Antineutrino Oscillation Results from MiniBooNE & Implications for Future Experiments

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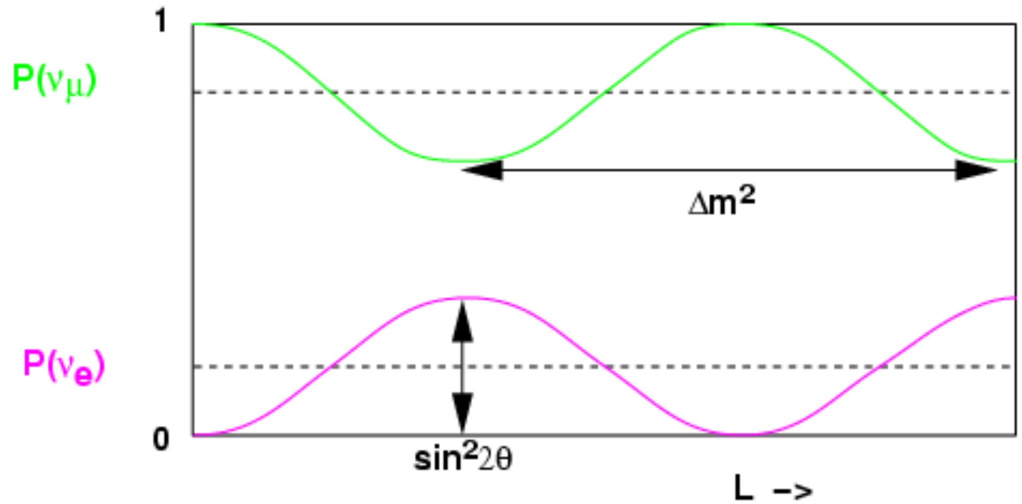
Outline

- Introduction
- LSND $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ Oscillation Results
- MiniBooNE ν_μ -> ν_e Oscillation Search
- MiniBooNE $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ Oscillation Search
- Fits to the World Antineutrino Data
- Testing LSND/MiniBooNE Signals with Future Experiments (MINOS, NOvA, LBNE, IceCube, BooNE, etc.)
- Conclusion

Neutrino Oscillations

Weak Eigenstates		Eigenstates of Propagation
ν_μ	=	$\cos\Theta\ \nu_1 + \sin\Theta\ \nu_2$
ν_e	=	$-\sin\Theta\ \nu_1 + \cos\Theta\ \nu_2$



$$P_{\nu_\mu \to \nu_e} = \sin^2(2\Theta)\ \sin^2(1.27\ \Delta m^2\ L/E_\nu)$$

$\Delta m^2 = m_2^2 - m_1^2$ in eV^2, L in meters, E_ν in MeV

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j \left|U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha j}\, U_{\beta j}\right| \sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

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

T & CP & CPT Violation in the Lepton Sector

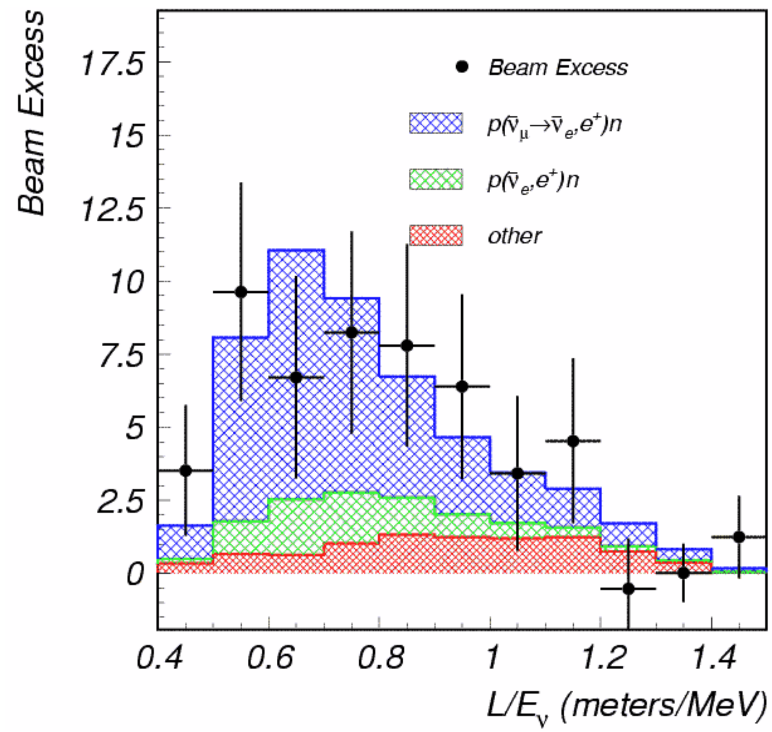
$\nu_\alpha \to \nu_\beta \neq \nu_\beta \to \nu_\alpha$ T Violation

$\nu_\alpha \to \nu_\beta \neq \bar{\nu}_\alpha \to \bar{\nu}_\beta$ CP Violation

$\nu_\alpha \to \nu_\beta \neq \bar{\nu}_\beta \to \bar{\nu}_\alpha$ CPT Violation

LSND Signal

- LSND experiment
- Stopped pion beam
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\quad\quad\quad \hookrightarrow e^+ + \nu_\mu + \nu_e$
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from e^+ with delayed γ from n-capture
- Excess=87.9 ± 22.4 ± 6 (3.8σ)

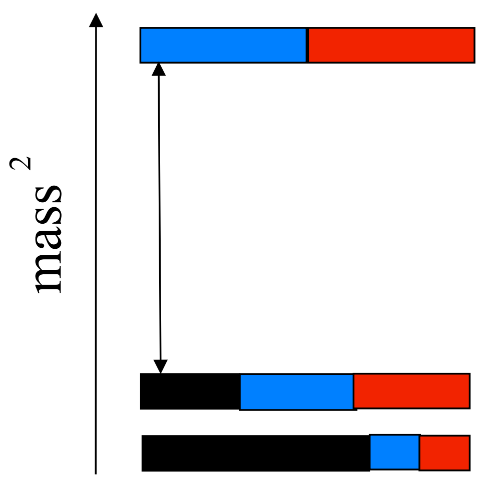


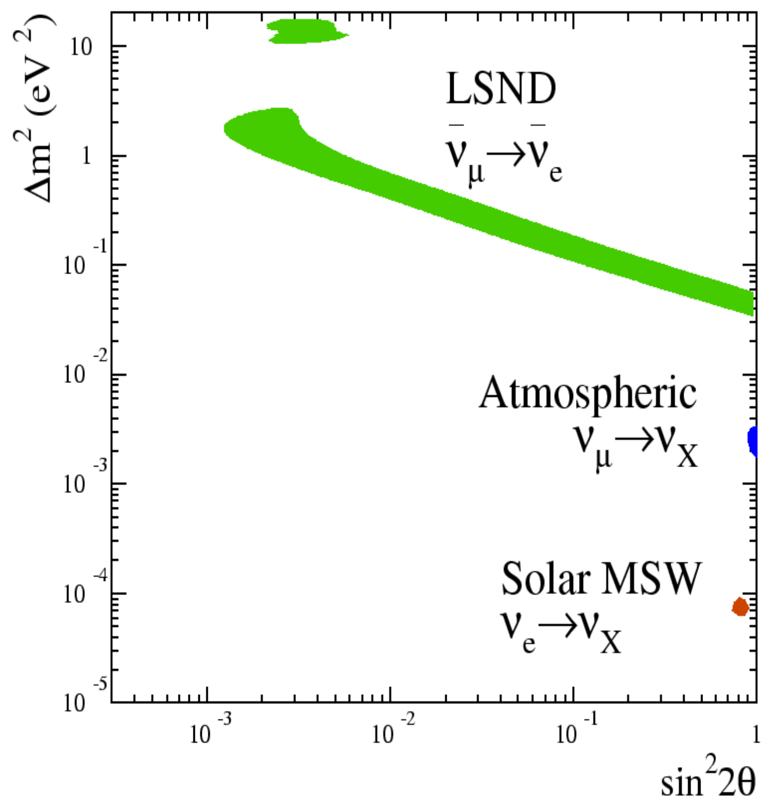
LSND Signal

- Assuming two neutrino oscillations

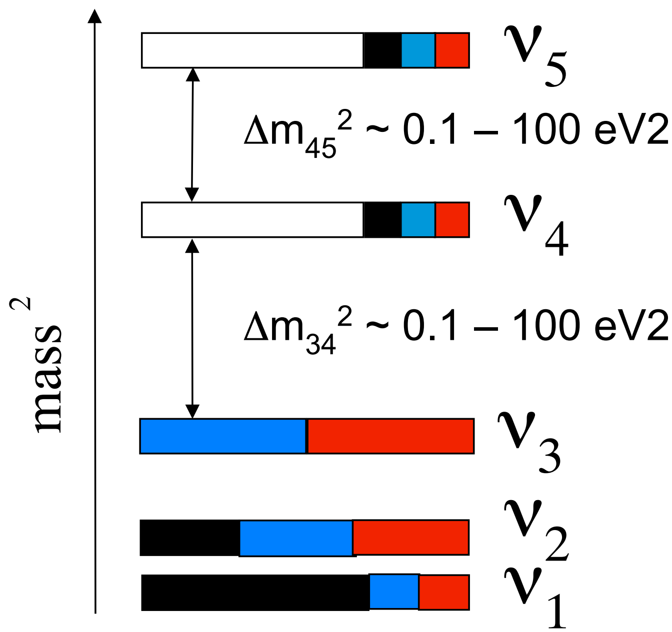
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\,L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splitings



