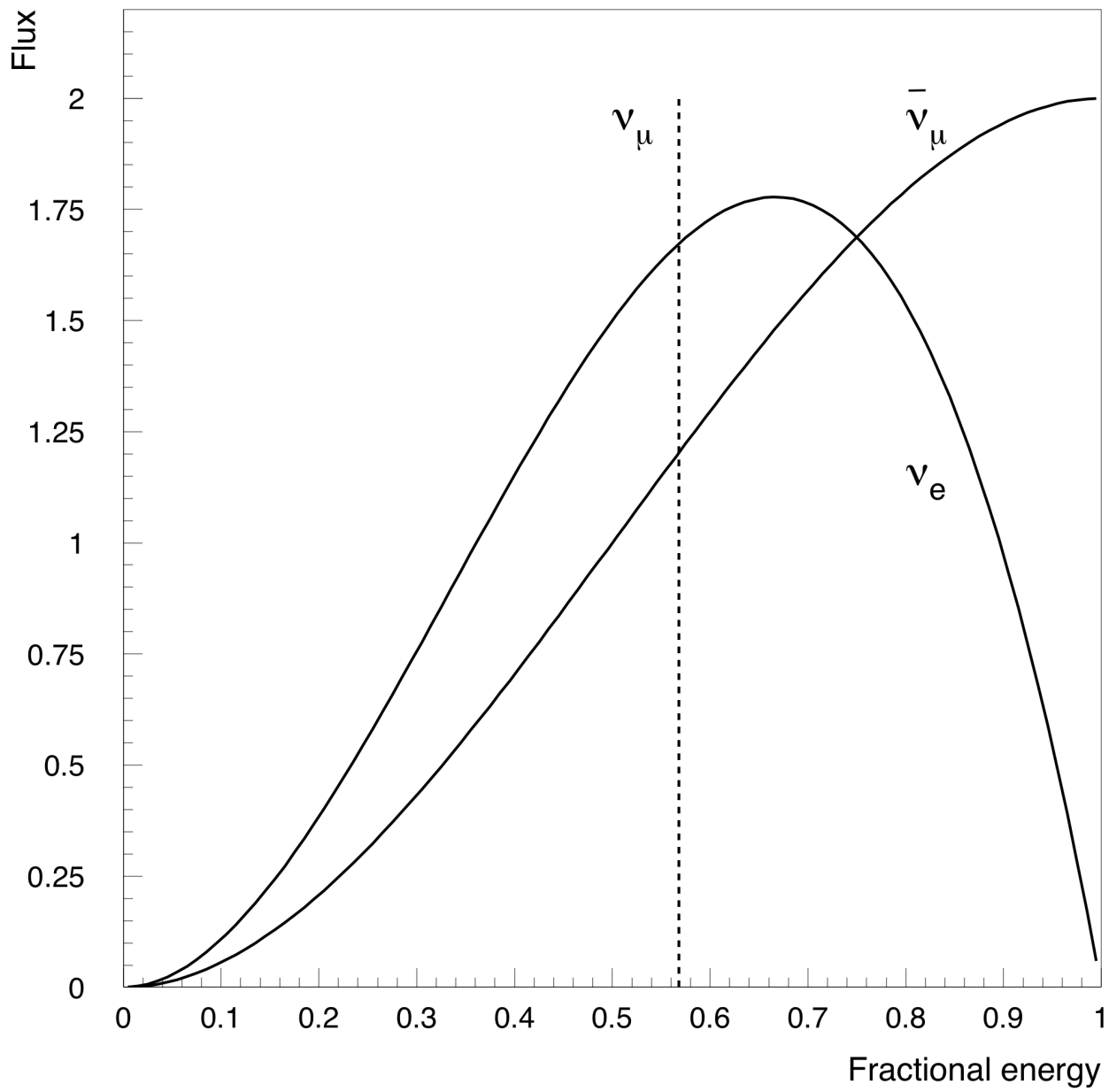
- These results (2-4 σ) are not directly ruled out by any other experiment.

LSND Experiment

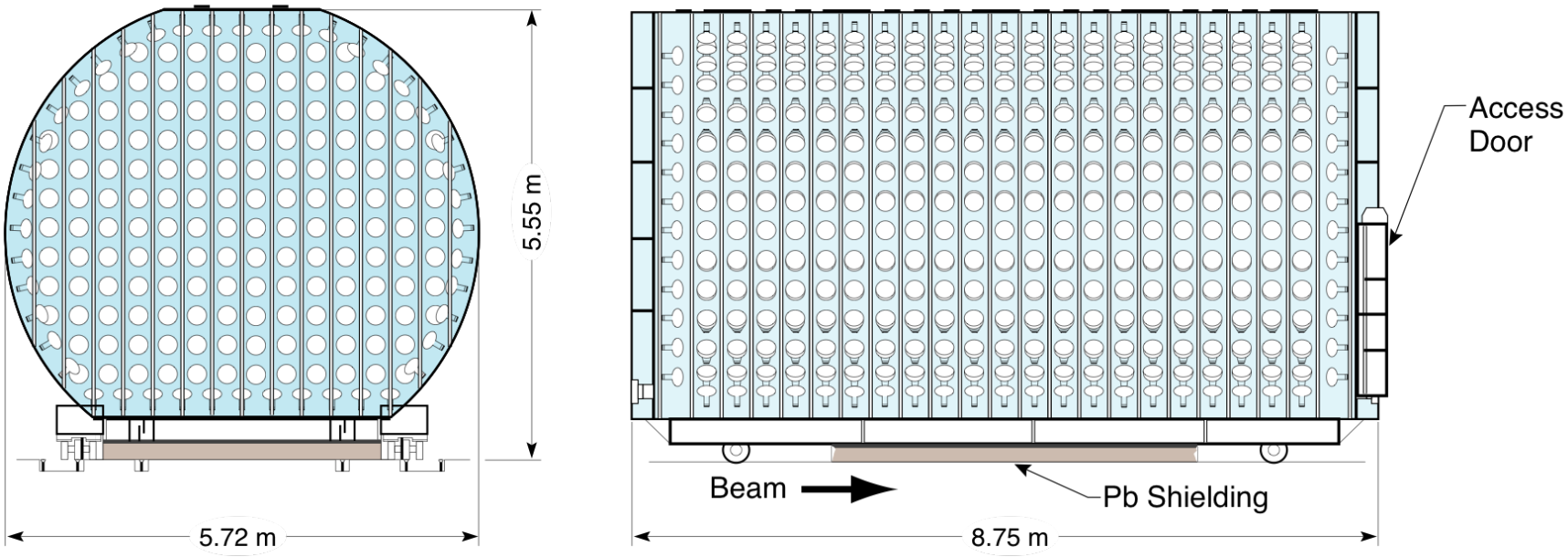
C. Athanassopoulos et al., Nucl. Instrum. Methods A 388, 149, (1997).

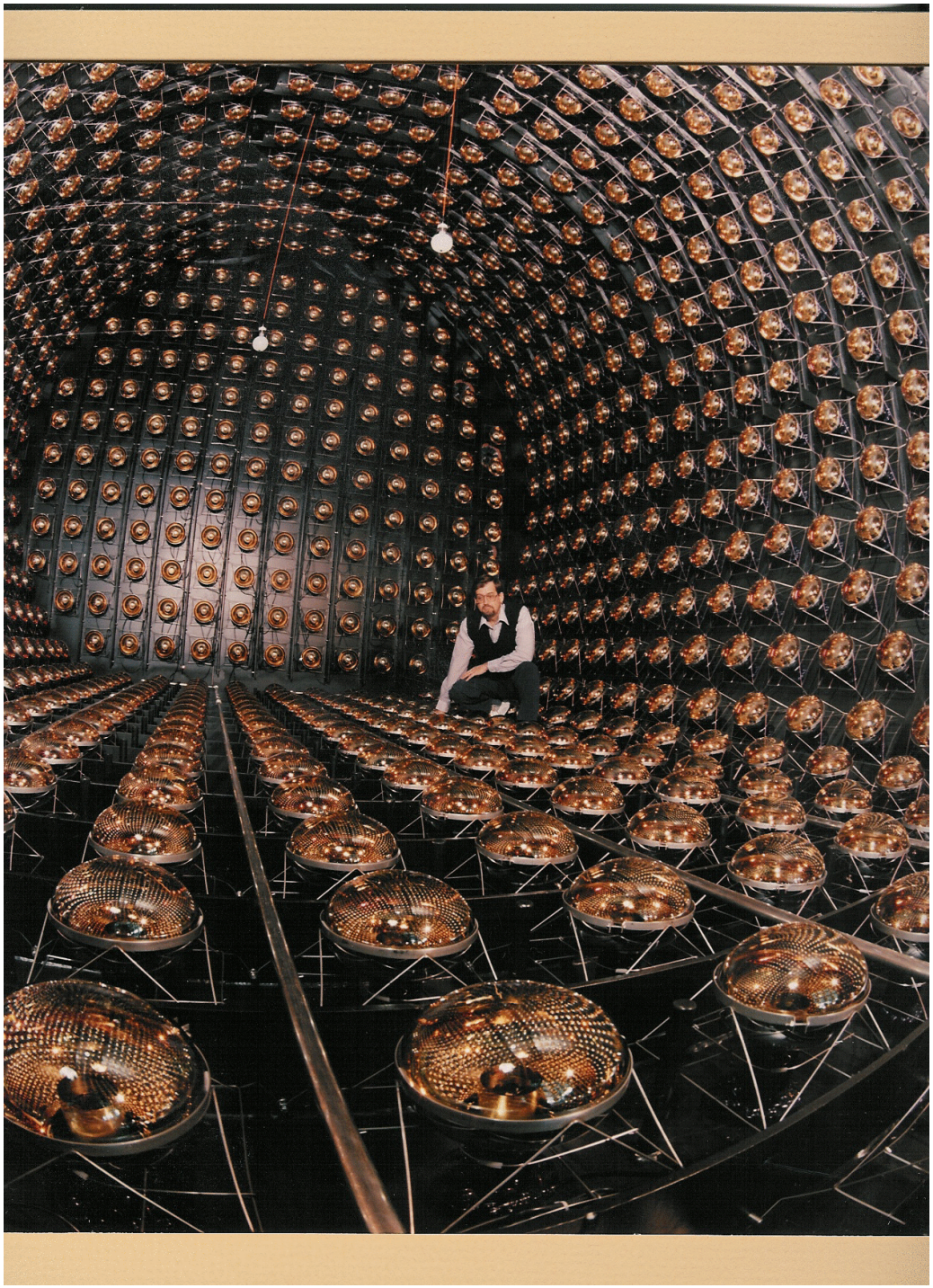
- 1 mA, 798 MeV proton beam with 6% DF
- 28,896 C (0.3 g) of protons on target from 1993-1998
- Neutrinos from π^+/μ^+ DAR: $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
- $\bar{\nu}_e/\nu_e \sim 8\times10^{-4}$
- 8.3 m long x 5.7 m diameter cylindrical tank
- Tank covered by 1220 8" PMTs (25% coverage)
- Tank filled with 167 tons of mineral oil + 0.031 g/l of b-PBD




Flux
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Fractional energy
ν_μ
$\bar{\nu}_\mu$
ν_e

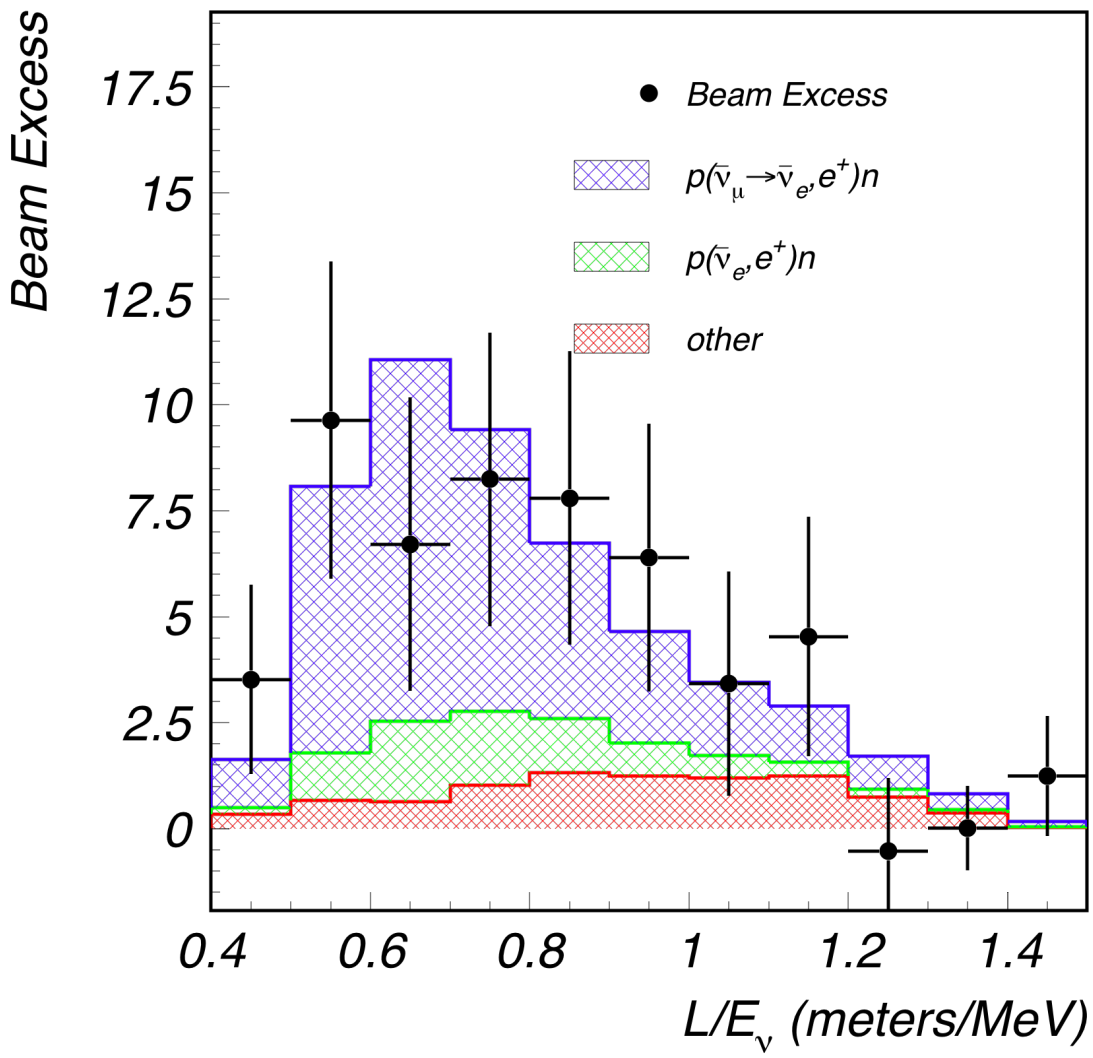
LSND Detector





LSND Antineutrino Results

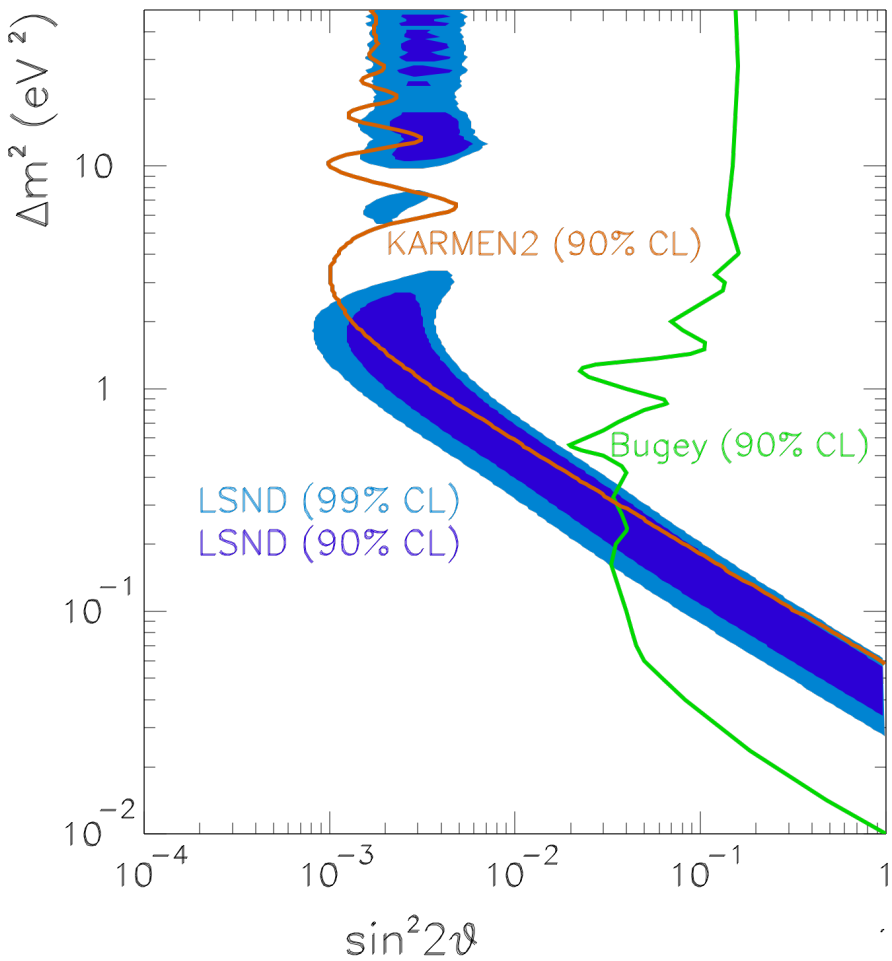
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)