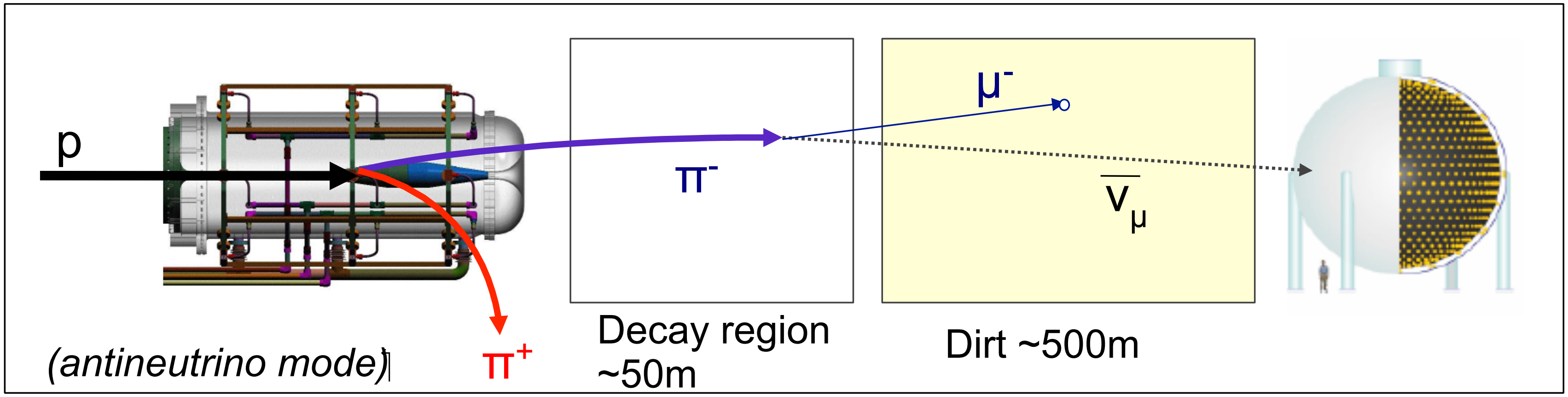


Sterile Neutrinos



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

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

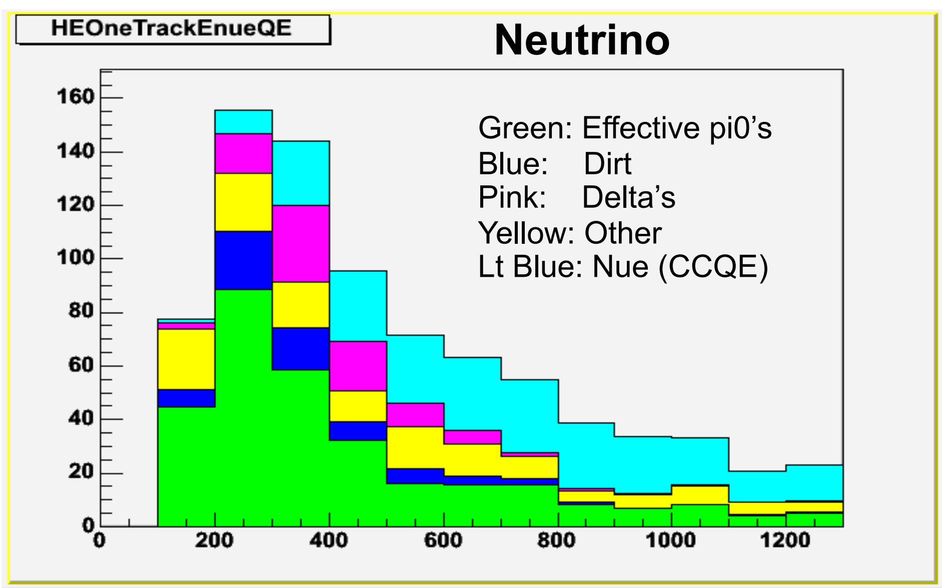
ν_e Event Rate Predictions

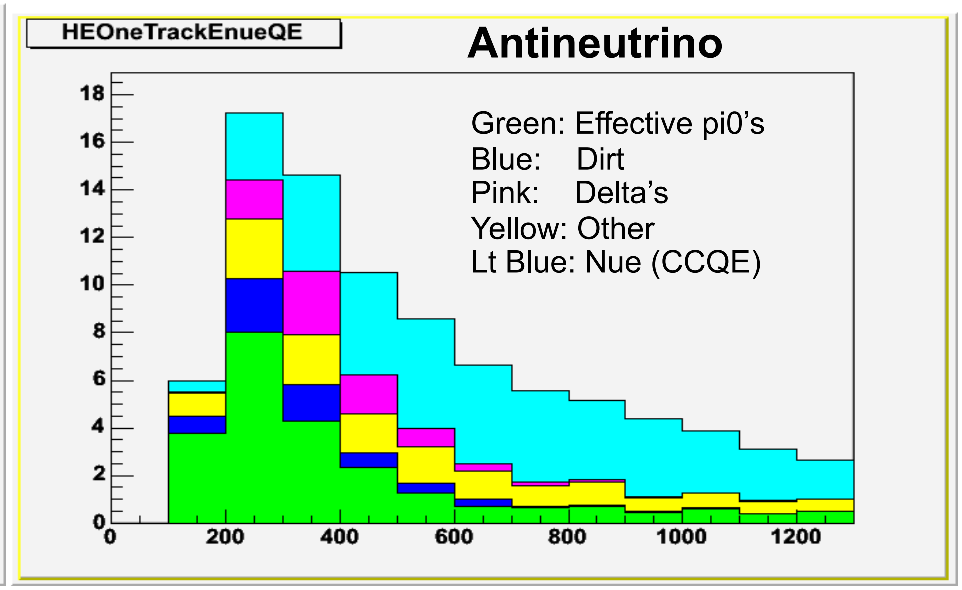
#Events = Flux x Cross-sections x Detector response

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

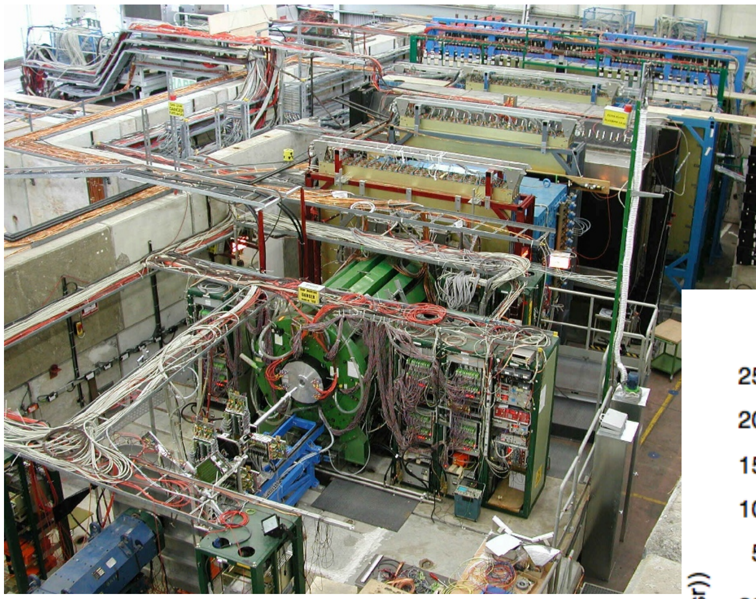
External and MiniBooNE measurements
-π^0, delta and dirt backgrounds constrained from data.

Detailed detector simulations checked with neutrino data and calibration sources.