3.8 σ excess of events

LSND Allowed Oscillation Region

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

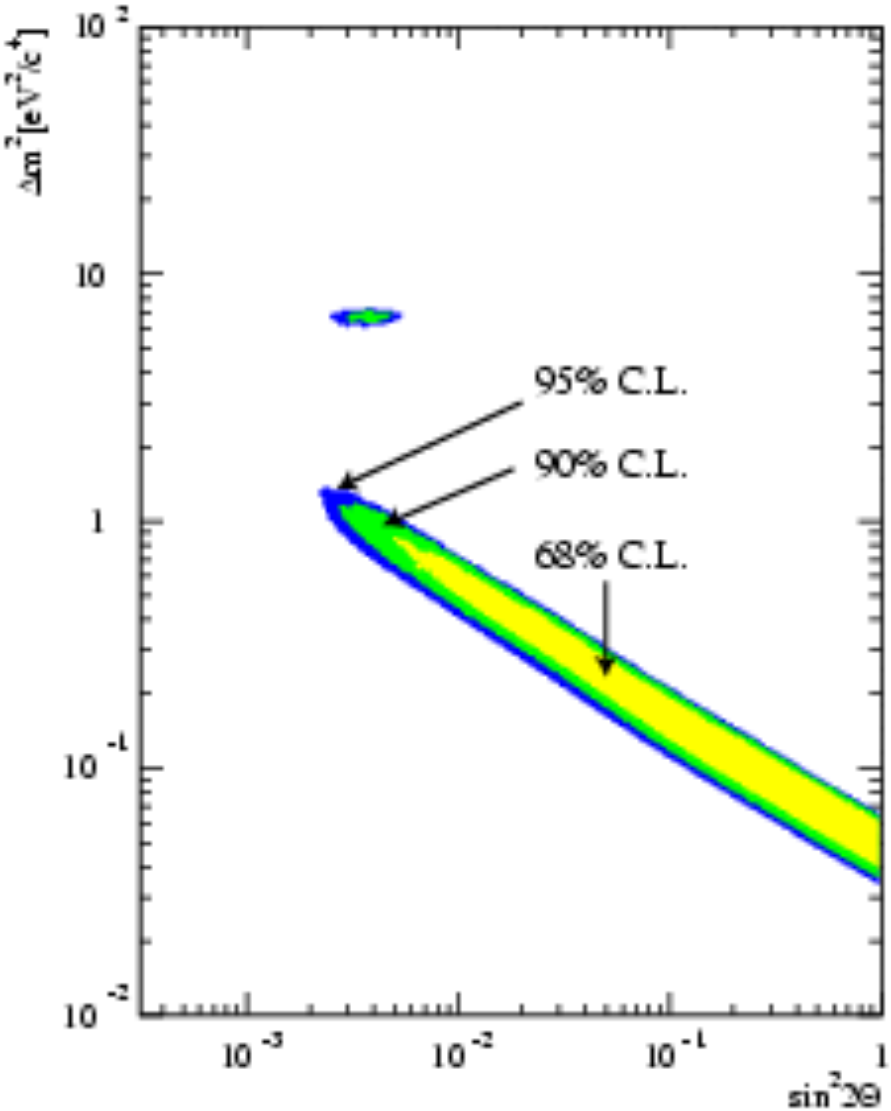


LSND & KARMEN Comparison

Property	**LSND**	**KARMEN**
Proton Energy	798 MeV	800 MeV
Proton Intensity	1000 μA	200 μA
Protons on Target	28,896 C	9425 C
Duty Factor	6×10^{-2}	1×10^{-5}
Total Mass	167 t	56 t
Neutrino Distance	30 m	17.7 m
Particle Identification	Yes	No
$\delta E/E$ at 50 MeV	6.6%	1.6%
Events for 100% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	33,300	14,000
Beam Angle	17°	90°

Joint LSND/KARMEN Fit

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



Two experiments are incompatible at 36% CL

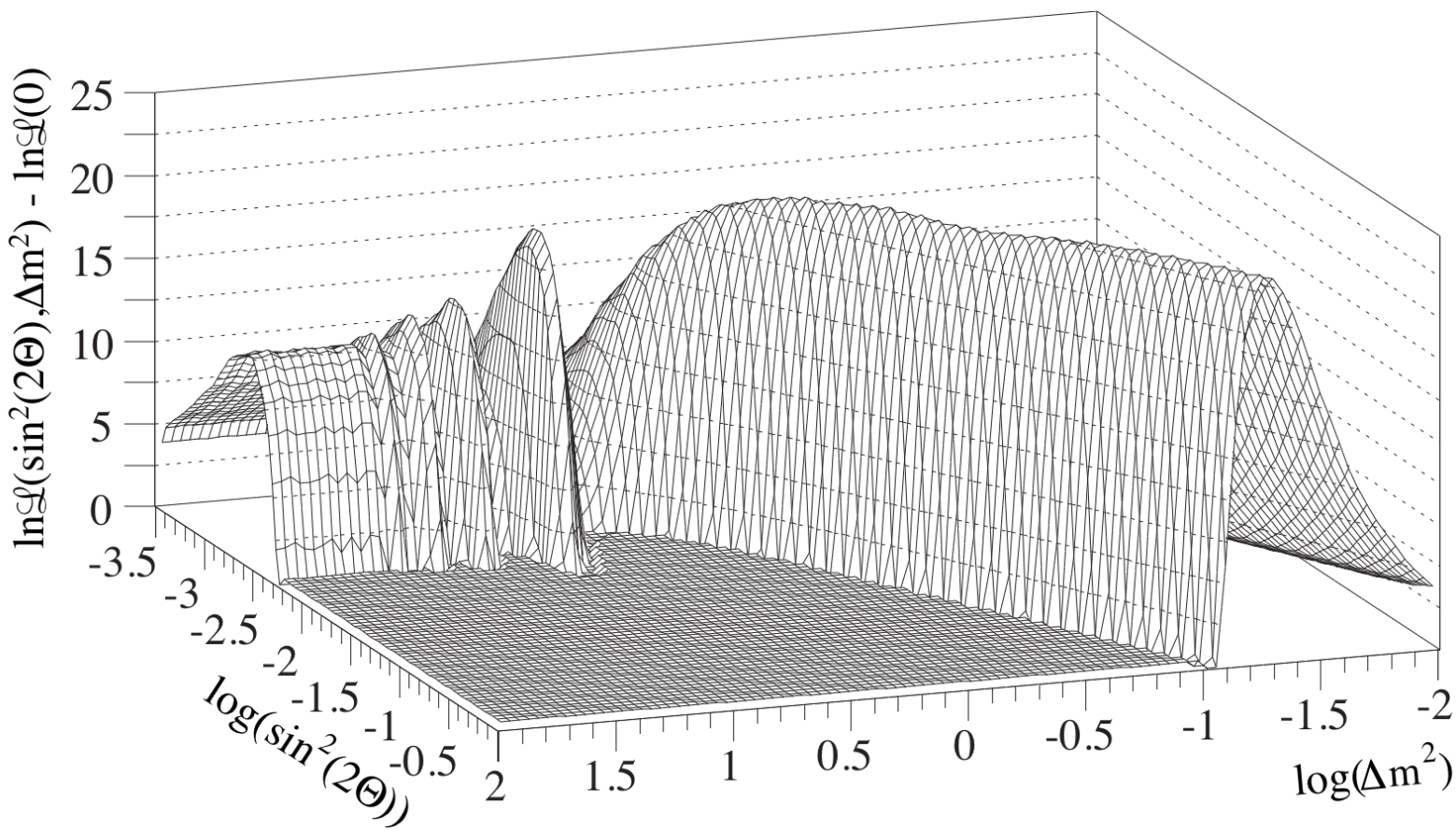
Best Fit at $\Delta m^2 = 0.05$ eV^2
$\sin^2 2\theta = 1$

logL(Best Fit – Null) = 21.5

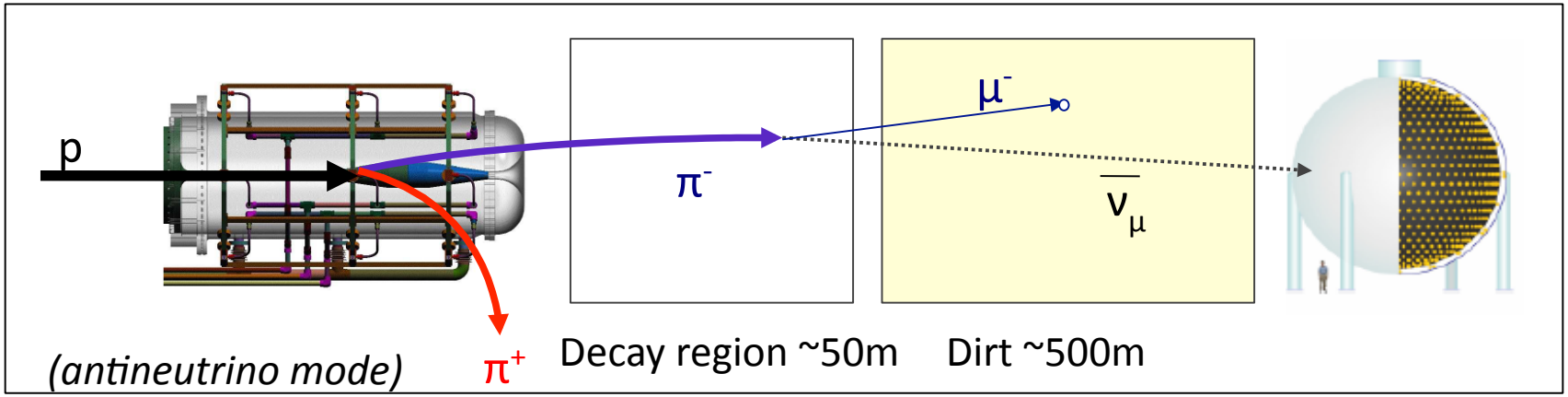
$\Delta\chi^2 \sim 43$

Joint Fit to LSND & KARMEN Data

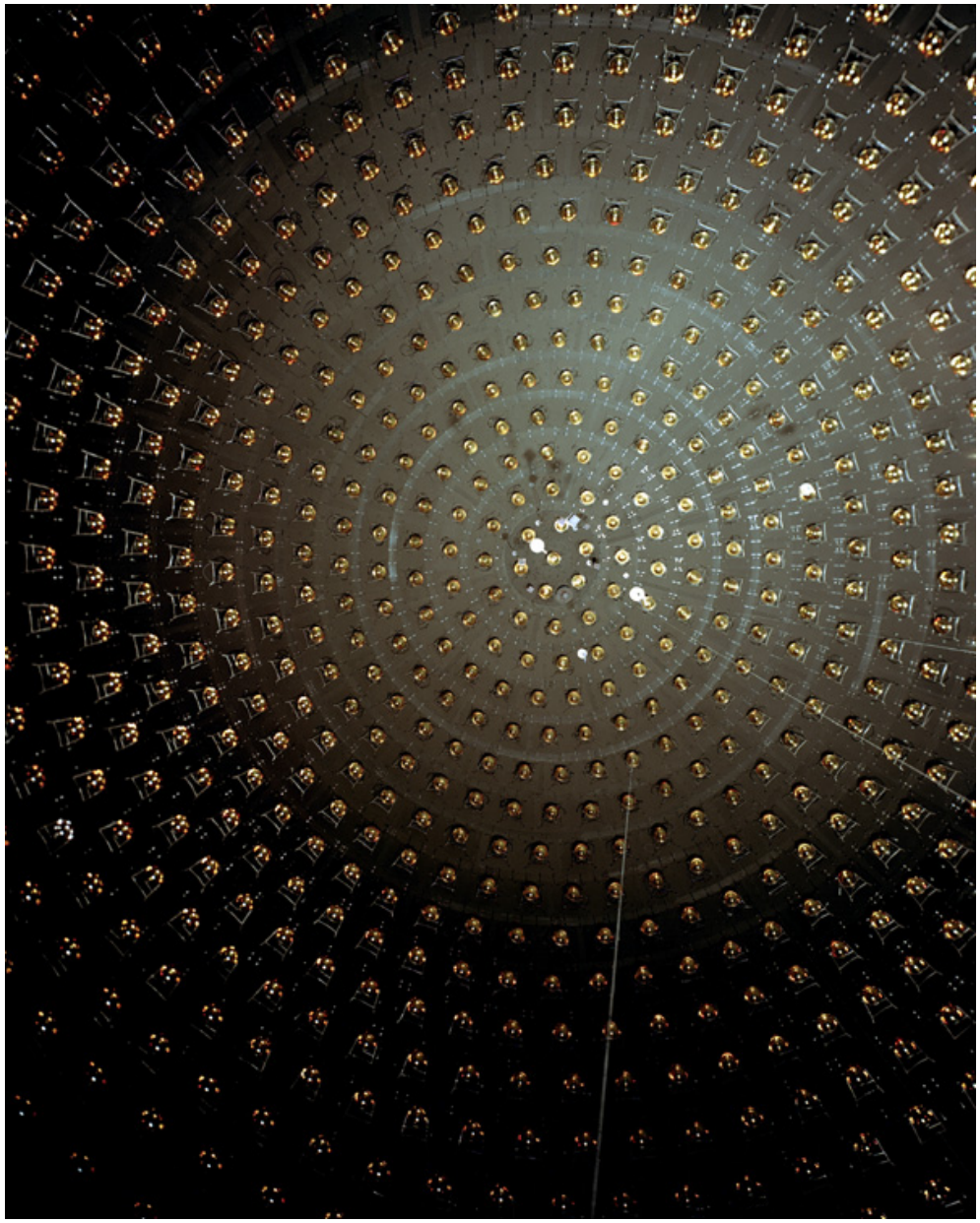
E. D. Church, K. Eitel, G. B. Mills, and M. Steidl, Phys. Rev. D66, 013001, (2002).



MiniBooNE Experiment



- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector



10% Photocathode coverage

Two types of
Hamamatsu Tubes:
R1408, R5912

Charge Resolution:
1.4 PE, 0.5 PE

Time Resolution
1.7 ns, 1.1ns

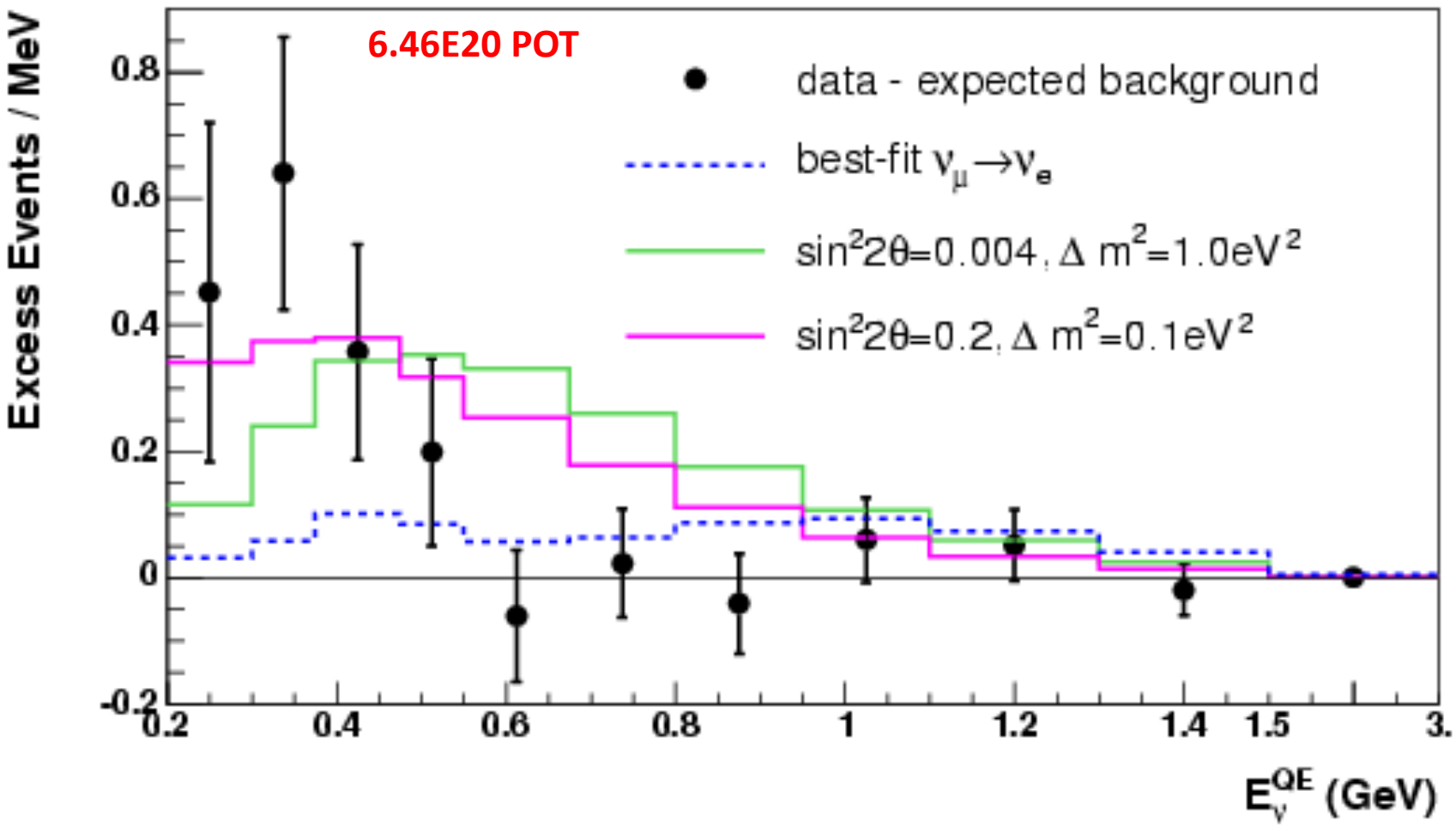
MiniBooNE Detector Tank

MiniBooNE Detector Tank

MiniBooNE Data Show a Low-Energy Excess

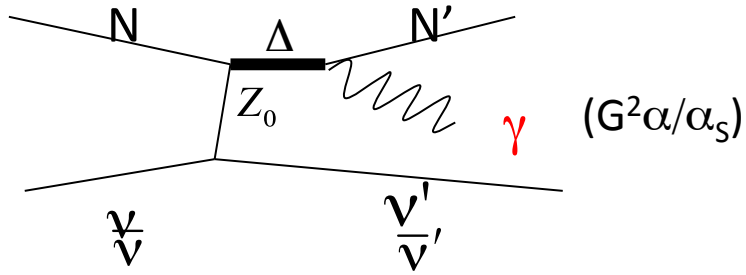
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

Excess from 200-1250 MeV = 146.5+-28.4+-40.1 events (3.0σ excess)

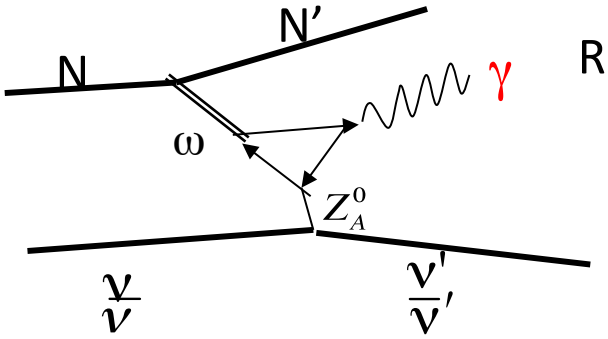


Backgrounds: Order ($G^2\alpha\alpha_s$) , single γ FS?

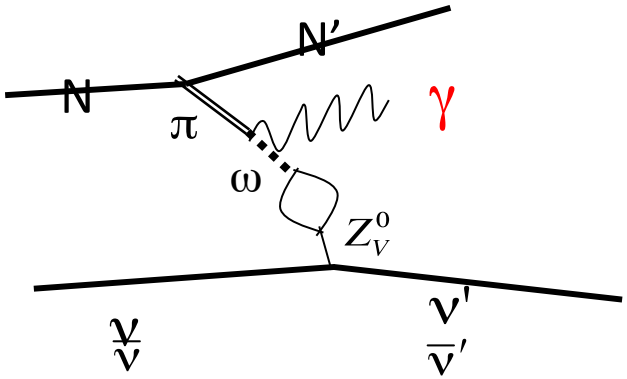
Dominant process accounted for in MC!



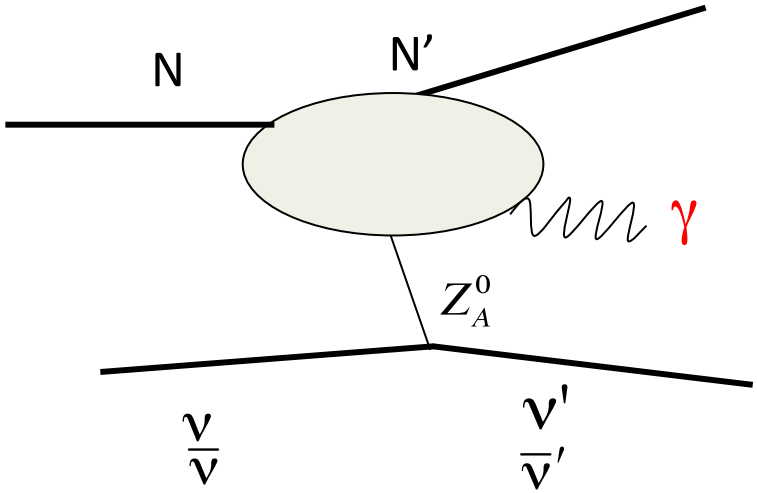
Radiative Delta Decay



Axial Anomaly



Other PCAC



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

R. Hill, arXiv:0905.0291

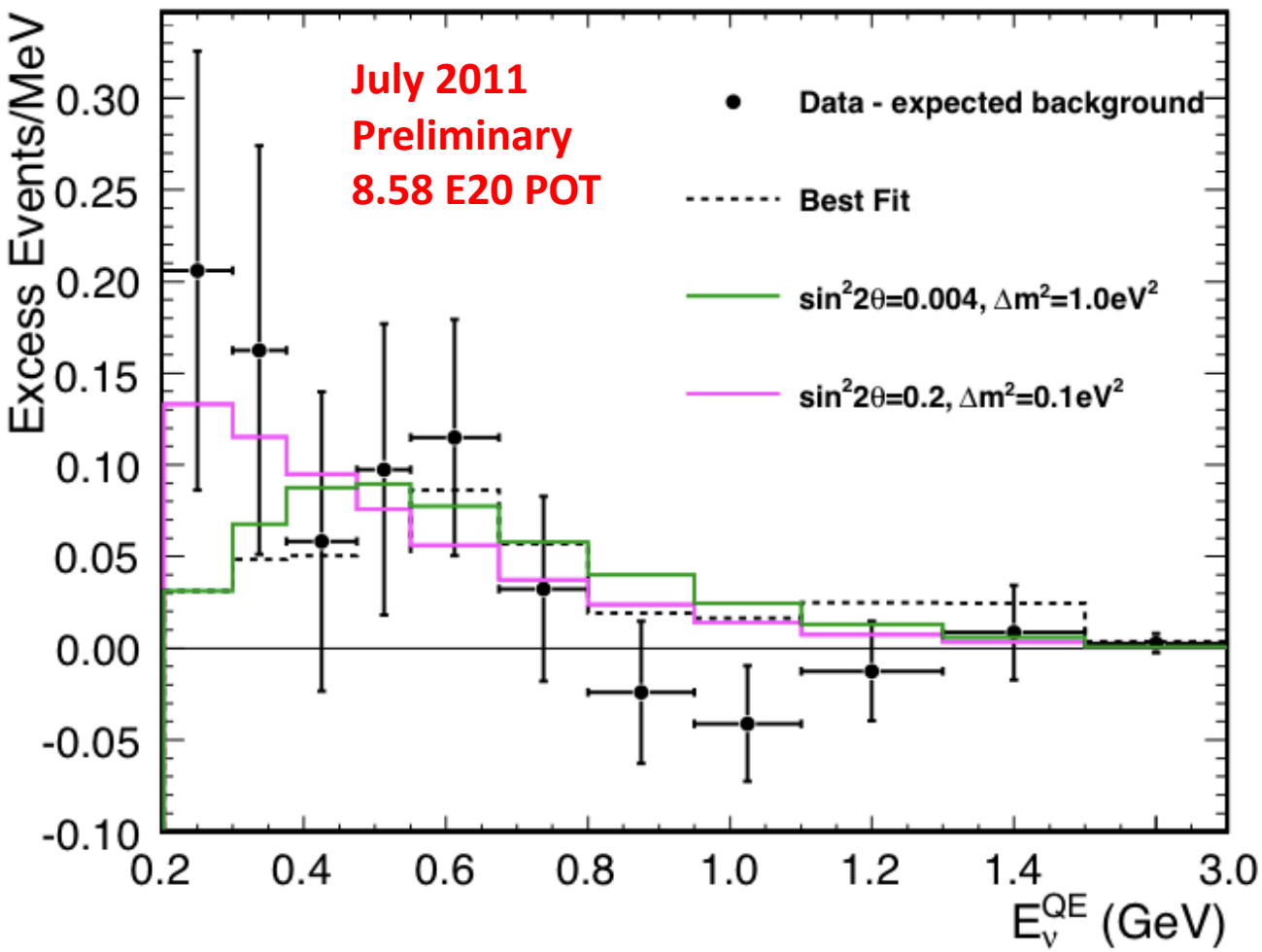
Jenkins & Goldman, arXiv:0906.0984

Serot & Zhang, arXiv:1011.5913

MiniBooNE Antineutrino Oscillation Results

update of A. A. Aguilar-Arevalo, Phys. Rev. Lett. 105, 181801 (2010)

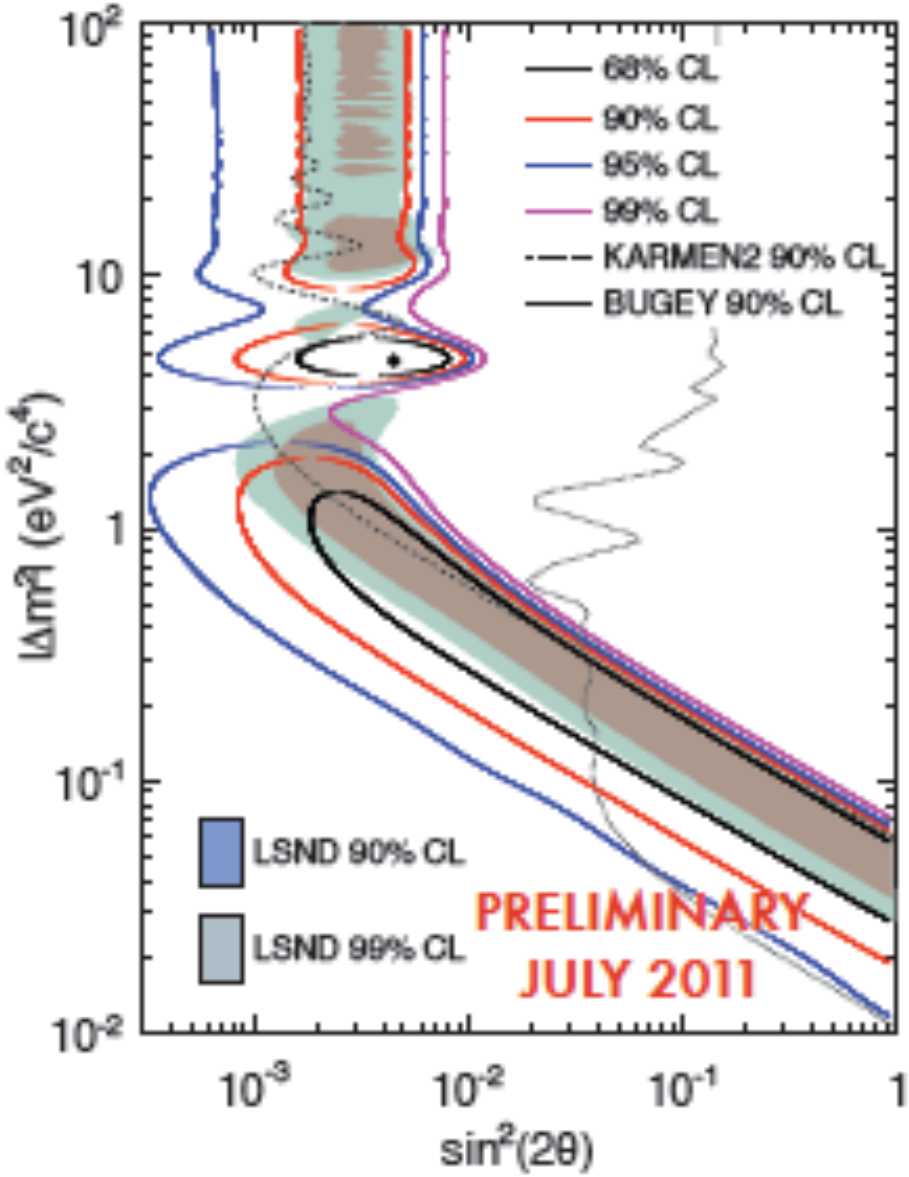
Excess = 54.9+-17.4+-16.3 (200-1250 MeV) **(2.3 σ excess so far; 32% more data & joint neutrino + antineutrino analysis soon)**



MiniBooNE Antineutrino Oscillation Fit

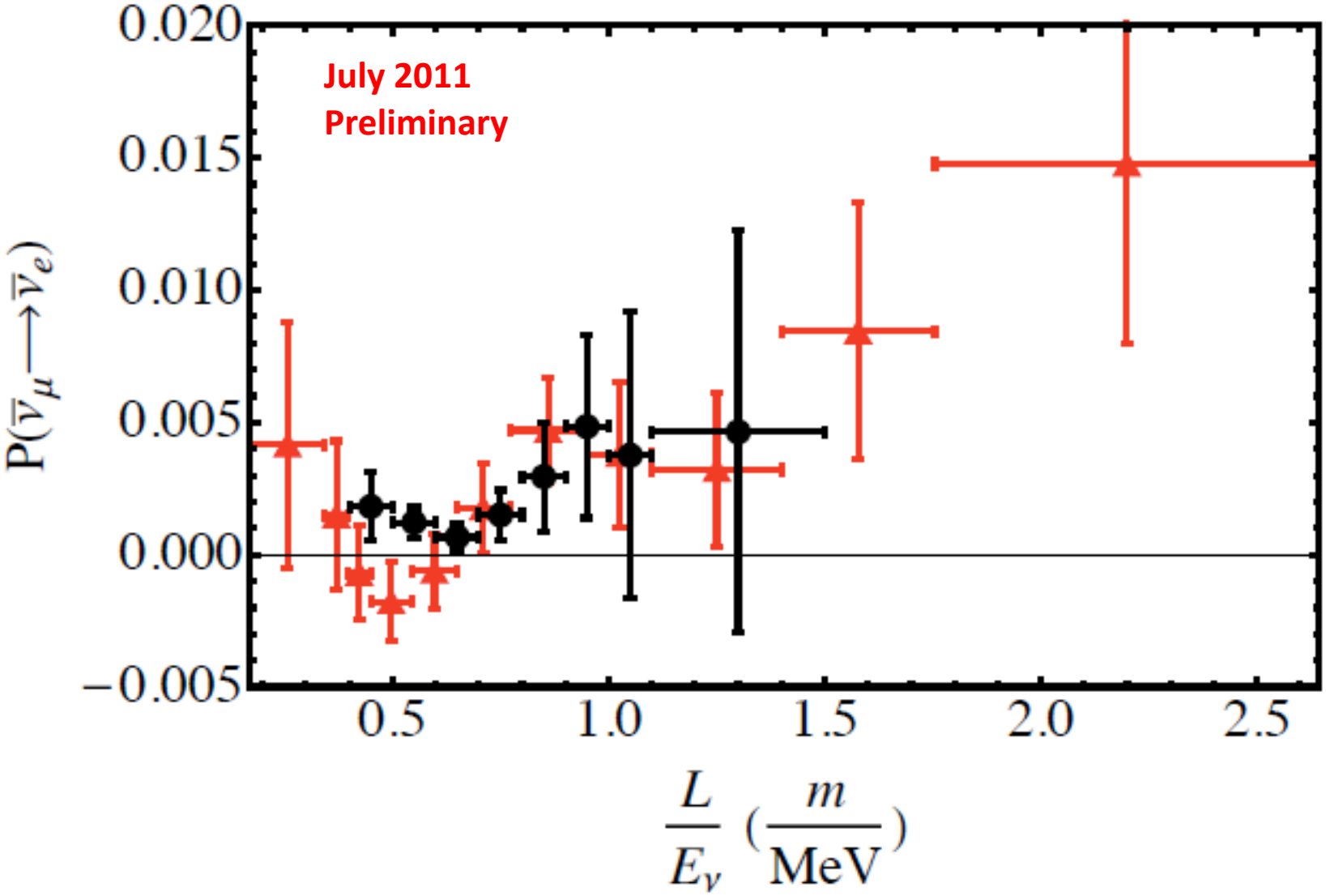
E>200 MeV

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations



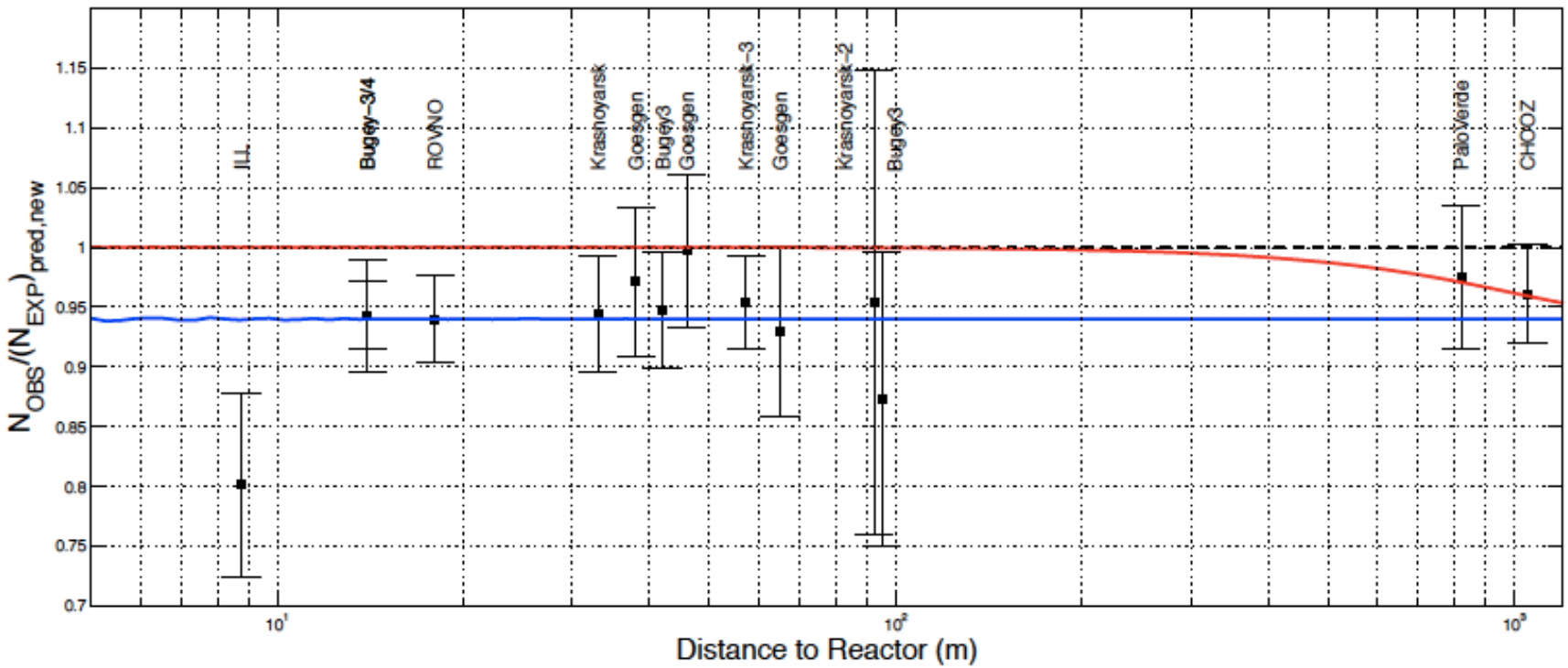
LSND vs MiniBooNE Antineutrino Results

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



Reactor Antineutrino Anomaly

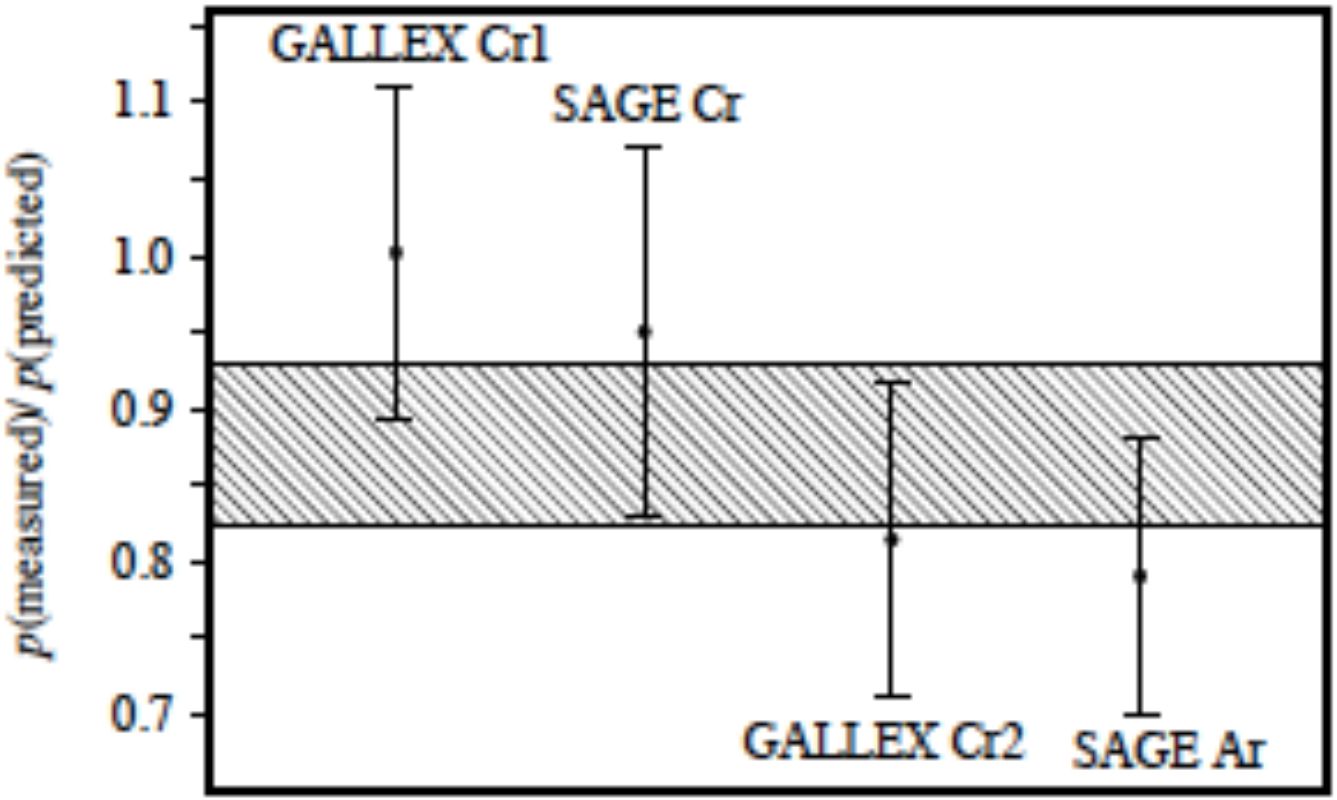
G. Mention et al., Phys.Rev.D83:073006,2011