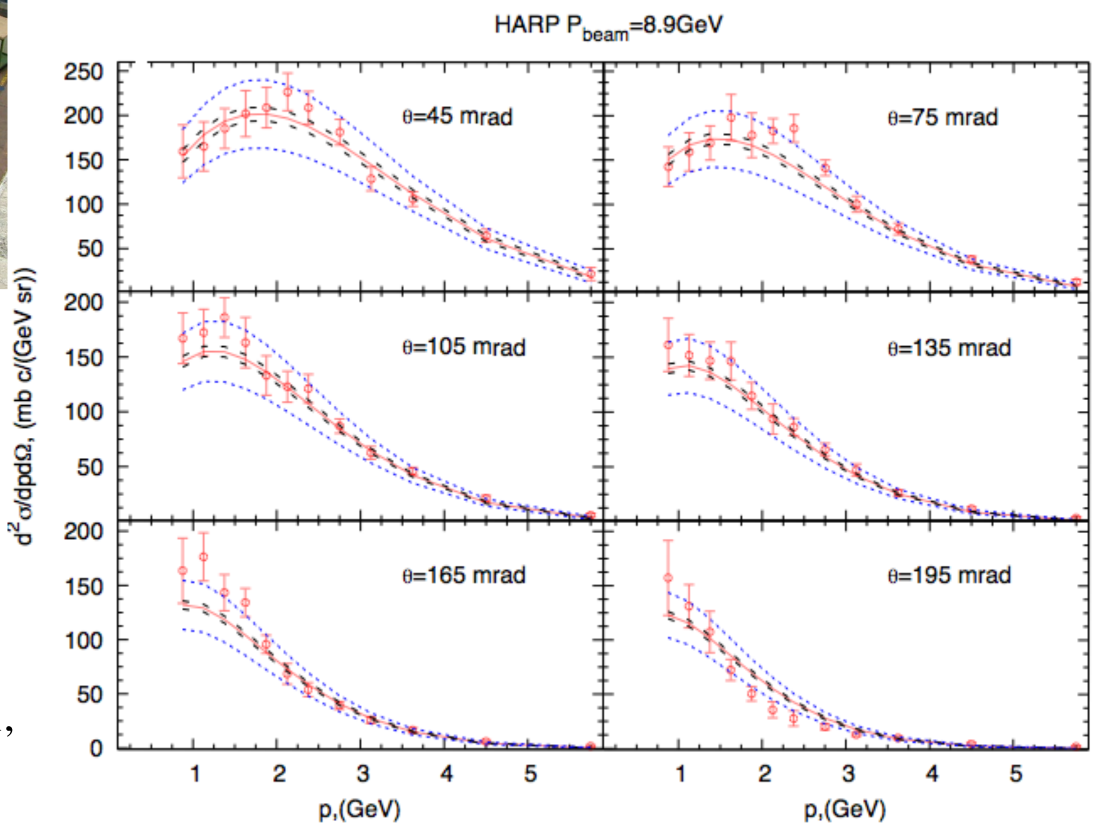




Modeling Production of Secondary Pions



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

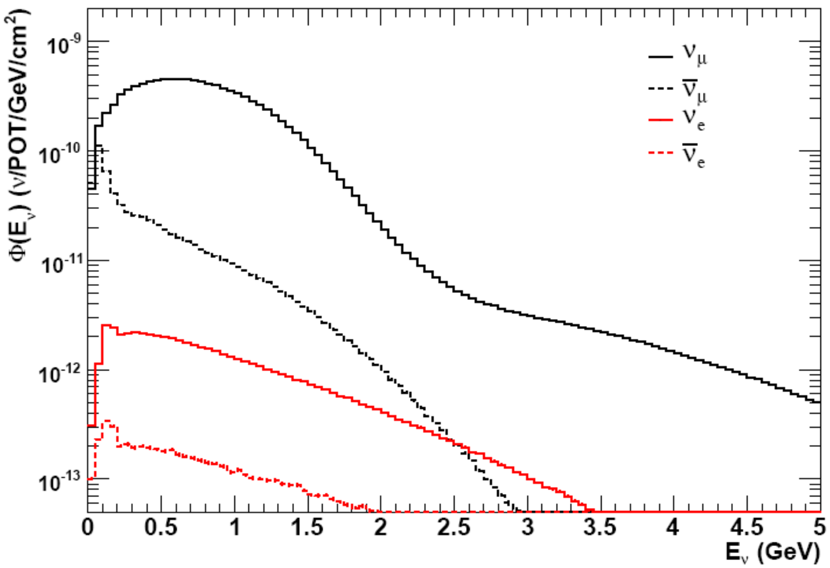


Data are fit to a Sanford-Wang parameterization.