R=0.927+-0.023

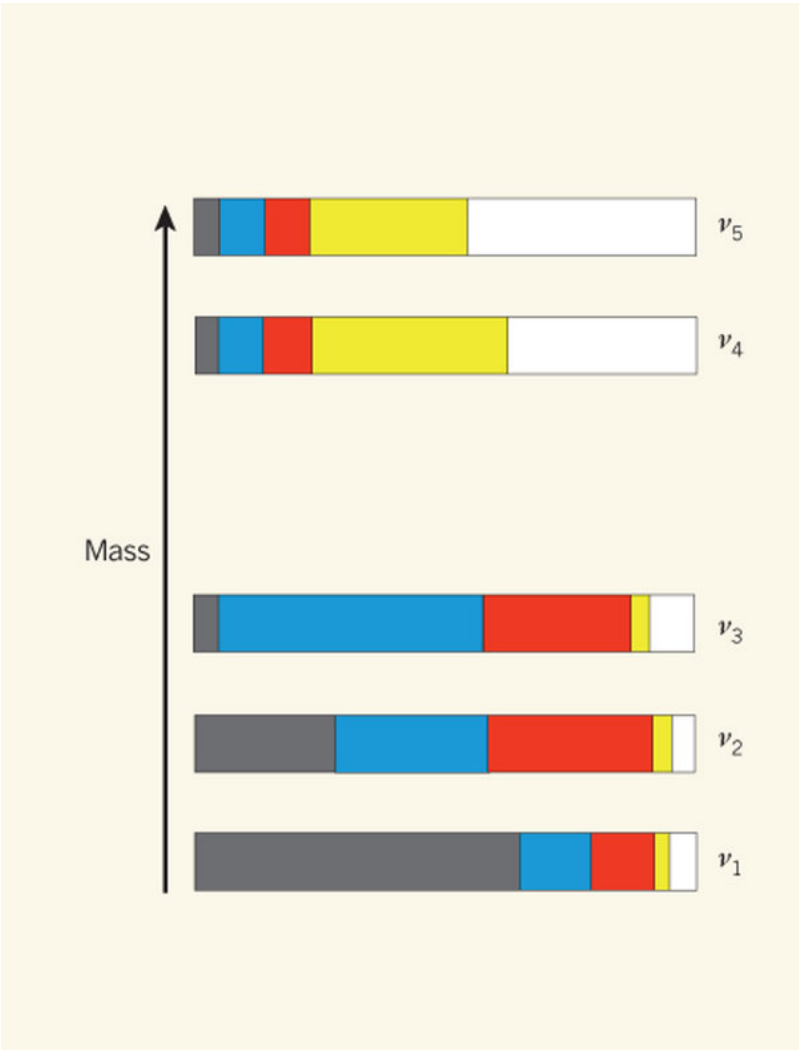
Radioactive Neutrino Source Anomaly

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



R = 0.86+-0.05 (Bahcall with no theoretical error)
R = 0.76+0.09-0.08 (Haxton)

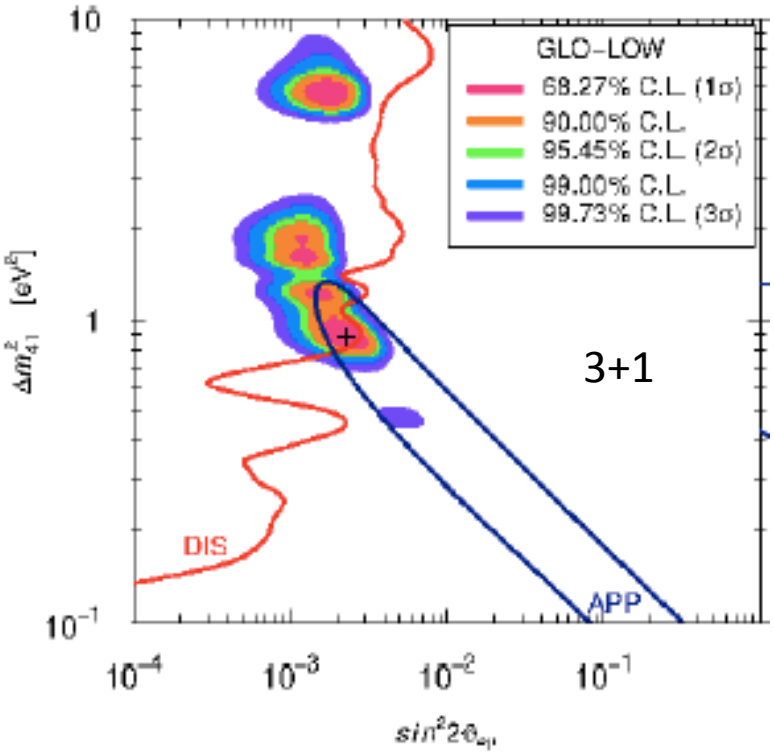
Sterile Neutrinos



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

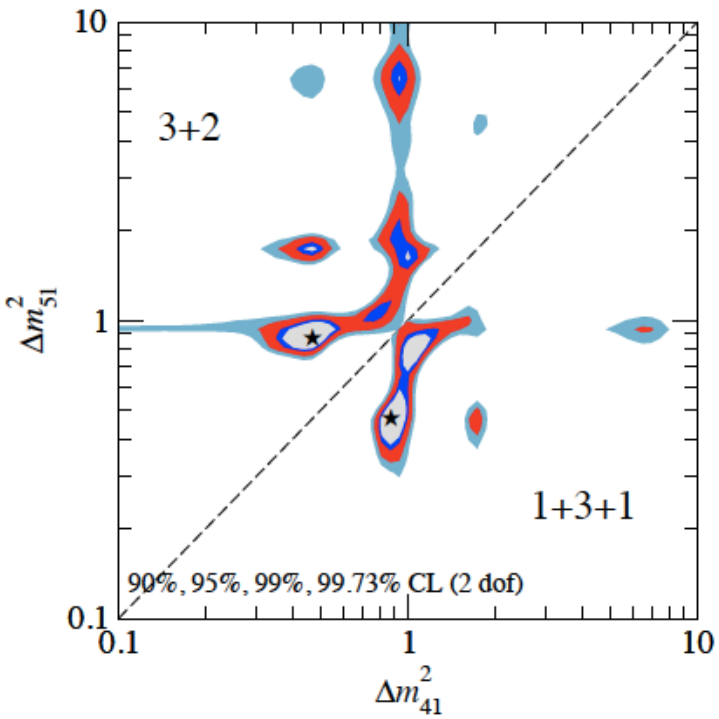
3+N Global Fits to World ν Data

all ν & $\bar{\nu}$



Giunti & Laveder, arXiv:1111.1069
(Some tension with ν_μ disappearance)
χ^2 = 152.4/144 DF (Prob = 30%)

all ν & $\bar{\nu}$



Kopp, Maltoni, & Schwetz,
Phys. Rev. Lett. 107, 091801 (2011)
χ^2 = 110.1/130 DF (Prob = 90%)

3+N Models Require Large ν_μ Disappearance!

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

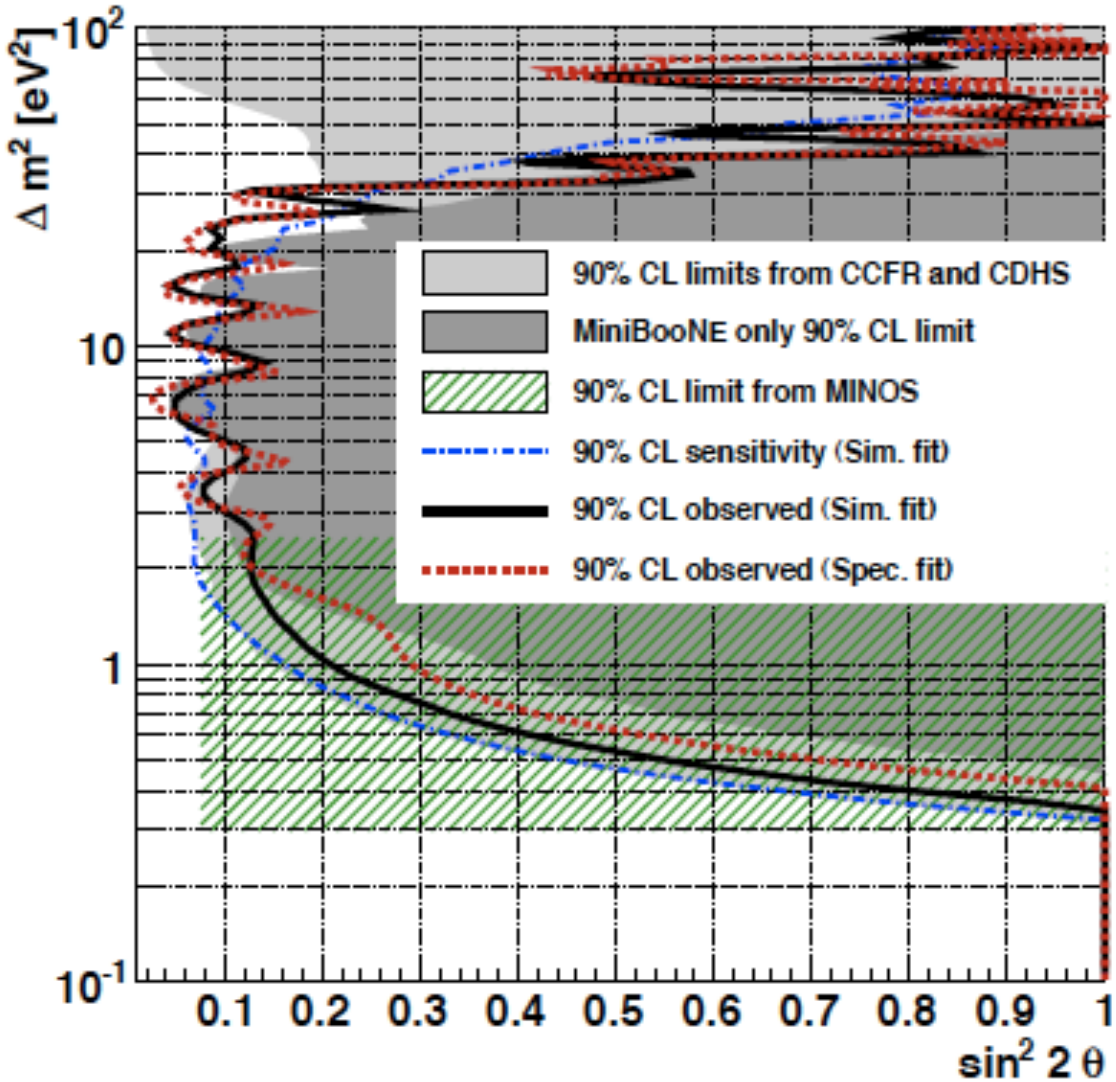
LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

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 (Antineutrino Next)

arXiv:1106.5685



Future ν Experiments

- There is a diverse set of experiments, spanning vastly different energy scales, that have been proposed to test the 3+N models & resolve the present anomalies:

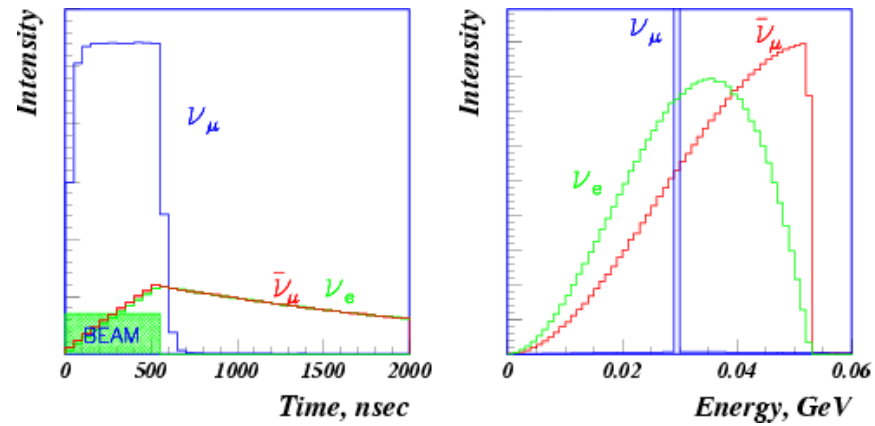
- Accelerator ν Experiments: MicroBooNE, MINOS+, NOvA with two near detectors, NOvA with cyclotron, BooNE (two oil detectors or two LAr detectors), μ storage ring at FNAL, Project X at FNAL, ICARUS at CERN, OscSNS at ORNL
- Reactor ν Experiments: SCRAAM, NEUTRINO4
- Radioactive Source ν Experiments: BOREXINO, Daya Bay, Baksan, LENS
- Atmospheric ν Experiments: IceCube

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

Answer: Search for disappearance oscillations of a NC reaction. (e.g. OscSNS!)

OscSNS at ORNL

- SNS spallation neutron source
- 1GeV protons @ 1.4MW
- Prolific source of neutrinos
- MiniBooNE-like detector at 30-60m from neutrino source



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

OscSNS Advantages Over Other Neutrino Oscillation Experiments

- Well understood ν flux
- Well understood ν cross sections
- Low duty factor
- Absence of nuclear effects
- Very low backgrounds (< 0.1%)
- Can actually observe ν oscillations in the detector
- Beam comes for free from the SNS
- SNS runs ~ 2/3 of the year

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 (x100) (less cosmic background)
- No DIF Background (backward direction)
- Lower Neutrino Background (x4) (60m vs 30m)
- Better Signal/Background (x4)
- For LSND parameters, expect ~350 ν_e oscillation events & <80 background events per year!

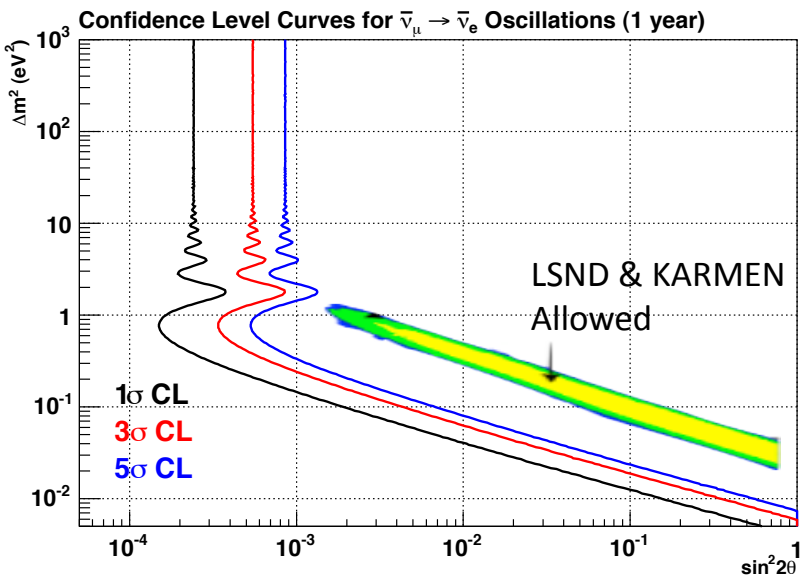
Goals of the OscSNS Experiment

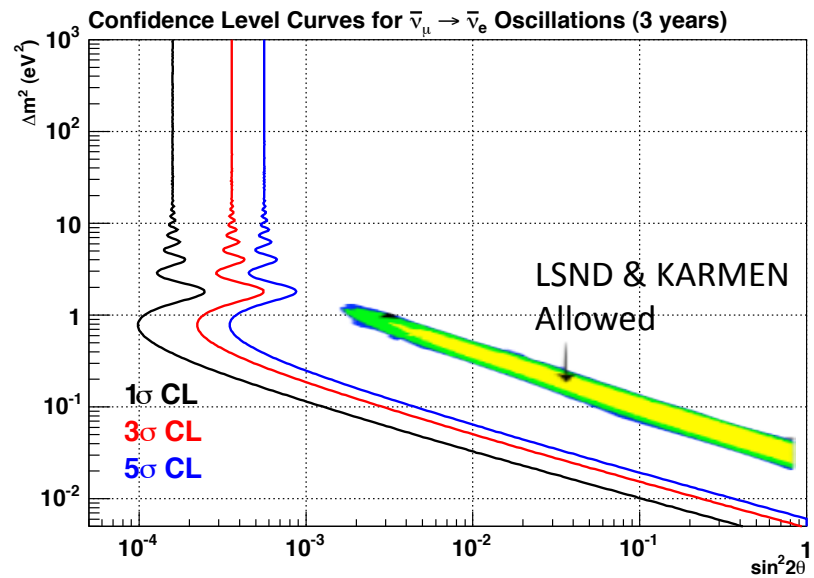
- Prove the existence of sterile neutrinos by comparing NC reactions in near and far detector
- Short baseline ν_e and $\overline{\nu}_e$ appearance
- Short baseline CP violation
- Short baseline ν_e, ν_μ and $\overline{\nu}_\mu$ disappearance
- The resolution of the current short-baseline anomalies

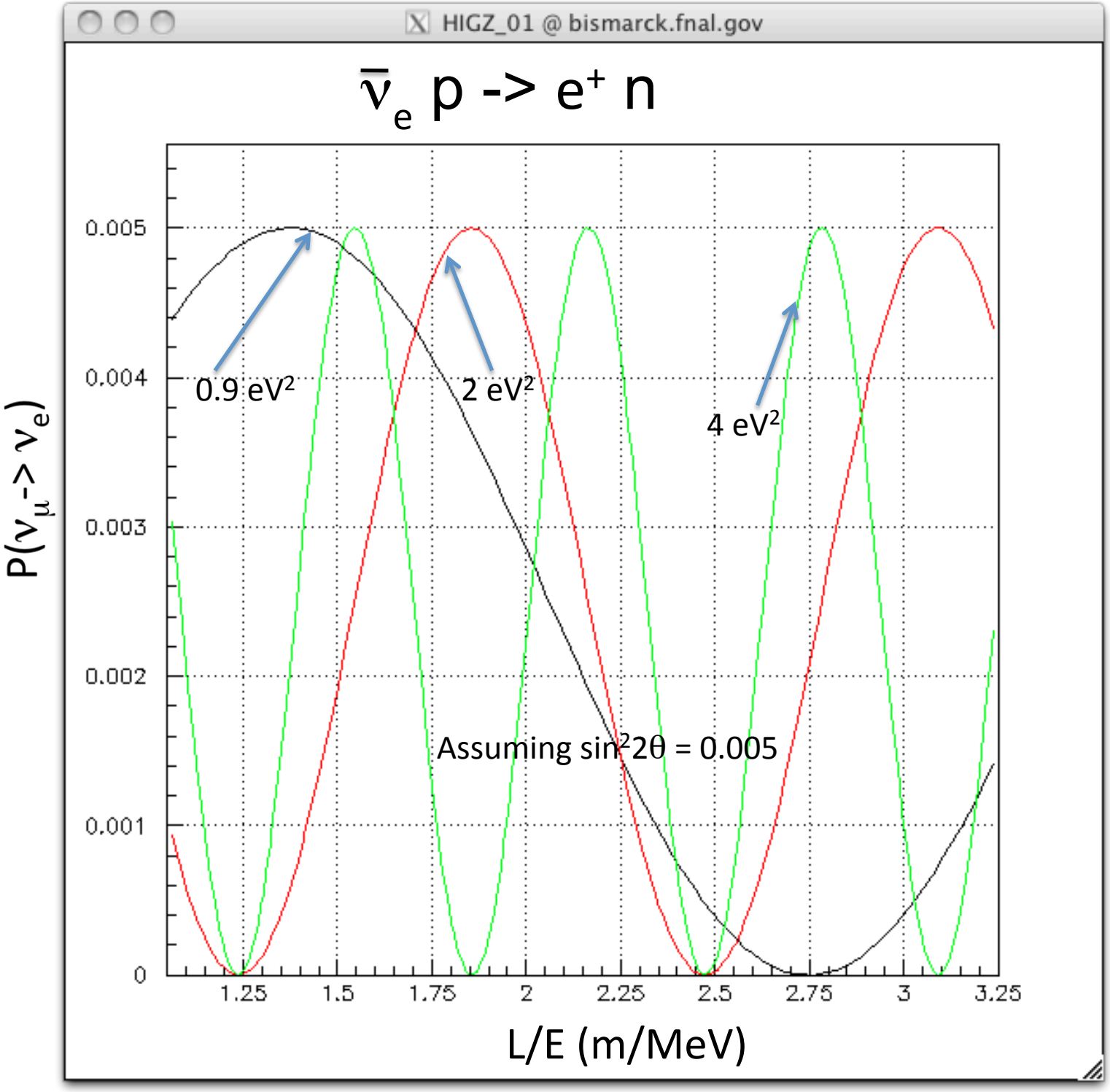
OscSNS at ORNL

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

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



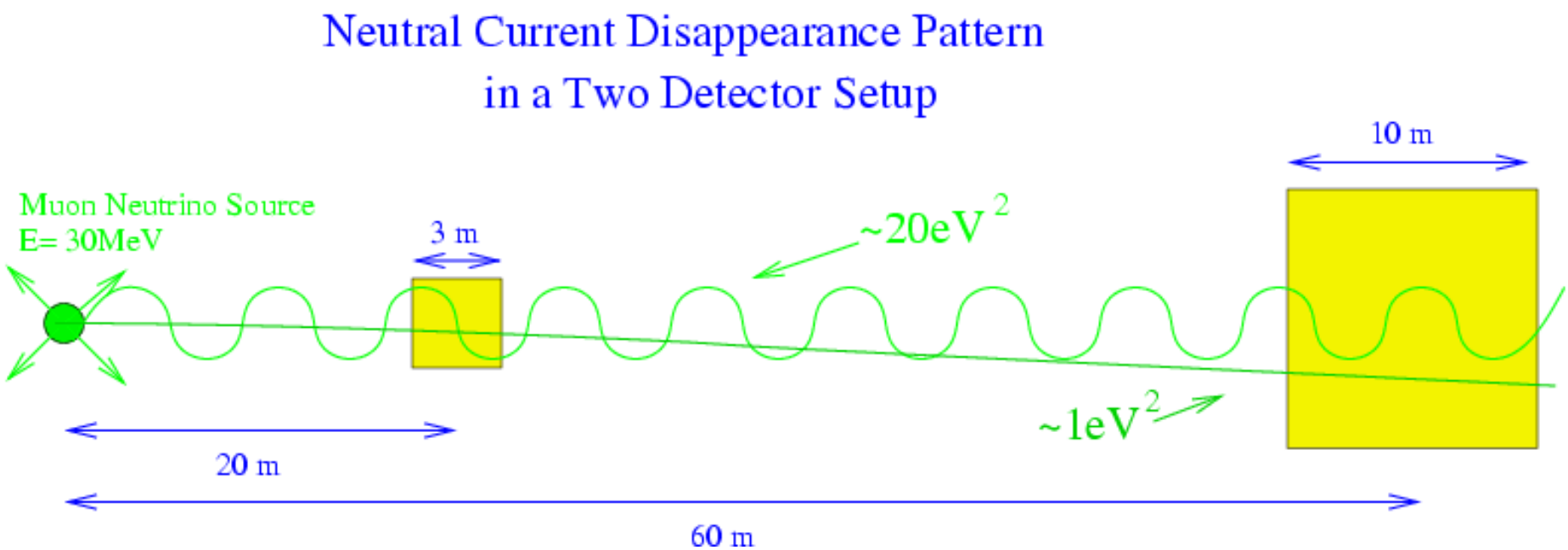



HIGZ_01 @ bismarck.fnal.gov
$\bar{\nu}_e$ p -> e^+ n
0.005
0.004
0.003
0.002
0.001
0
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25
0.9 eV²
2 eV²
4 eV²
Assuming sin²2θ = 0.005
P(ν_μ -> ν_e)
L/E (m/MeV)

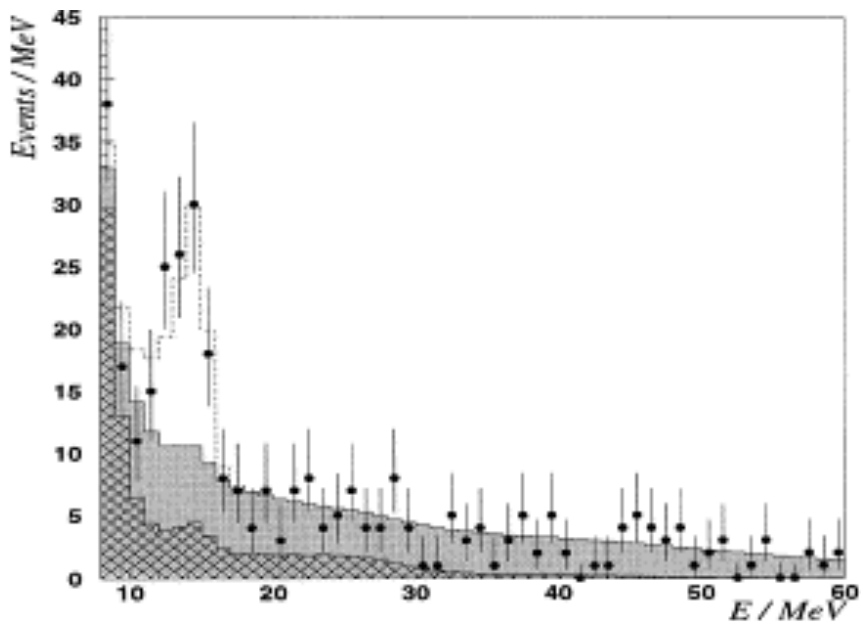
Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:

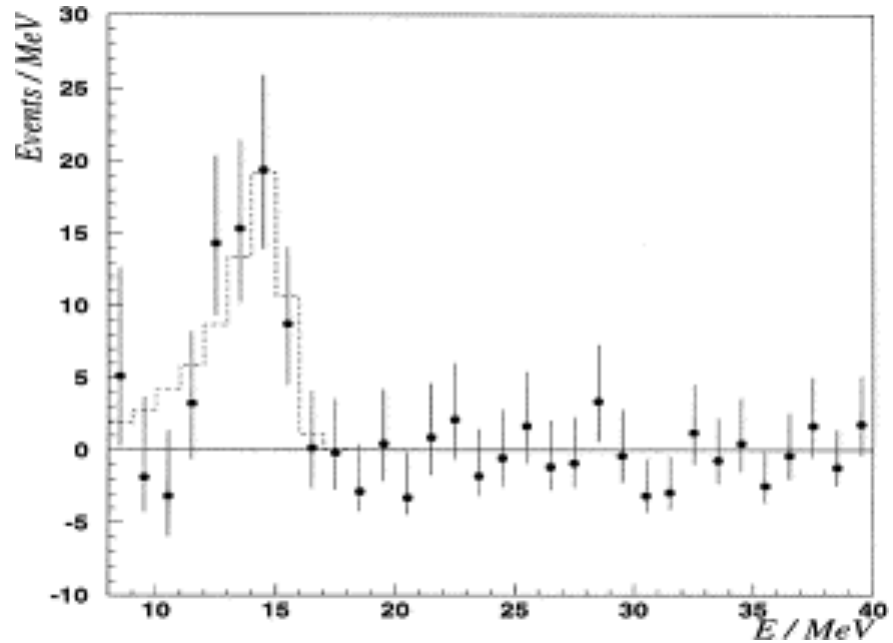
ν_μ C -> ν_μ C*(15.11)

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



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



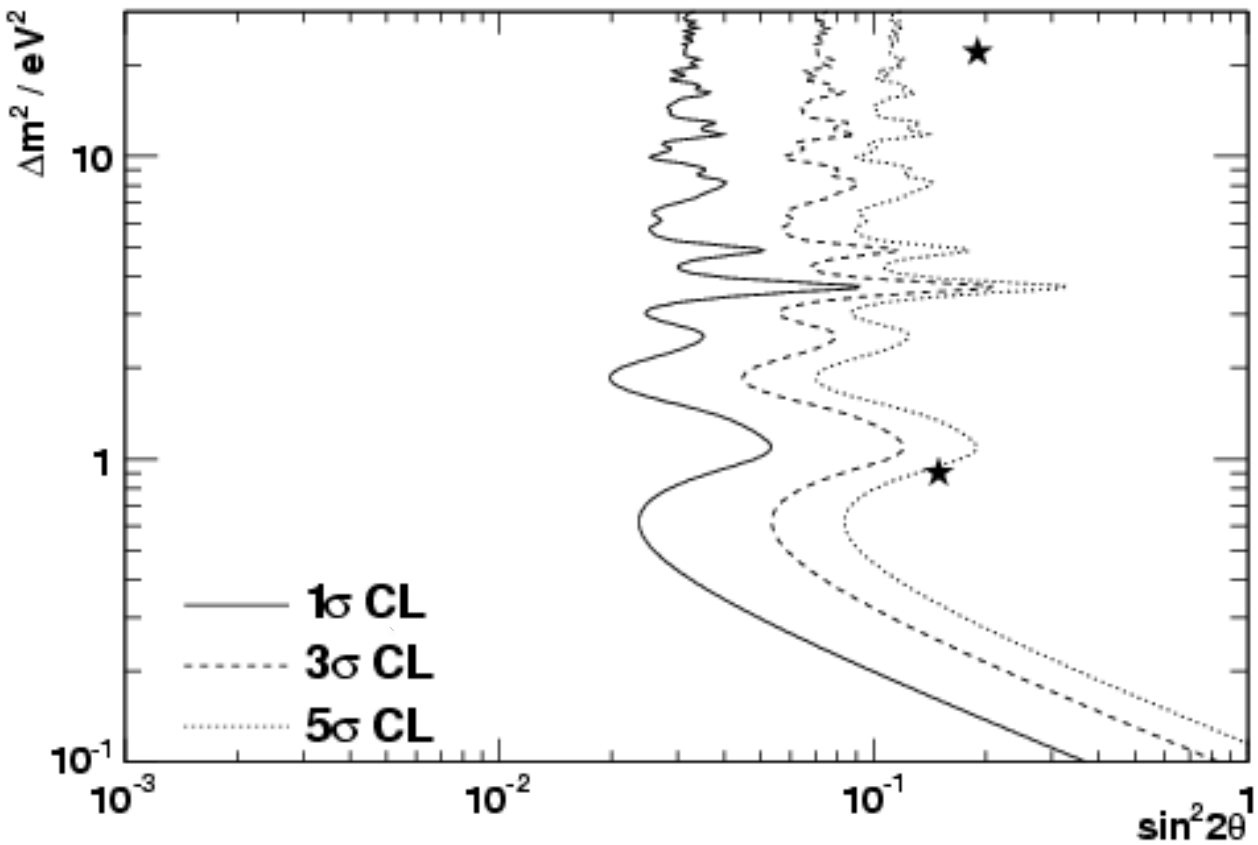


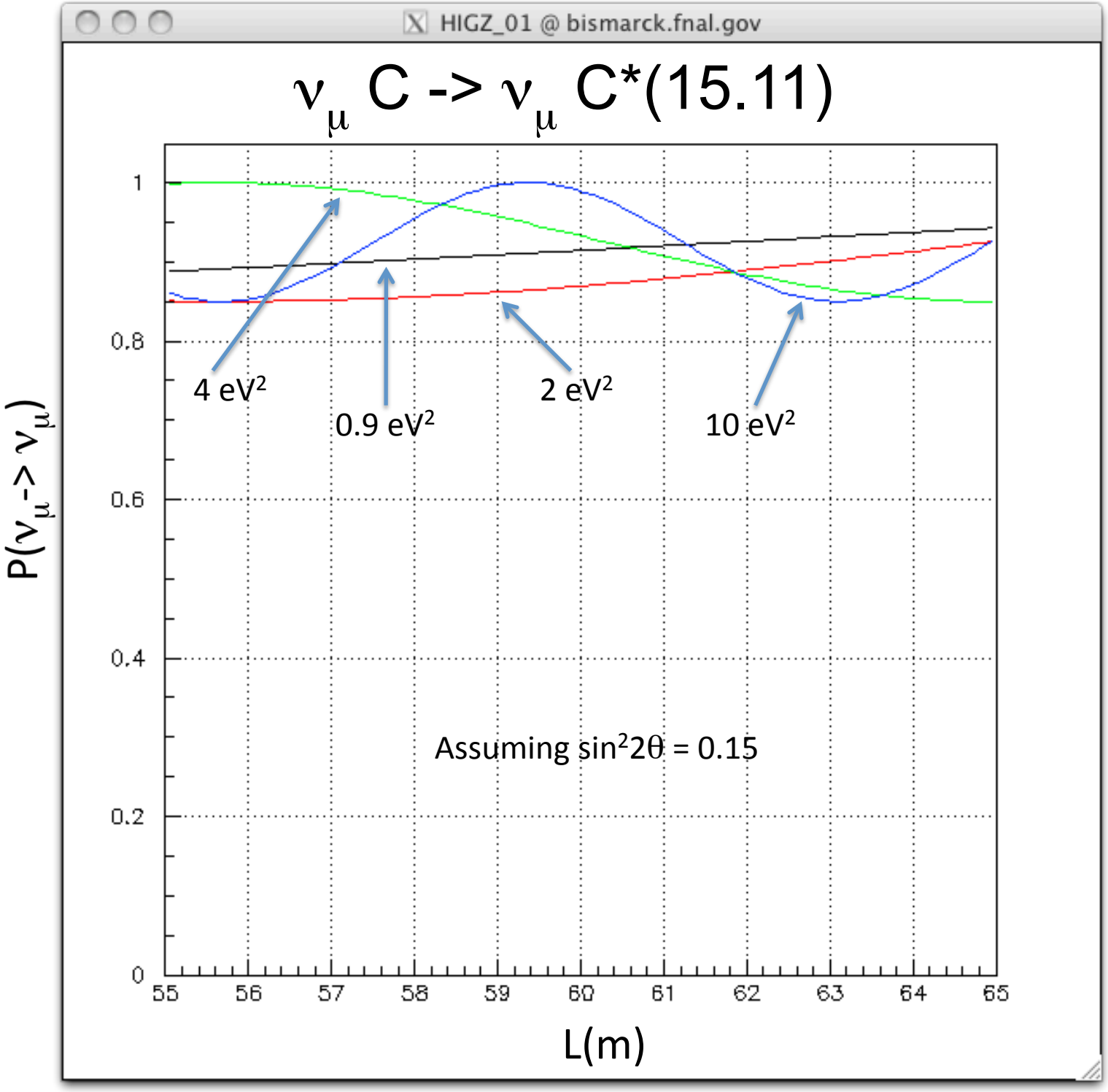
σ_{NC} = (3.2+-0.5+-0.4)x10^{-42} cm^2 (B. Armbruster et al., Phys. Lett. B423 (1998) 15)