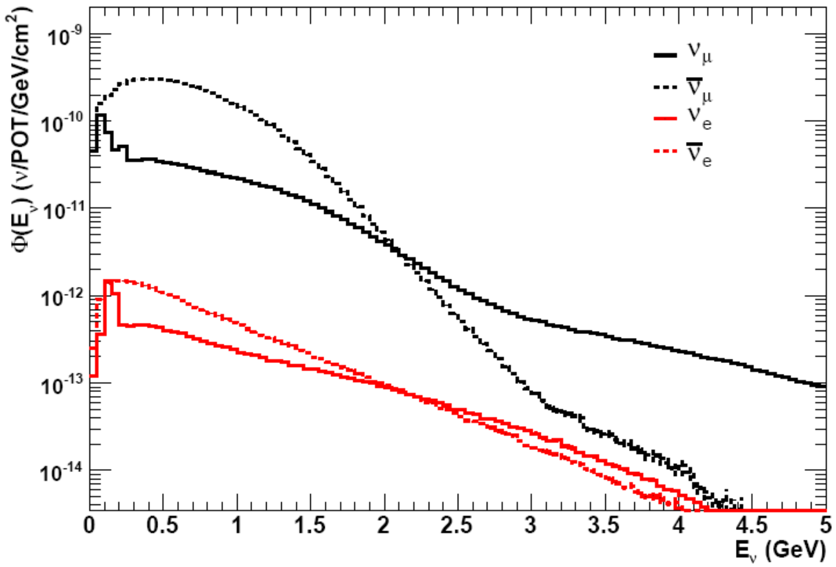
HARP collaboration,
hep-ex/0702024

Neutrino Flux from GEANT4 Simulation

Neutrino-Mode Flux

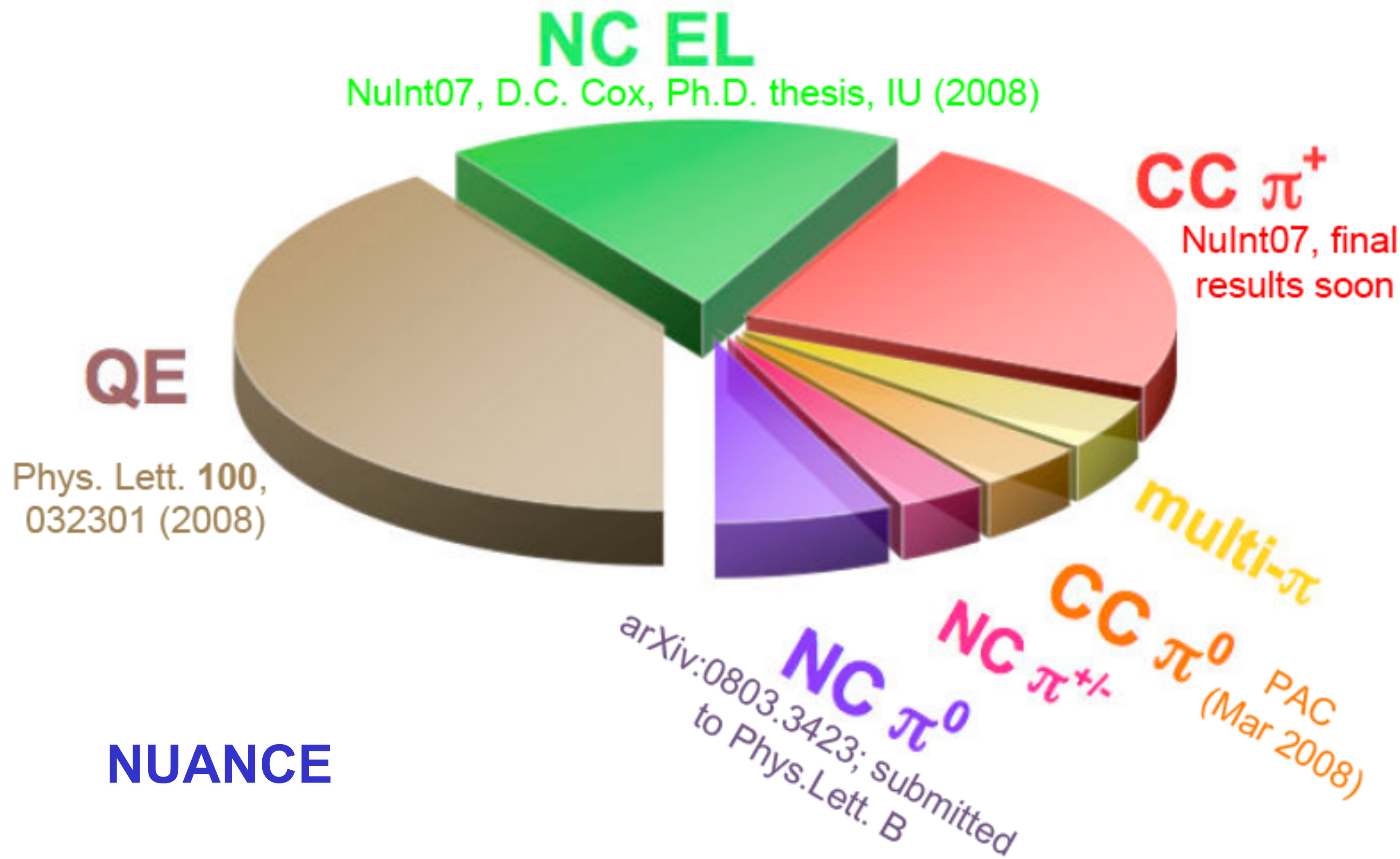


Antineutrino-Mode Flux

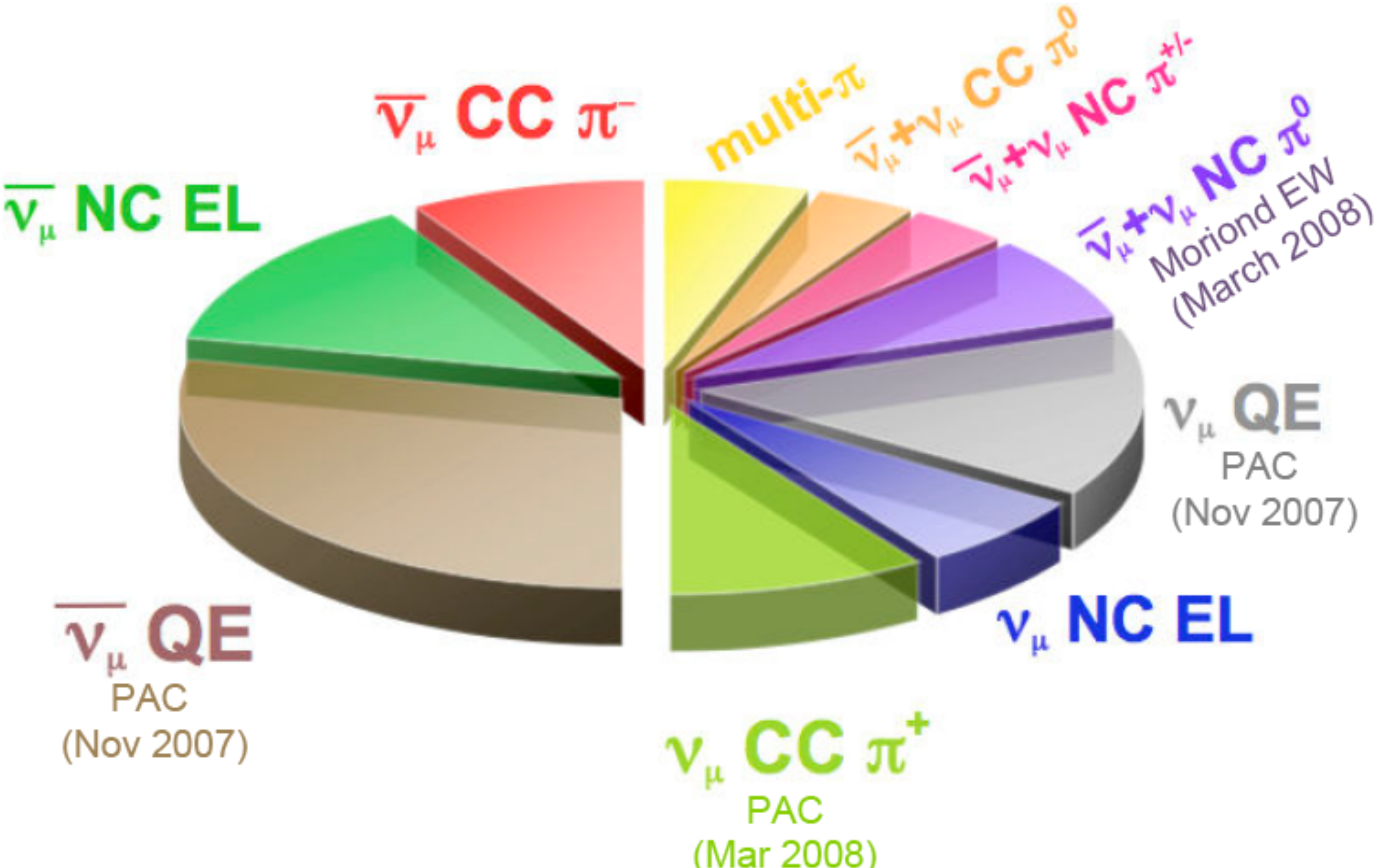


Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode
Instrinsic ν_e background is ~0.5% for both Nu-Mode & Antinu-Mode