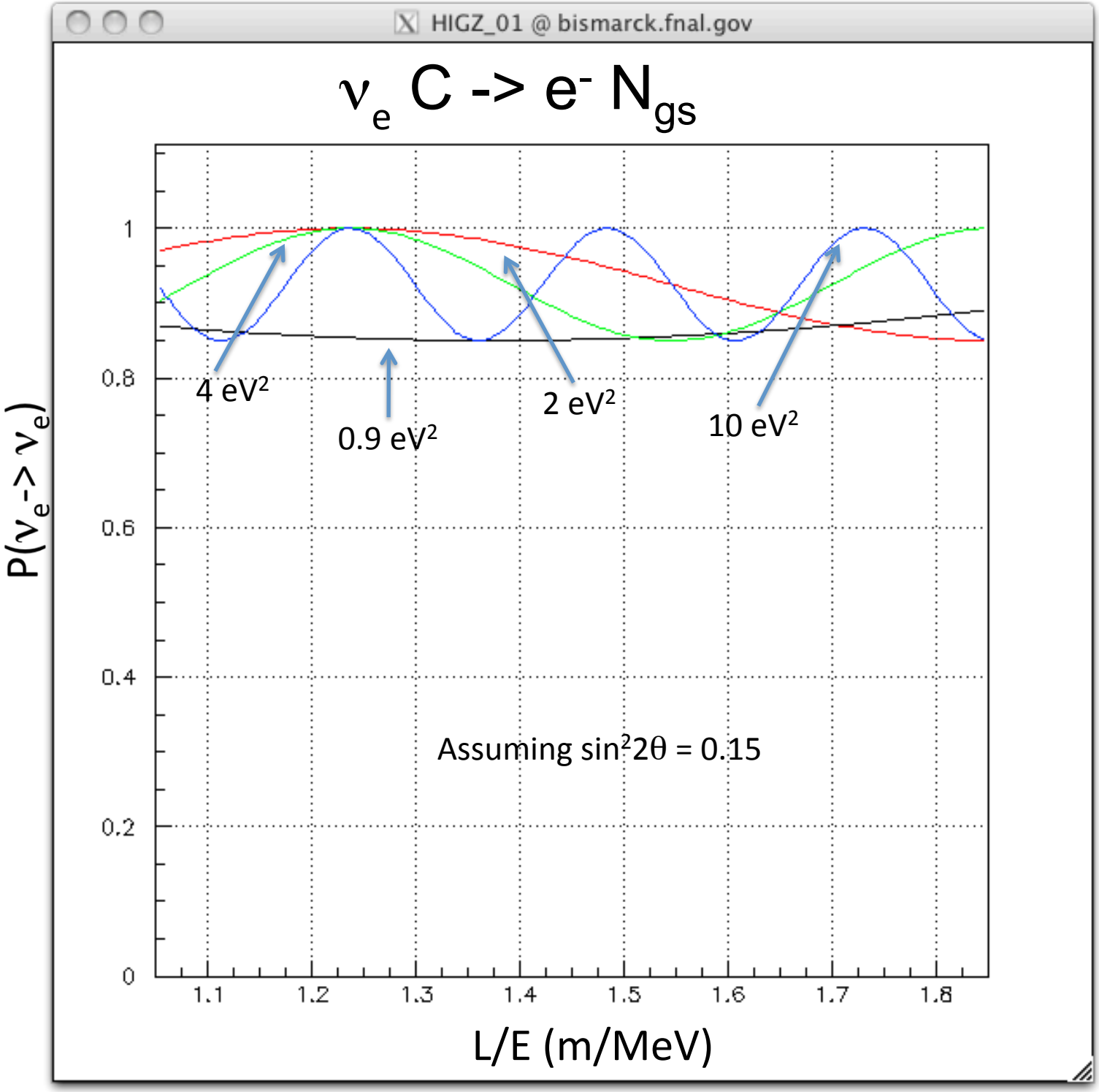
σ_{NC} ~2.8x10^{-42} cm^2 (Kolbe, Langanke, & Vogel, Nucl. Phys. A652 (1999) 91)

Measurement of Oscillation Parameters with Two Detectors

ν_μ disappearance




HIGZ_01 @ bismarck.fnal.gov
ν_μ C -> ν_μ C*(15.11)
$P(\nu_\mu \to \nu_\mu)$
L(m)
4 eV^2
0.9 eV^2
2 eV^2
10 eV^2
Assuming $\sin^2 2\theta = 0.15$
0
0.2
0.4
0.6
0.8
1
55
56
57
58
59
60
61
62
63
64
65


HIGZ_01 @ bismarck.fnal.gov
ν_e C -> e^- N_{gs}
$P(\nu_e \to \nu_e)$
L/E (m/MeV)
4 eV²
0.9 eV²
2 eV²
10 eV²
Assuming $\sin^2 2\theta = 0.15$
0
0.2
0.4
0.6
0.8
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

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
100% $\bar{\nu}_\mu$ -> $\bar{\nu}_e$, $\bar{\nu}_e$ p -> e^+ n	99,275
0.4% $\bar{\nu}_\mu$ -> $\bar{\nu}_e$, $\bar{\nu}_e$ p -> e^+ n	397

Conclusion

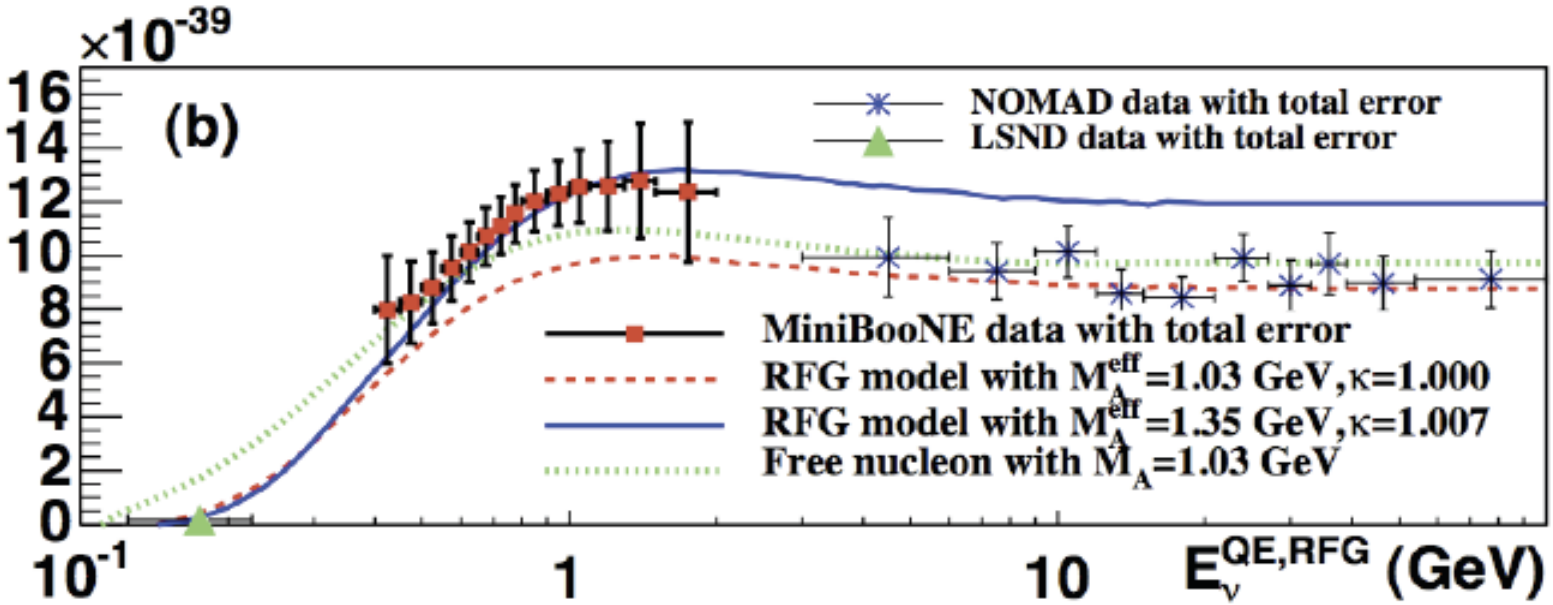
- There are anomalies in short baseline ν experiments that cannot be explained by the 3 ν paradigm and that suggest the existence of sterile ν.
- Sterile ν would contribute to the dark matter of the universe and would have a big impact on astrophysics and cosmology.
- The world neutrino & antineutrino data can be fit fairly well to a 3+N oscillation model with large ν_μ disappearance (>7%).
- Future ν experiments (e.g. OscSNS) can prove the existence of sterile neutrinos.

Sterile Neutrino White Paper: arXiv:1204.5379

Backup

ν_μ CCQE Scattering

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



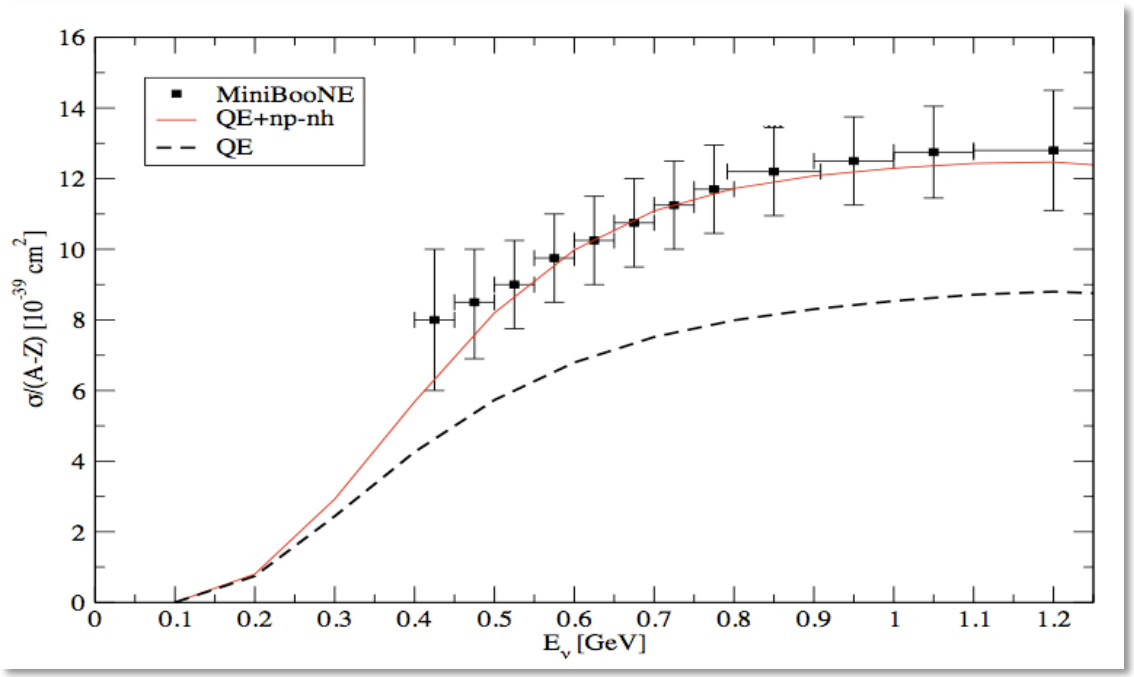
Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}C)>6\ \sigma_{\nu\mu}(n)$

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

A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys.Rev.**C65,** 024002 (2002); Martini et al., PRC80, 065001 (2009).

Nuclear Effects to the Rescue?

- *possible explanation*: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)



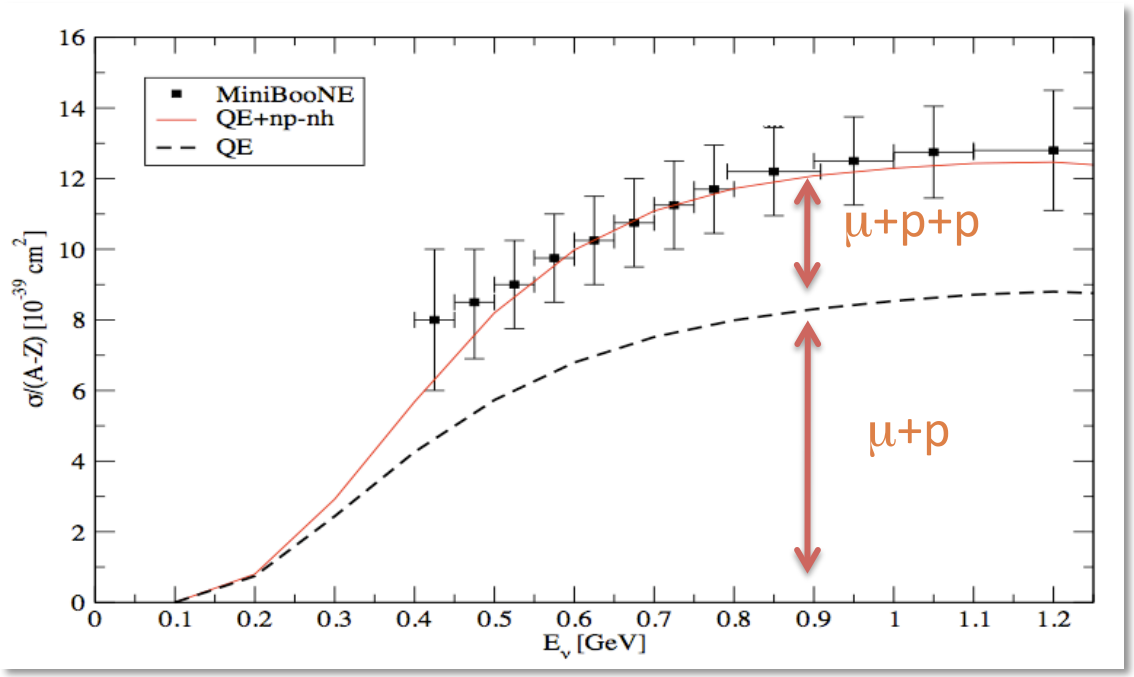
Martini *et al.*, PRC **80**, 065001 (2009)

- large enhancement from short range correlations (SRC) and 2-body currents
- can predict MiniBooNE data without having to increase M_A (here, M_A=1.0 GeV)

From Sam Zeller

Nuclear Effects to the Rescue?

- *possible explanation*: extra contributions from multi-nucleon correlations in the nucleus (all prior calcs assume indep particles)



Martini *et al.*, PRC **80**, 065001 (2009)

- could this explain the difference between MiniBooNE & NOMAD?

NOMAD: μ & μ + p

MiniBooNE: μ + no π's
+ any # p's

jury is still out on this

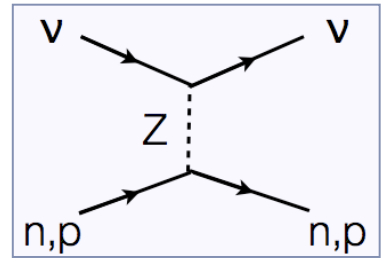
need to be clear
what we mean by "QE"

From Sam Zeller

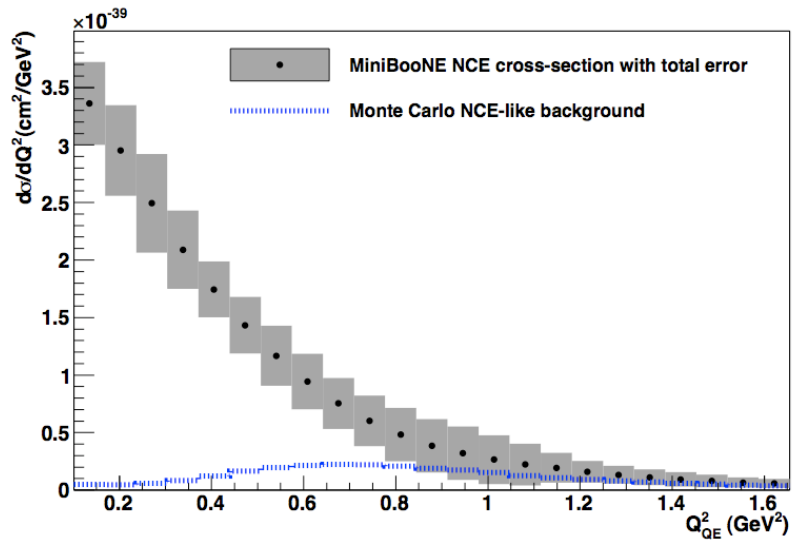
Neutrino Neutral Current Elastic

Phys.Rev.D82:092005,2010

- Neutral current elastic process probes similar formalism as charged-current quasi-elastic
  - sensitive to structure of both nucleon type.



- Protons fitter developed that reconstructs protons above Cherenkov threshold (T_p > 350 MeV)
- 94,531 events (~65% purity)
- Measured quantities:
  - $d\sigma/dQ^2$
  - Δs = 0.08+-0.26
  - M_A = 1.39+-0.11



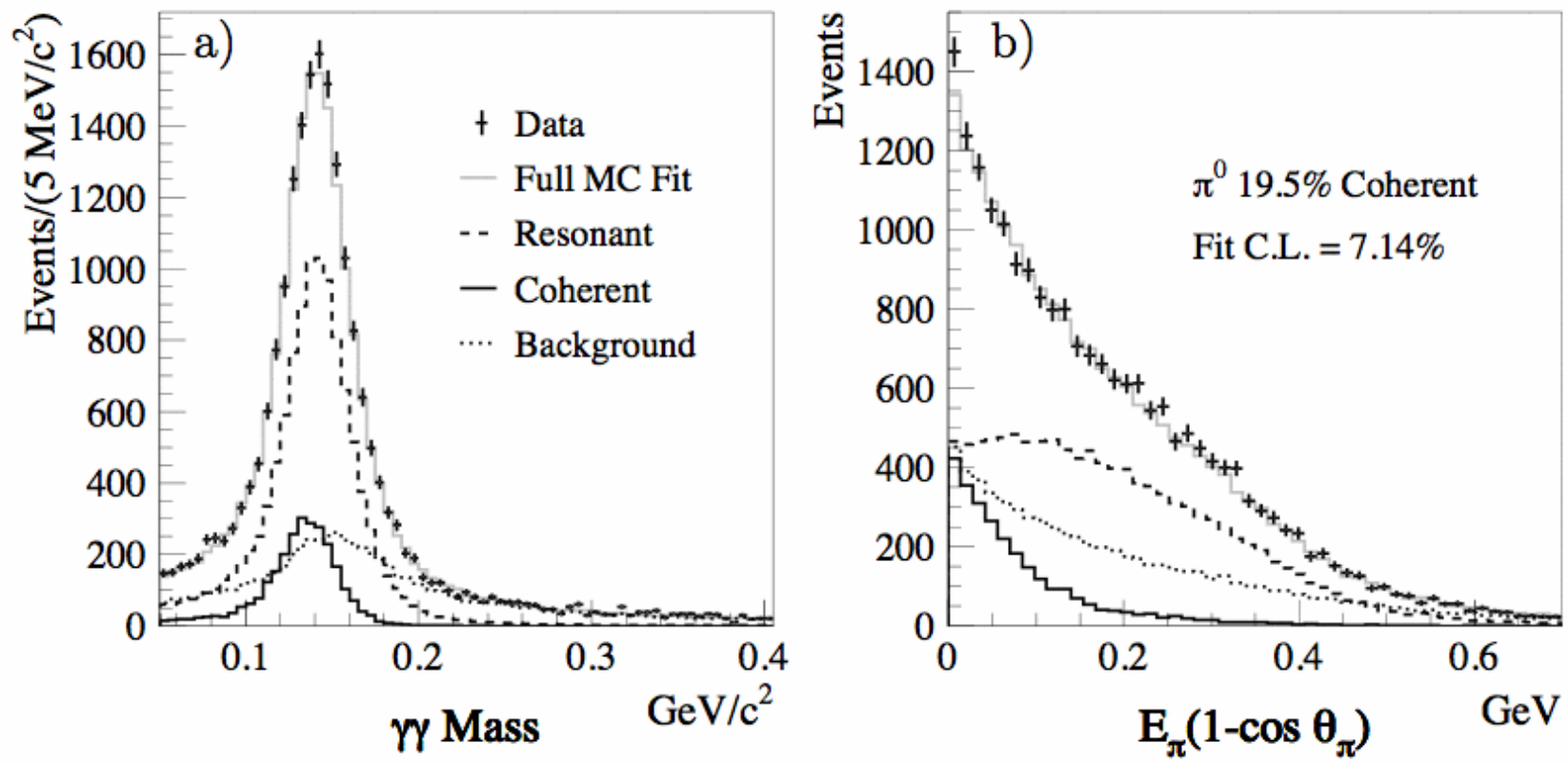
Ph.D. thesis, D. Perevalov, University of Alabama
Phys. Rev. D. **82**, 092005 (2010)

From D. Perevalov

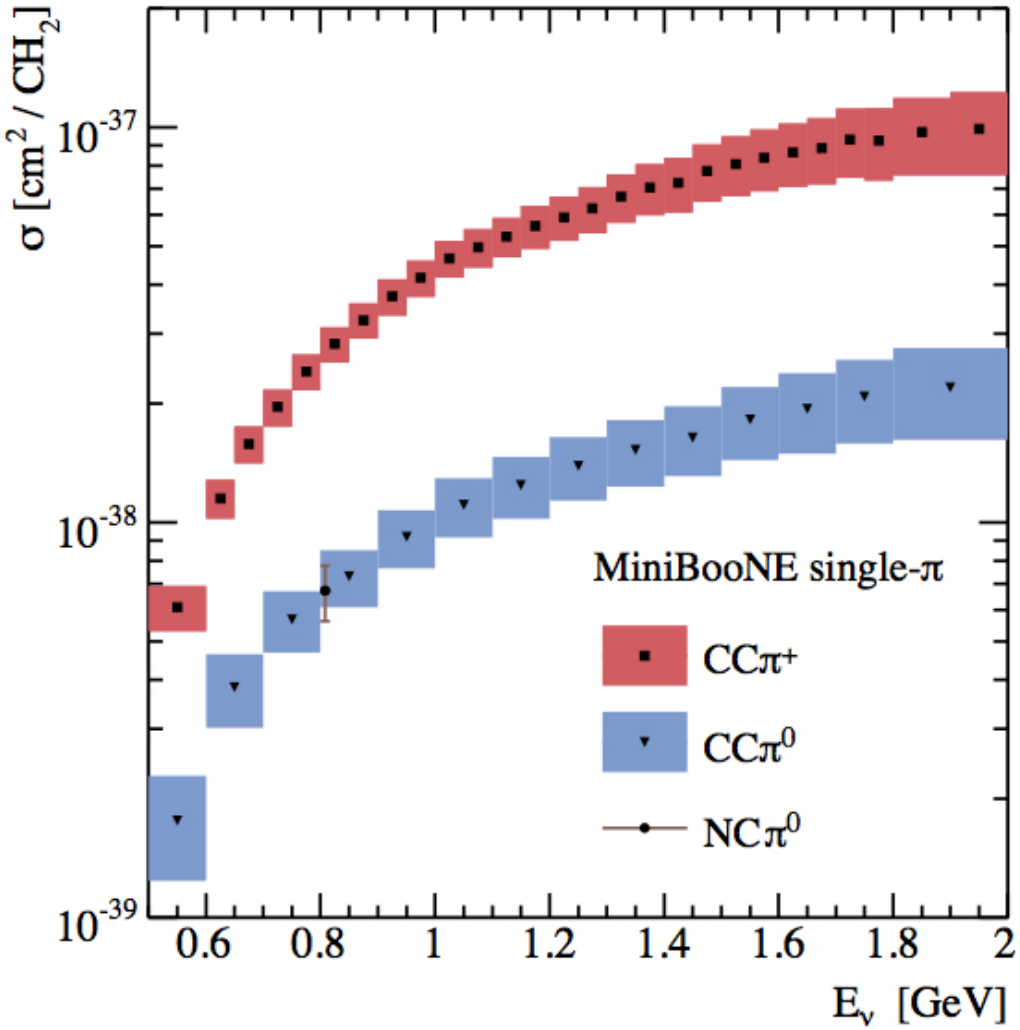
NCπ^0 Scattering

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

coherent fraction=19.5+-1.1+-2.5%

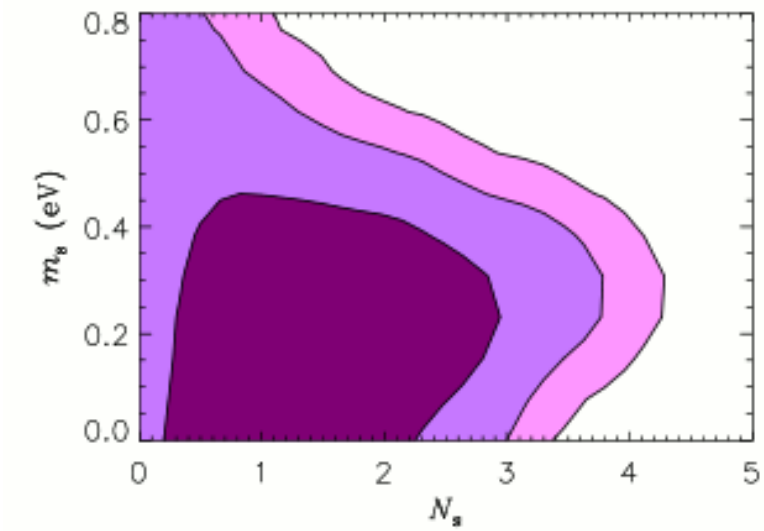


Single Pion Cross Sections

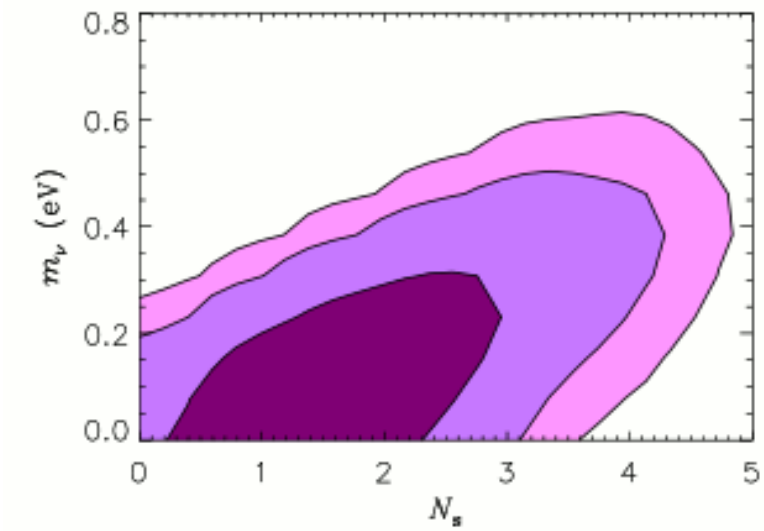


(R. Nelson, NuInt11)

Cosmology Data Consistent with Extra Sterile Neutrinos (J. Hamann, et. al., arXiv:1006.5276)



$3 + N_s$
$m_\nu = 0$



$3 + N_s$
$m_s = 0$

CERN-PH-TH/2012-046

Neutrino energy reconstruction problems and neutrino oscillations

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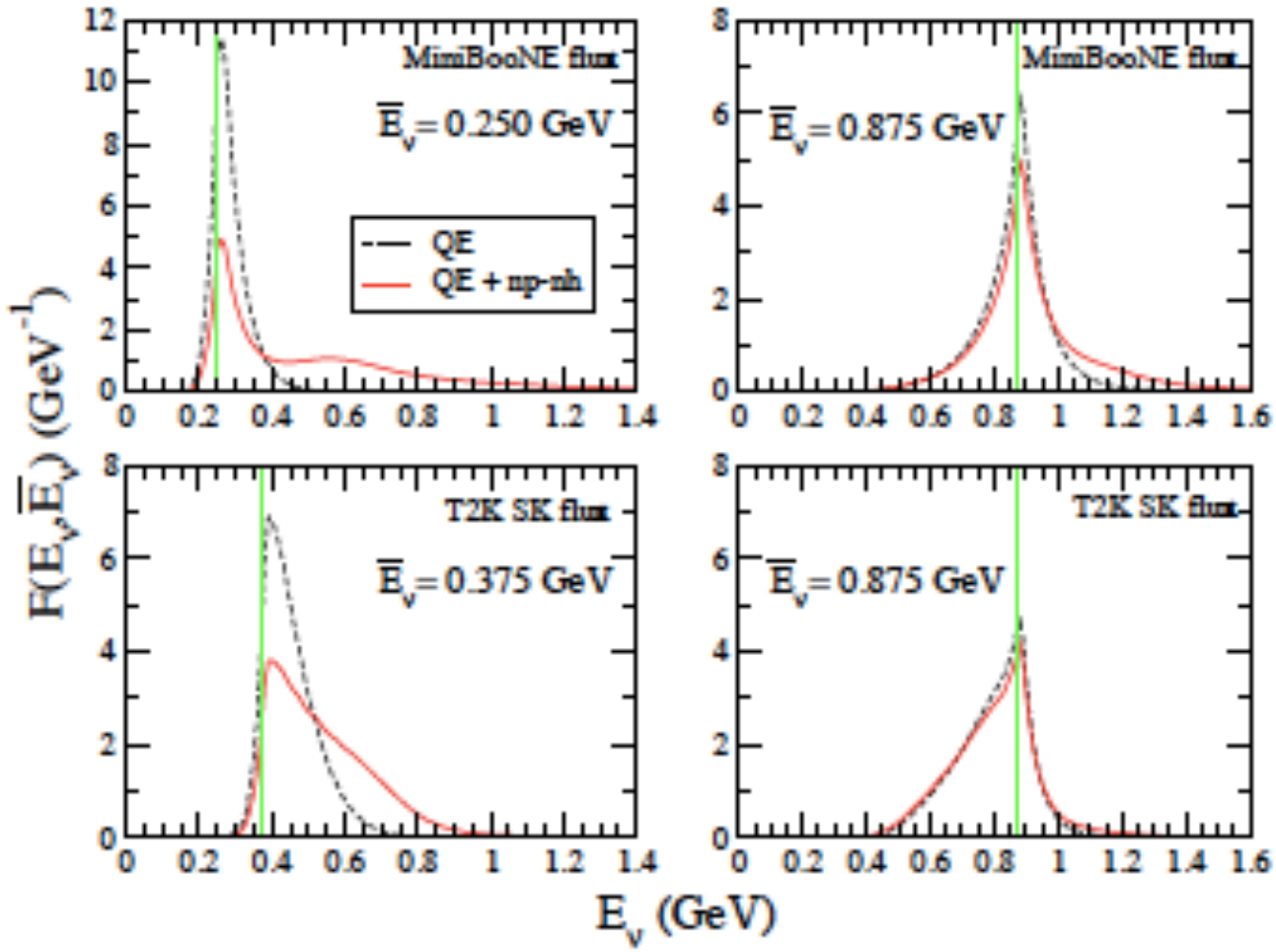


FIG. 10: (Color online) Normalized probability distribution for some $\overline{E_\nu}$ values corresponding to the different vertical lines. The MiniBooNE flux and the T2K far detector Super Kamiokande ν_e flux are used.

	MiniBooNE		T2K ND	
$\overline{E_\nu}$ (MeV)	QE + np-nh	QE	QE + np-nh	QE
300	546	335	514	350
400	579	435	529	446
500	638	527	575	528
600	711	619	638	606
800	861	799	781	758
1000	1024	981	937	914
1200	1190	1164	1116	1104

TABLE I: The average neutrino energy, Eq. (7), in MeV for various values of $\overline{E_\nu}$ considering the MiniBooNE and T2K near detector neutrino fluxes. The results are obtained with (QE+np-nh columns) and without (QE columns) the multinucleon contribution in the cross sections.

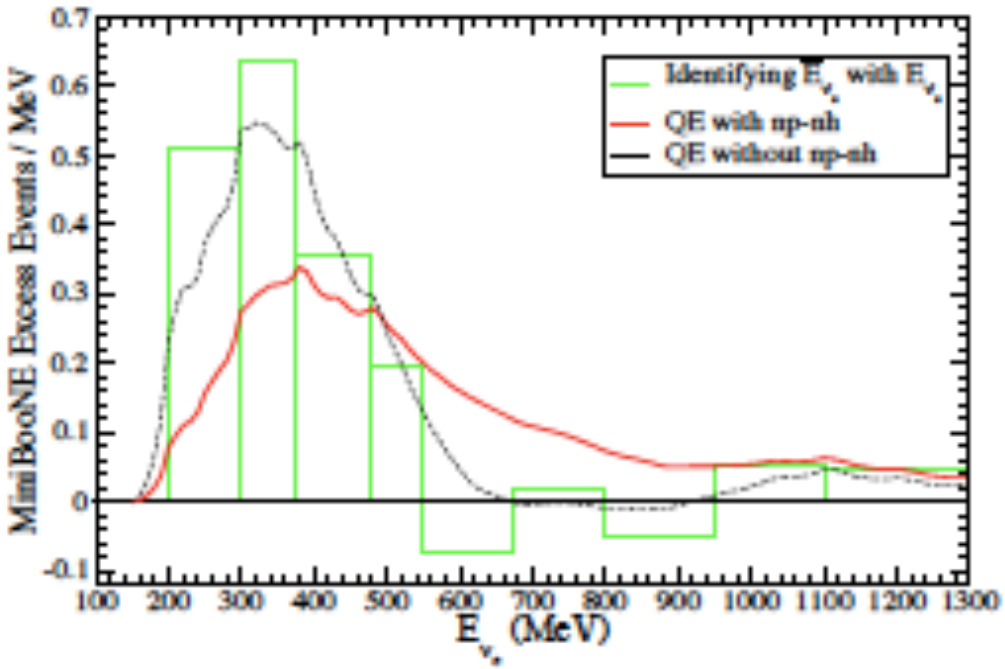


FIG. 11: (Color online) Three different treatments of experimental MiniBooNE data [11] on electron neutrino excess events. The histogram is obtained identifying the reconstructed neutrino energy $\overline{E_\nu}$ with the true neutrino energy E_ν. The full line is our smeared distribution including the multinucleon contribution. The dashed line is our smeared distribution without the multinucleon contribution.

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

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

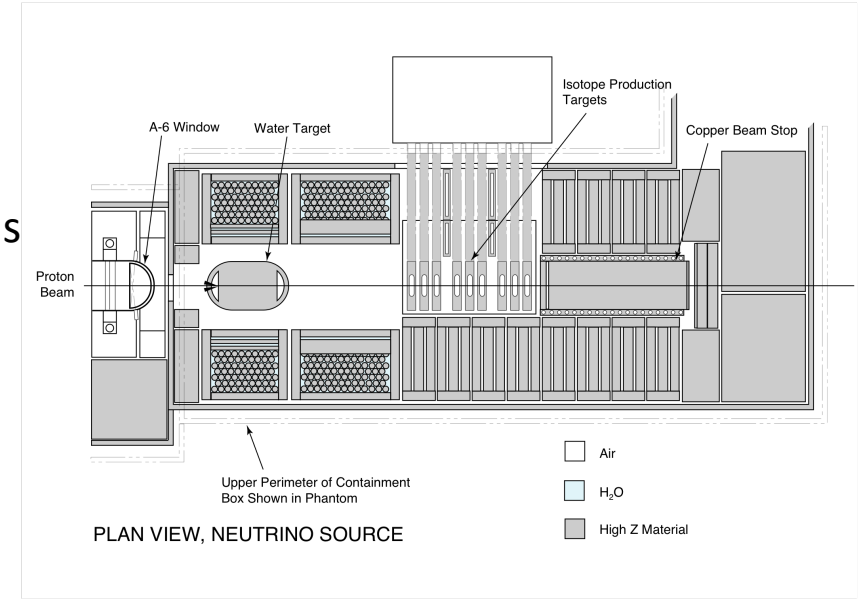
Process	**LSND Data**	**LSND Flux Estimate**	**HARP-CDP Flux Estimate**
ν_μ C -> μ^- N_{gs}	77.8+-8.9	78+-8	184+-18
ν_μ C -> μ^- X	2464+-50	3208+-642	6382+-1276
$\bar{\nu}_\mu$ p -> μ^+ n	286+-27	389+-78	1176+-235