Neutrino Cross Sections

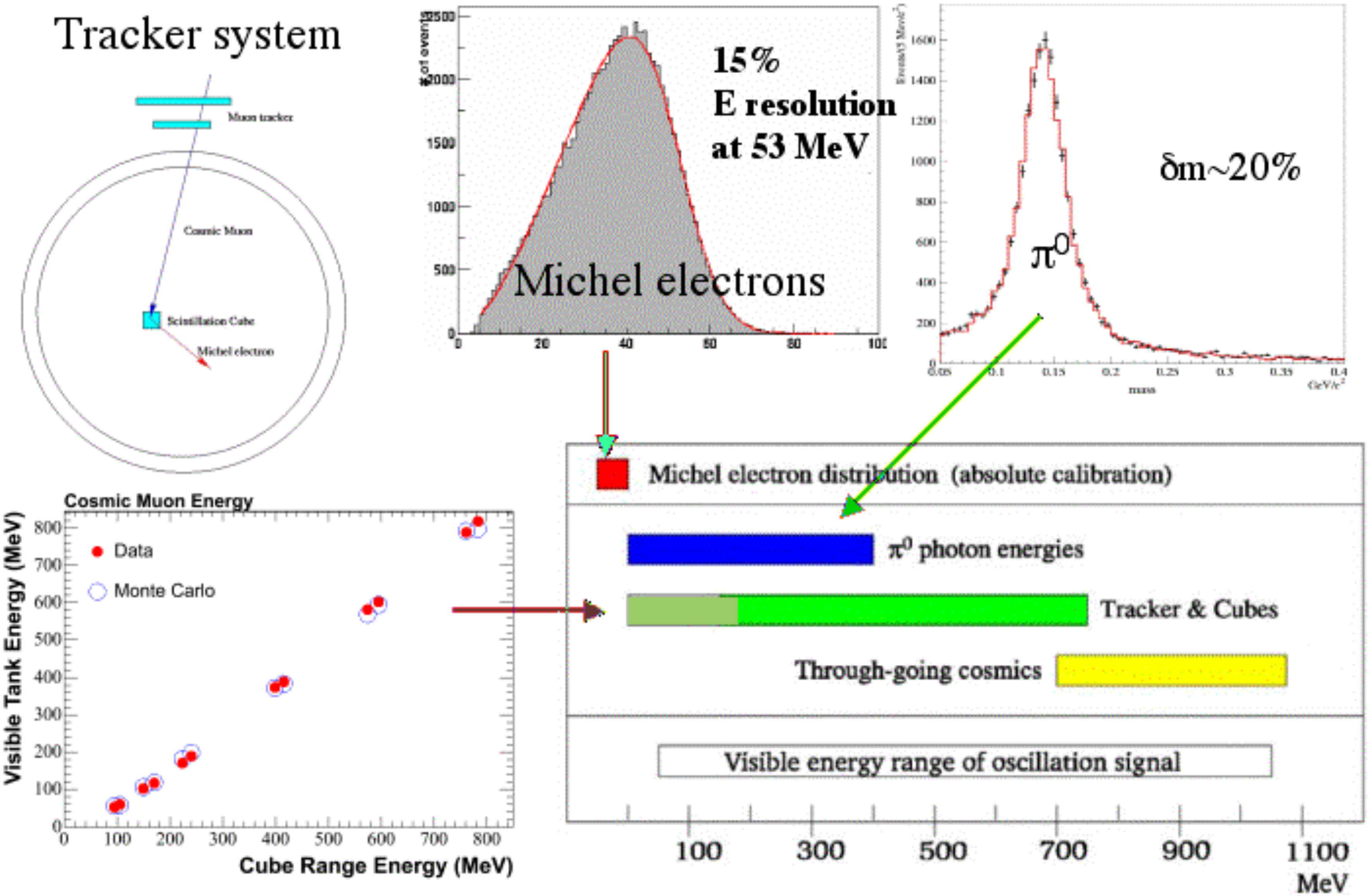


Antineutrino Cross Sections



NUANCE

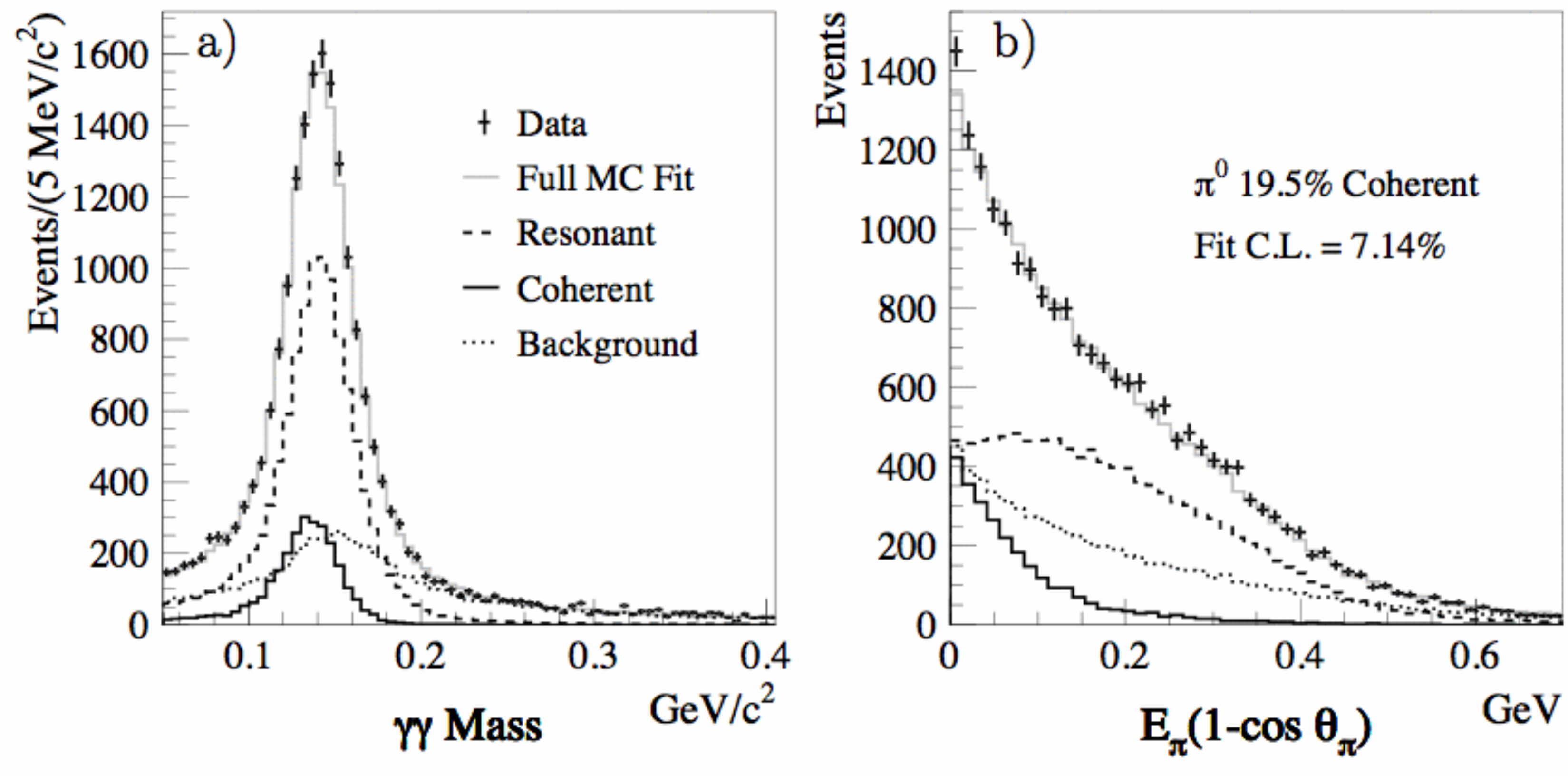
Calibration Sources



NCπ^0 Scattering

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

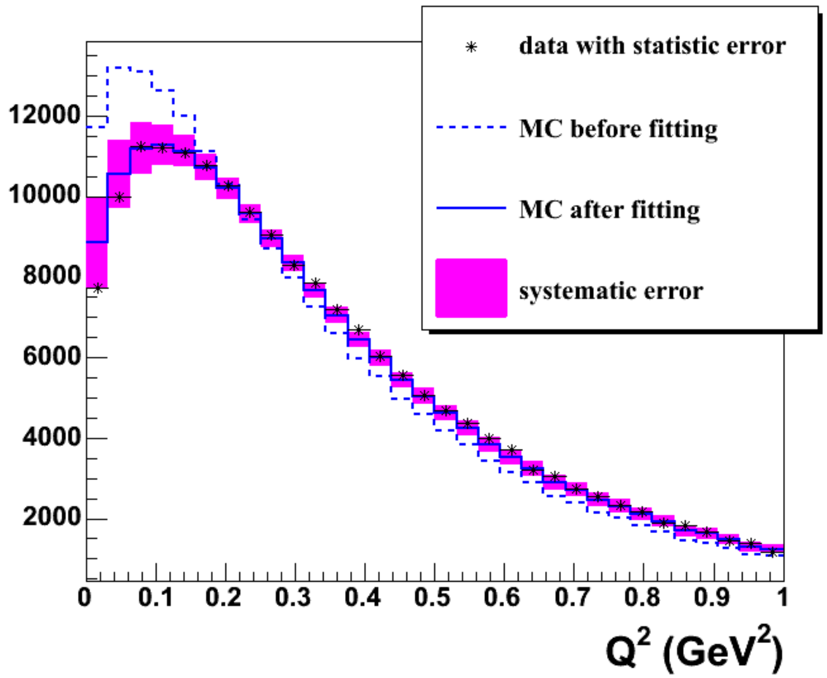
coherent fraction=19.5+-1.1+-2.5%



ν_μ CCQE Scattering

A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. 100, 032301 (2008)

186000 muon neutrino events



From Q^2 fits to MB ν_μ CCQE data:

M_A^{eff} -- effective axial mass

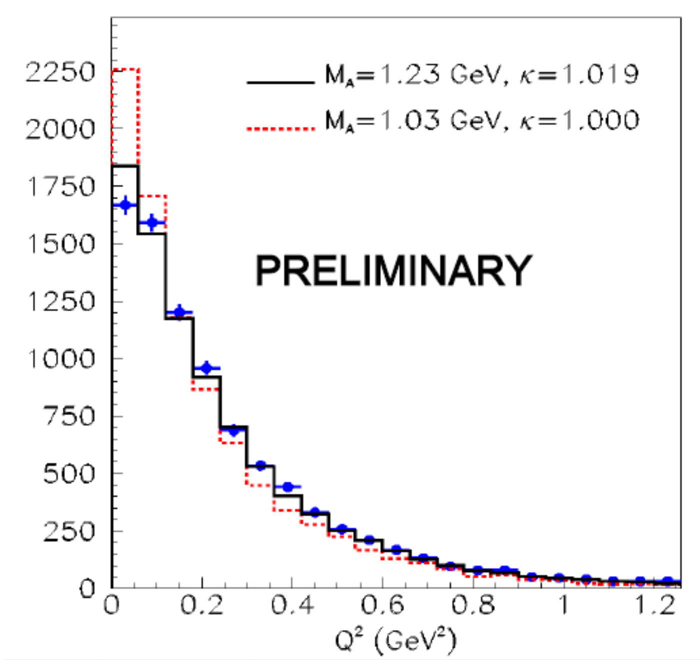
$\varkappa$ -- Pauli Blocking parameter

From electron scattering data:

E_b -- binding energy

p_f -- Fermi momentum

14000 anti-muon neutrinos



Fermi Gas Model describes CCQE ν_μ data well

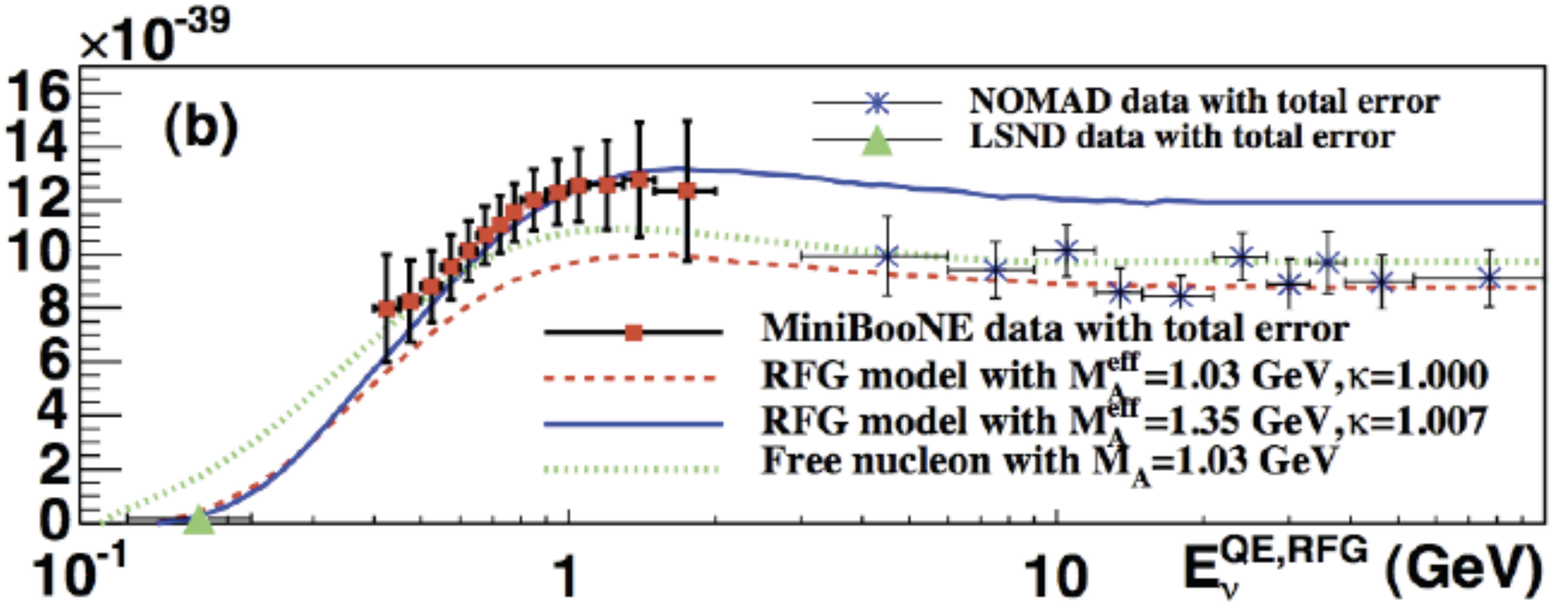
$M_A = 1.23 +- 0.20$ GeV

$\varkappa = 1.019 +- 0.011$

Also used to model ν_e and $\overline{\nu}_e$ interactions

ν_μ CCQE Scattering

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



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

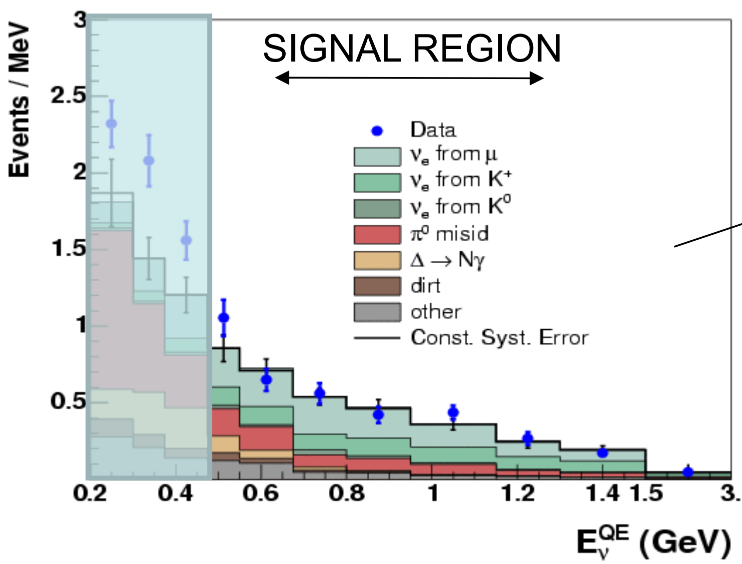
How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

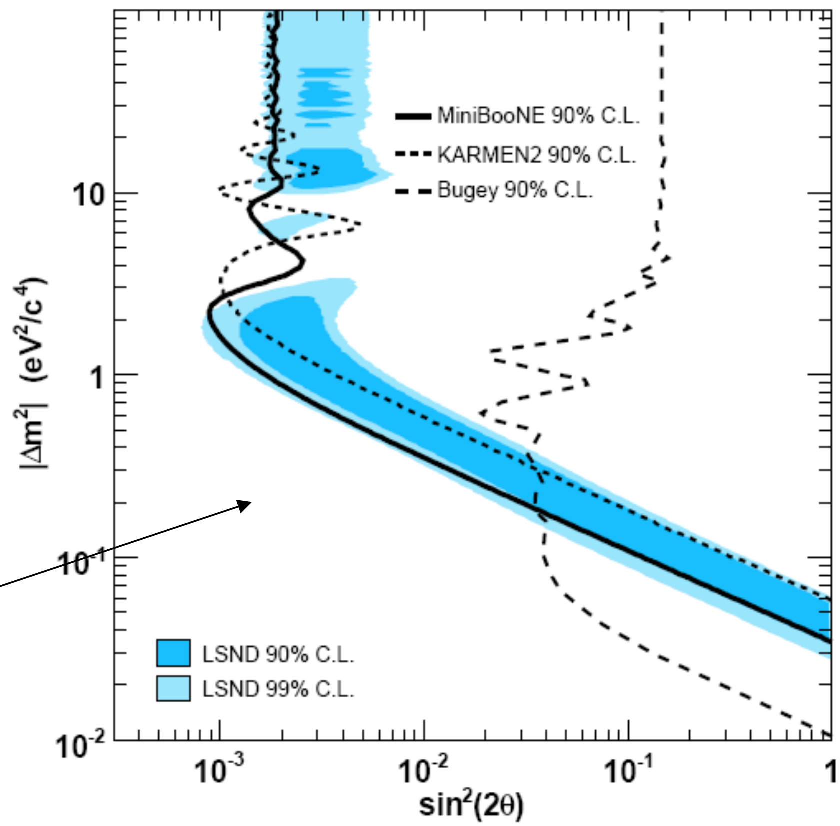
A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys.Rev.**C65,** 024002 (2002) & Gerry Garvey.