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

Target and Beam Dump

800 MeV protons

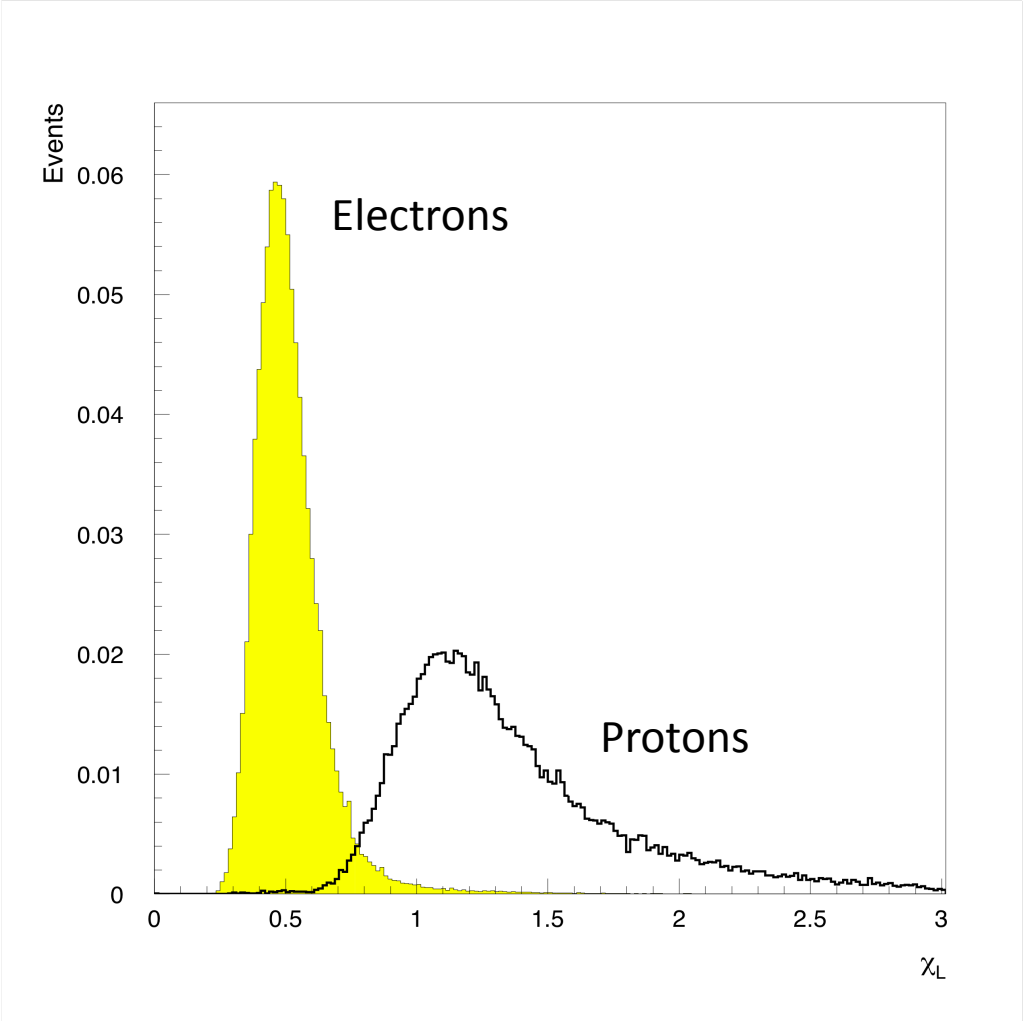


$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

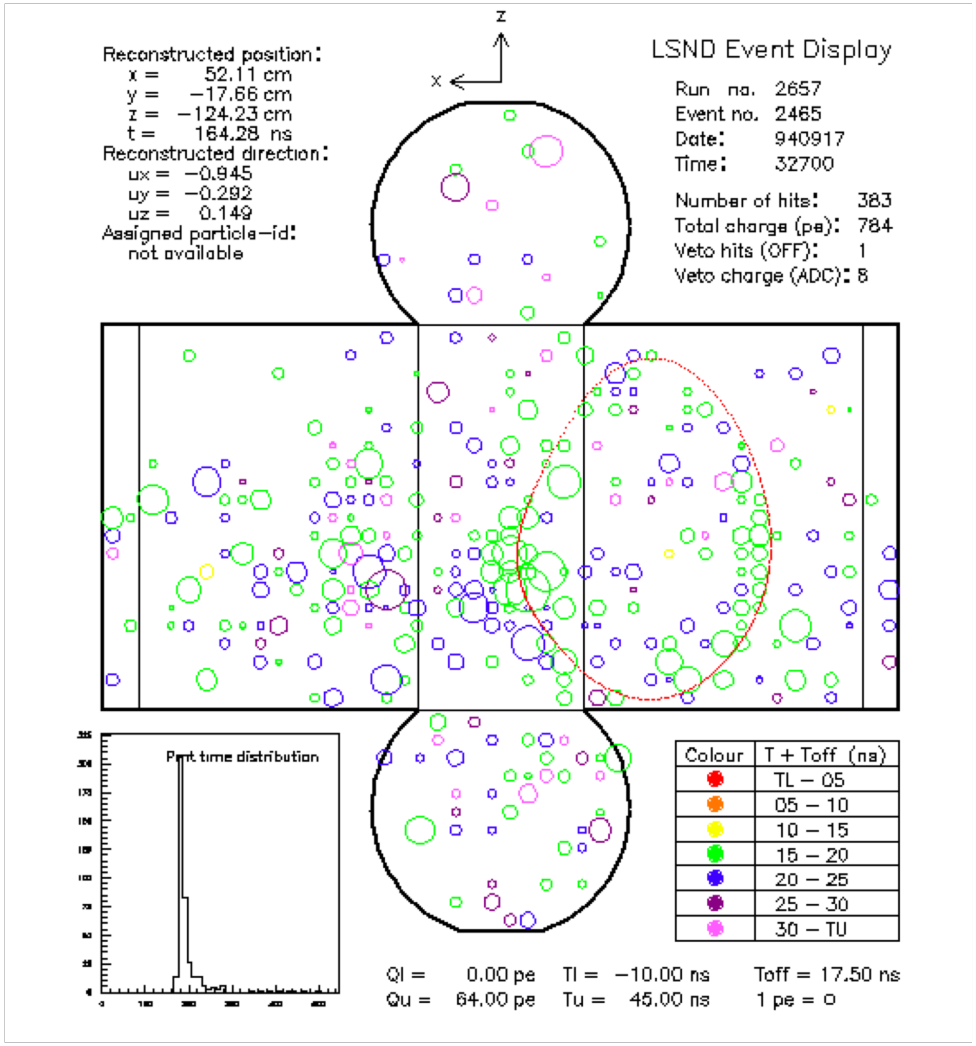
$\bar{\nu}_e/\bar{\nu}_\mu \sim 8\times10^{-4}$

Particle Identification

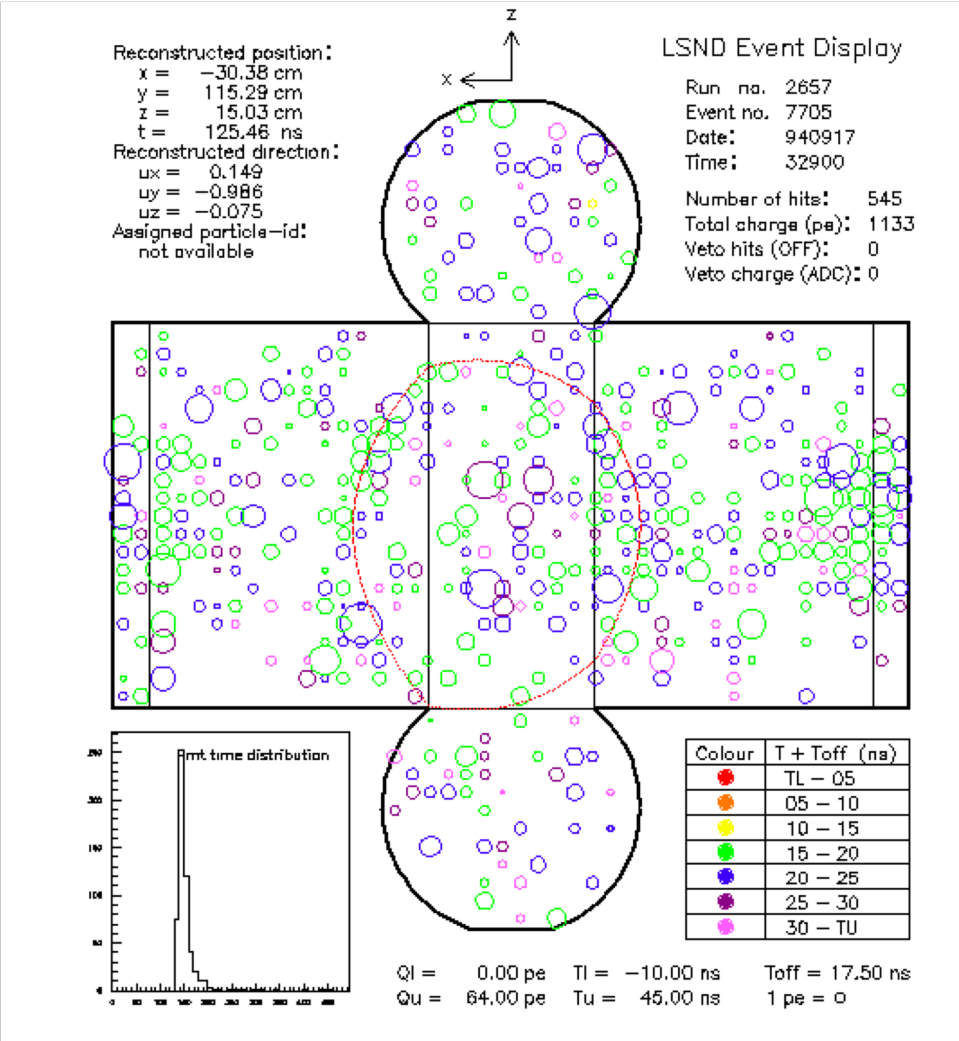


χ_r and χ_a are the quantities minimized for the determination of the event position and direction, and χ_t is the fraction of PMT hits that occur more than 12 ns after the fitted event time. $\chi_L = (\chi_r)(\chi_a)(\chi_t)$

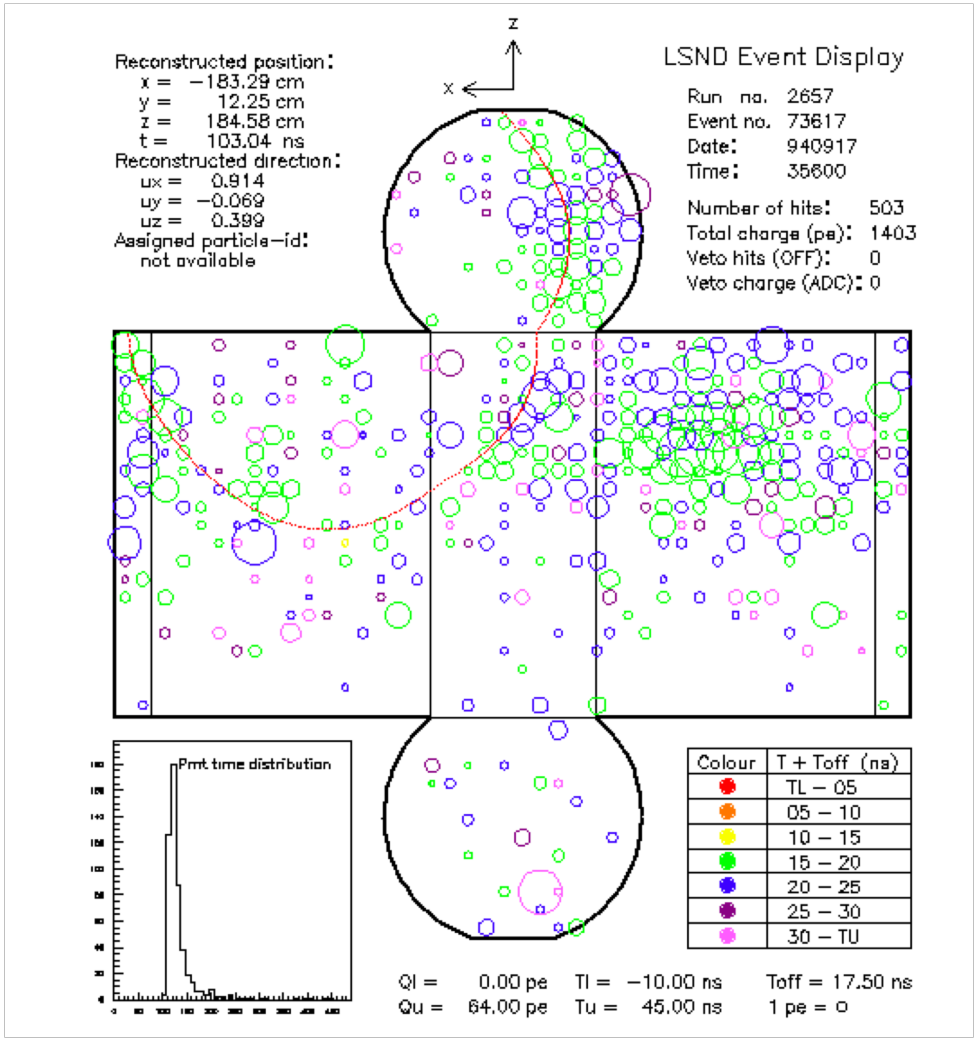
Typical Michel Electron Event Display



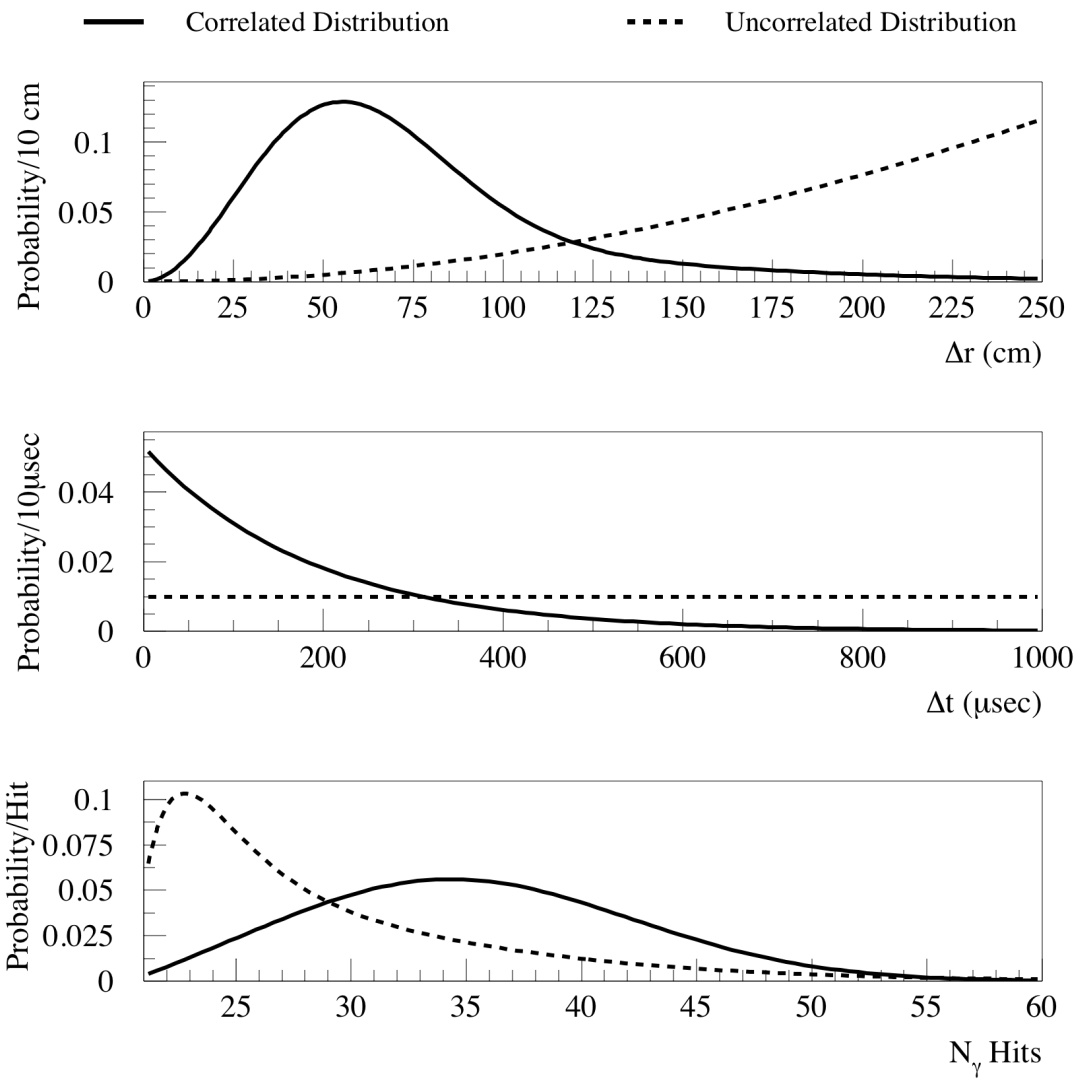
Typical Michel Electron Event Display



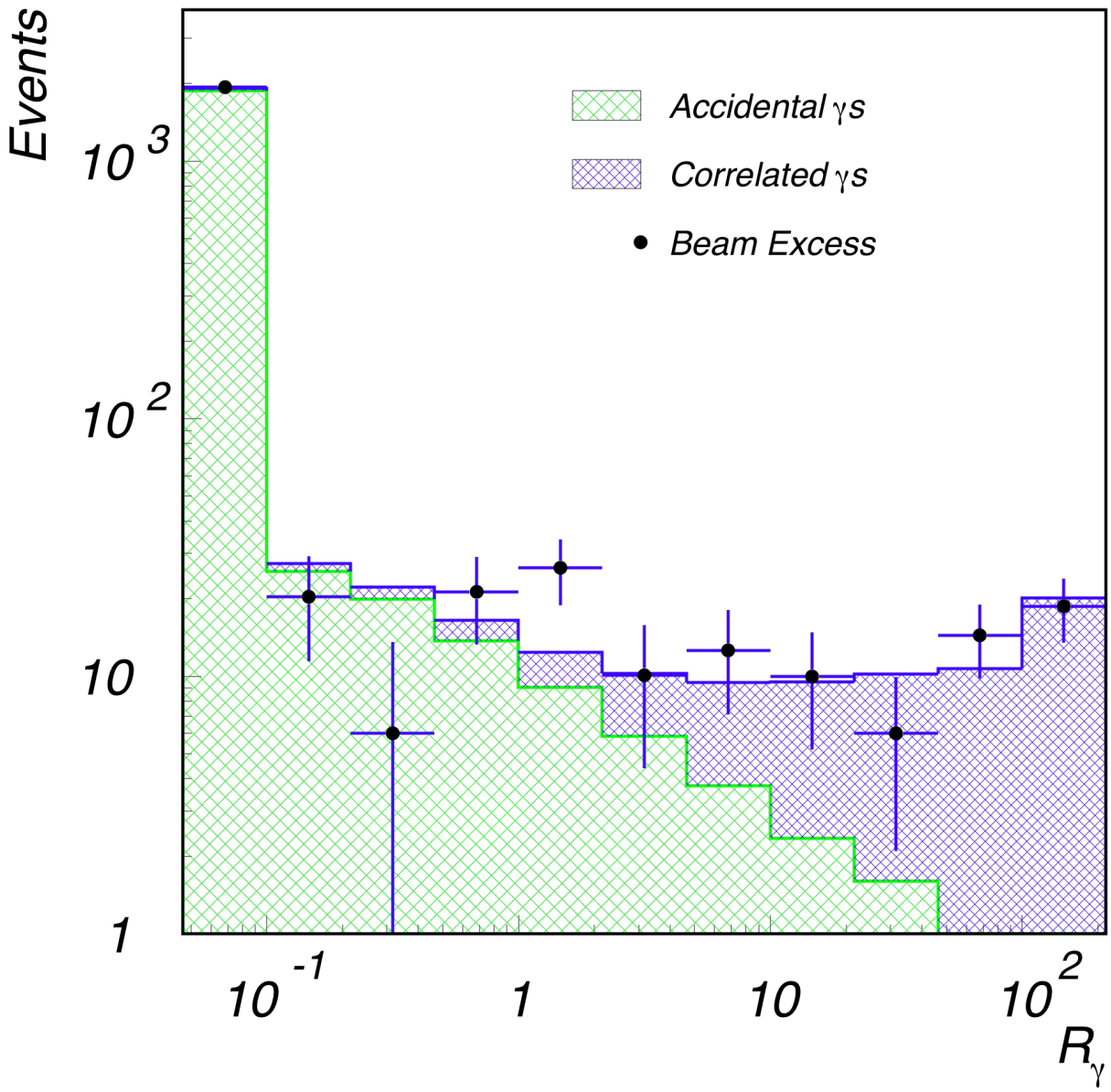
Typical Michel Electron Event Display



2.2 MeV γ Identification



Fit for Correlated γs



f_γ = 0.0567+-0.0108
χ^2=10.7/9 DF
Correlated γ = 117.9+-22.4
Excess = 87.9+-22.4+-6.0
P_{osc} = (0.264+-0.067+-0.045)%