MiniBooNE Neutrino Oscillation Results

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

- 6.5e20 POT
- No excess of events in signal region (E>475 MeV)
- Ruled out simple 2ν oscillations as LSND explanation (assuming no CP violation)





Phys. Rev. Lett. 98, 231801 (2007)

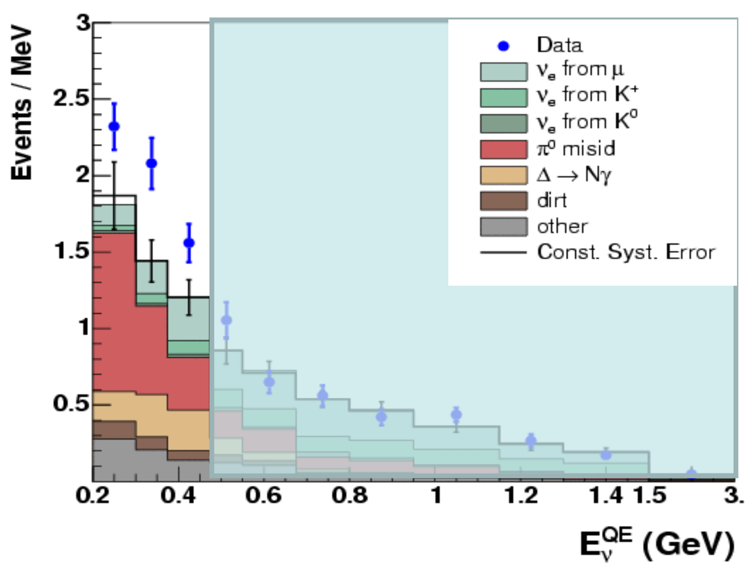
MiniBooNE Neutrino Oscillation Results

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

Excess of events observed at low energy: 128.8 ± 20.4 ± 38.3 (3.0σ)

Shape not consistent with simple 2ν oscillations

Magnitude consistent with LSND



Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281

CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.

Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009

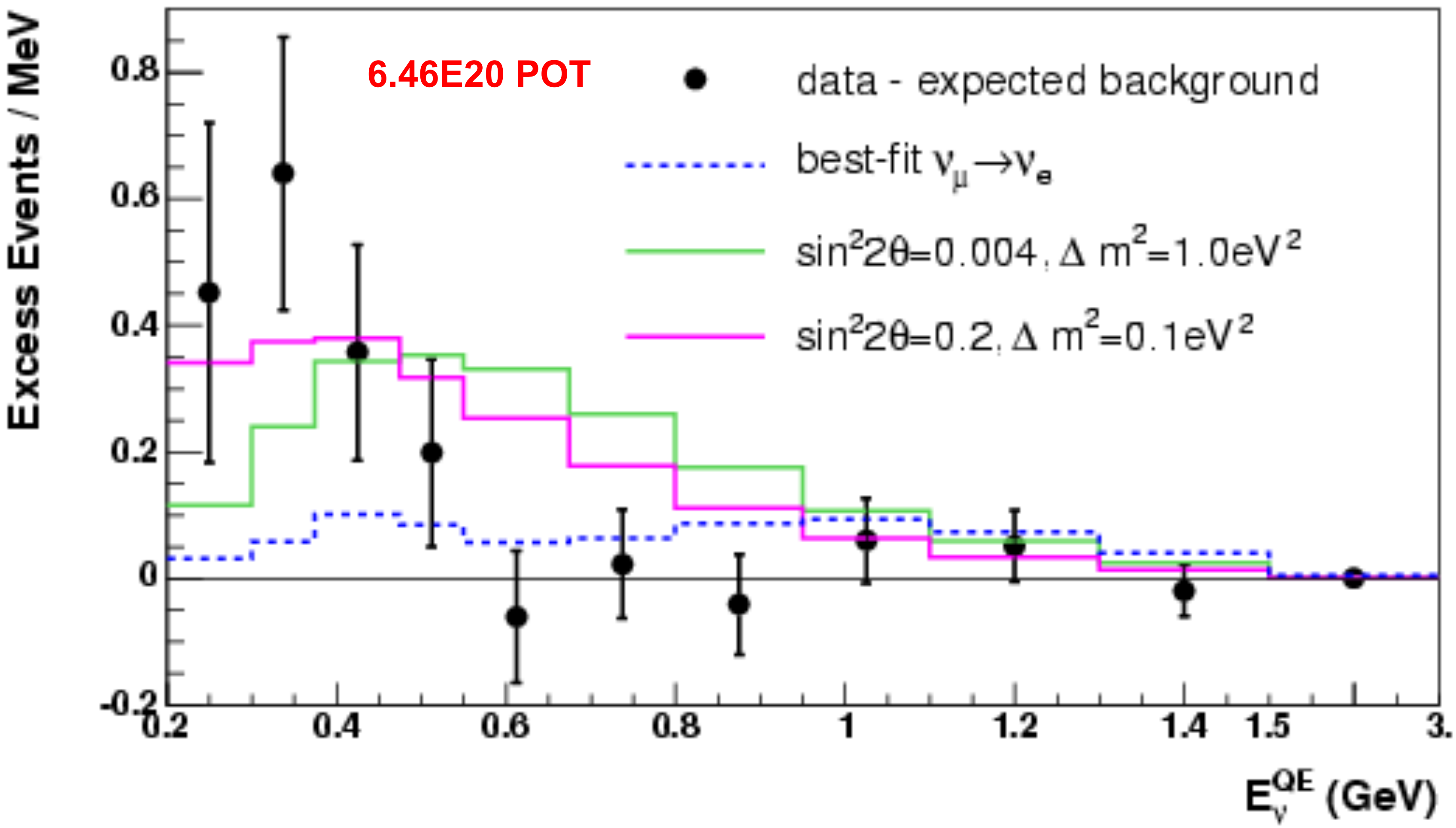
CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

New Gauge Boson with Sterile Neutrinos: Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363

MiniBooNE Data Show a Low-Energy Excess

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

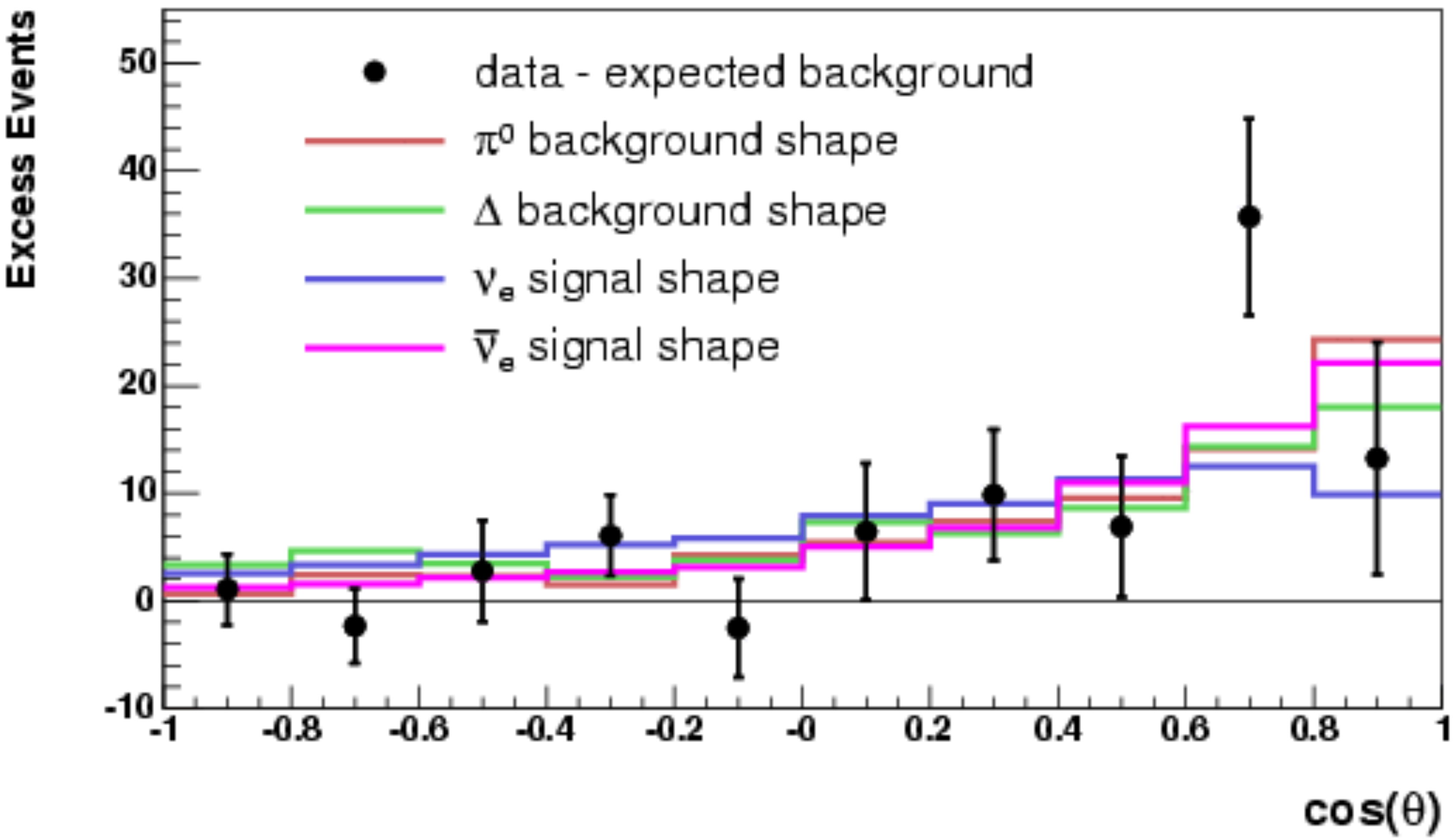
Excess from 200-475 MeV = 128.8+-20.4+-38.3 events



Number of Excess Events

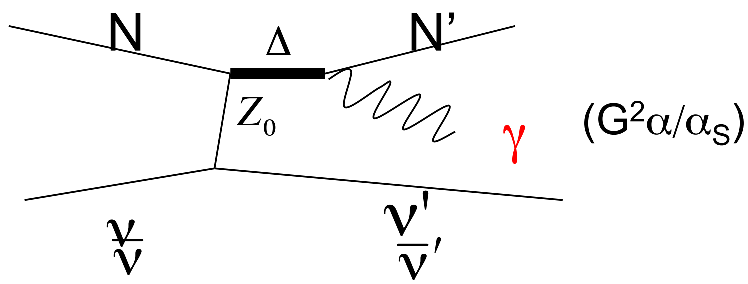
Energy (MeV)	Data	Background	Excess	$\#\sigma_{tot}$ ($\#\sigma_{stat}$)
200-300	232	186.8+-26.0	45.2+-13.7+-22.1	1.7 (3.3)
300-475	312	228.3+-24.5	83.7+-15.1+-19.3	3.4 (5.5)
200-475	544	415.2+-43.4	128.8+-20.4+-38.3	3.0 (6.3)
475-1250	408	385.9+-35.7	22.1+-19.6+-29.8	0.6 (1.1)
200-1250	952	801.0+-58.1	151.0+-28.3+-50.7	2.6 (5.3)

Low-Energy Excess vs cosθ

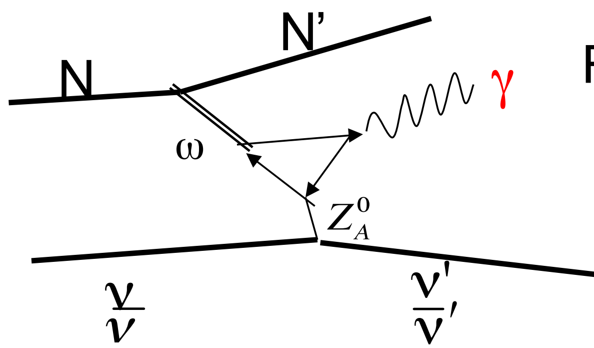


Backgrounds: Order ($G^2\alpha\alpha_s$) , single γ FS?

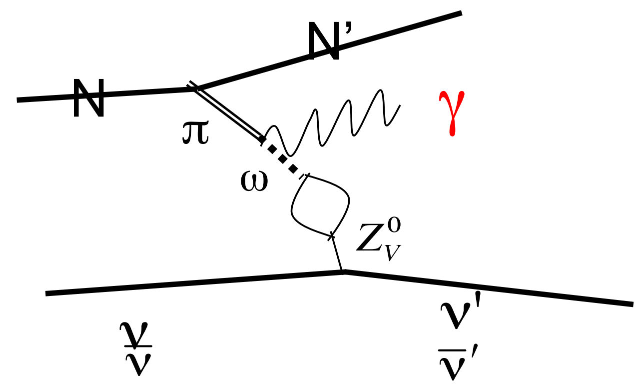
Dominant process accounted for in MC!



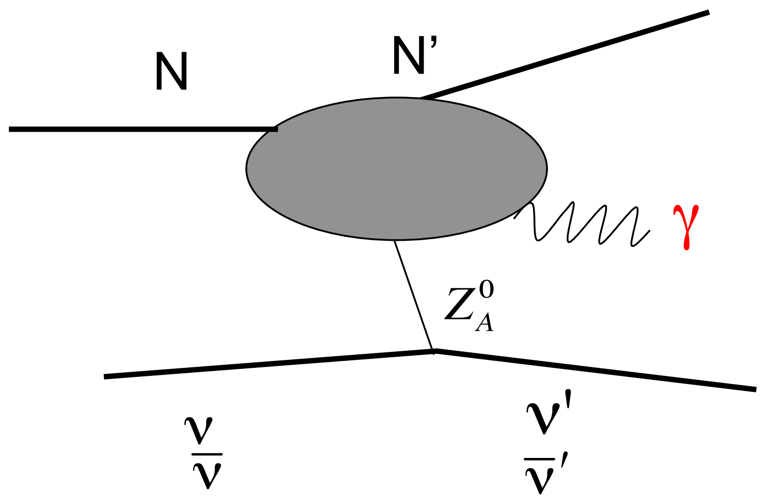
Radiative Delta Decay



Axial Anomaly



Other PCAC



So far no one has found a NC process to account for the $\nu,\bar{\nu}$ difference & the ν low-energy excess. Work is in progress:

R. Hill, arXiv:0905.0291

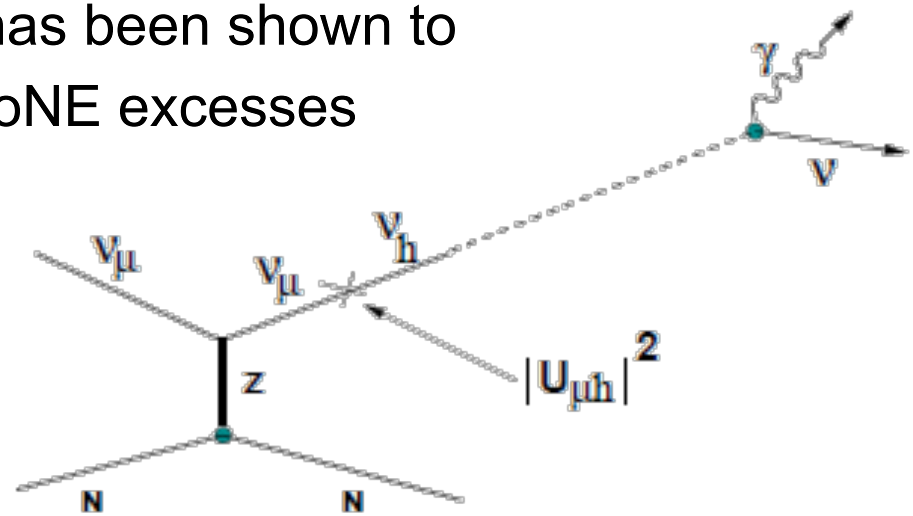
Jenkins & Goldman, arXiv:0906.0984

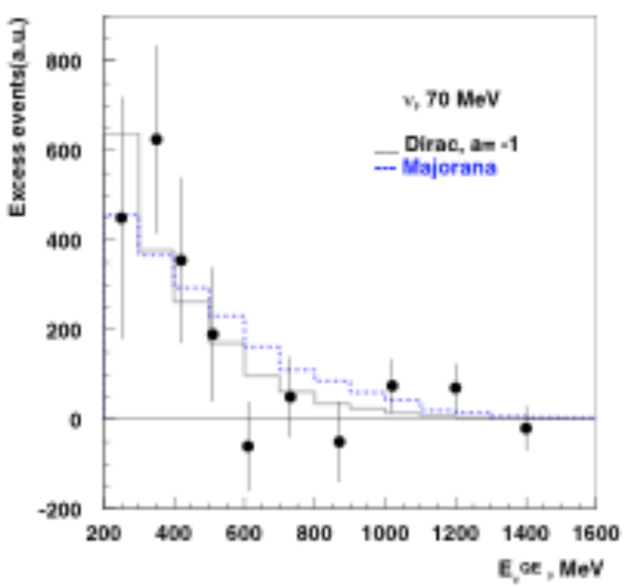
Serot & Zhang, arXiv:1011.5913

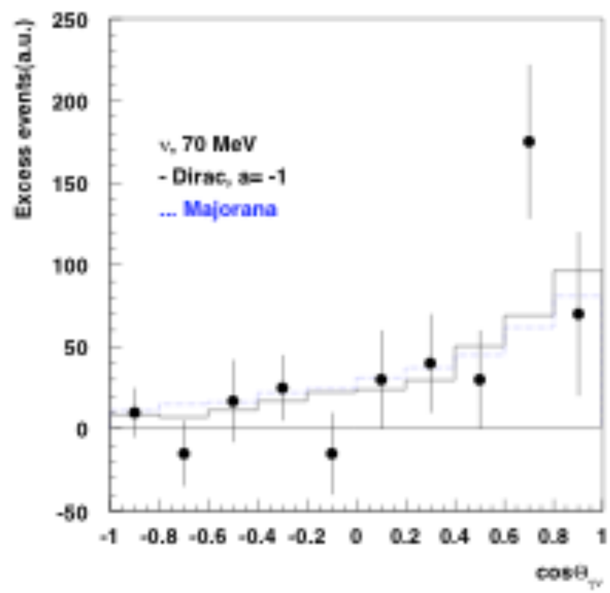
Sterile ν Decay?

- The decay of a ~50 MeV sterile ν has been shown to accommodate the LSND & MiniBooNE excesses
  - **Gninenko, PRL 103, 241802 (2009)**

    arXiv:1009.5536







Lorentz Violation?

A simple Lorentz-violating texture for neutrino mixing

Jorge S. Díaz and V. Alan Kostelecký

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

(Dated: IUHET 552, December 2010)

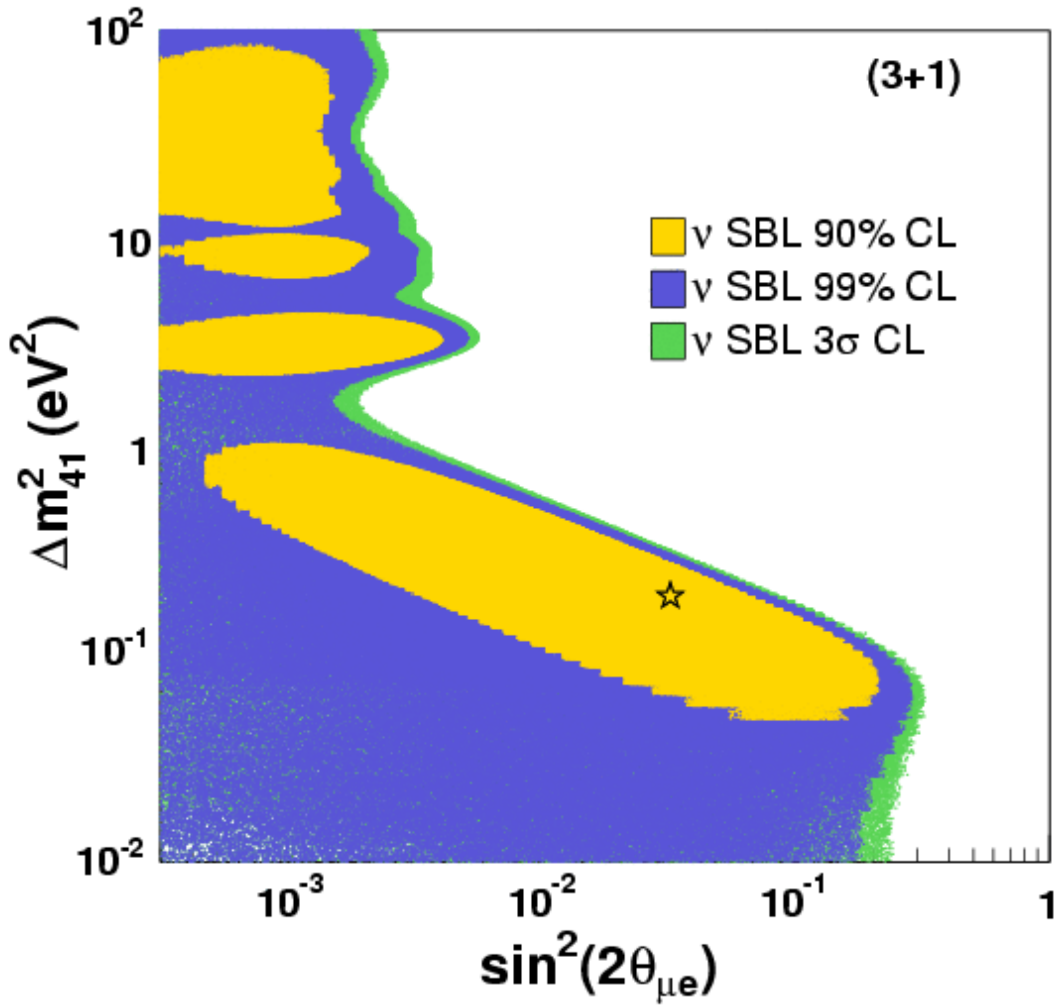
Abstract

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

arxiv: 1012.5985

More Complicated ν Oscillations?

3+1 Global Fit to World Neutrino Data Only



G. Karagiorgi et al., arXiv:0906.1997

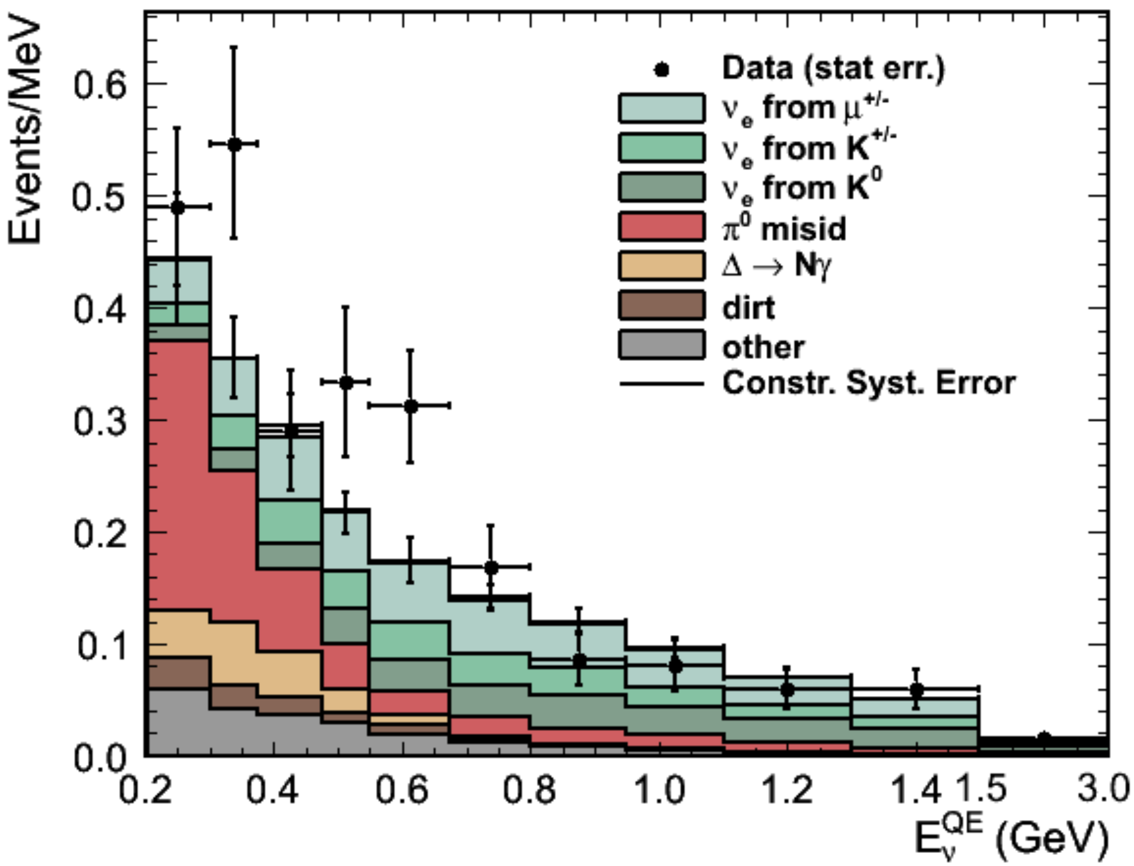
Best 3+1 Fit:
$\Delta m_{41}{}^2$ = 0.19 eV^2
$\sin^2 2\theta_{\mu e}$ = 0.031
χ^2 = 90.5/90 DOF
Prob. = 46%

Predicts ν_μ & ν_e disappearance of $\sin^2 2\theta_{\mu\mu}$ ~ 3.1% and $\sin^2 2\theta_{ee}$ ~ 3.4%

MiniBooNE Antineutrino Oscillation Results

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

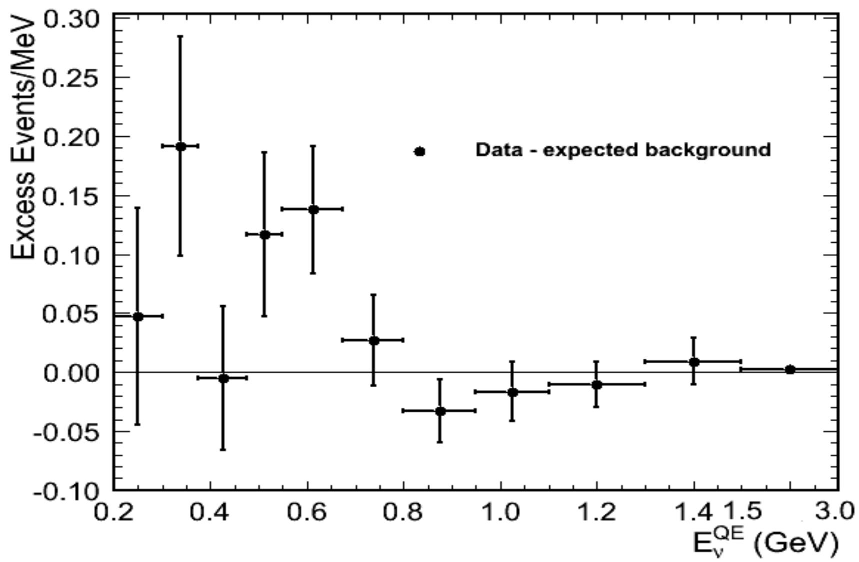
- 5.66e20 POT



MiniBooNE Antineutrino Null Probability

- Absolute χ^2 probability of null point (background only) - model independent
- Frequentist approach

475-1250 MeV	chi2/NDF	probability
$\nu_\mu \to \nu_e$	6.1/6	40%
$\bar{\nu}_\mu \to \bar{\nu}_e$	18.5/6	0.5%

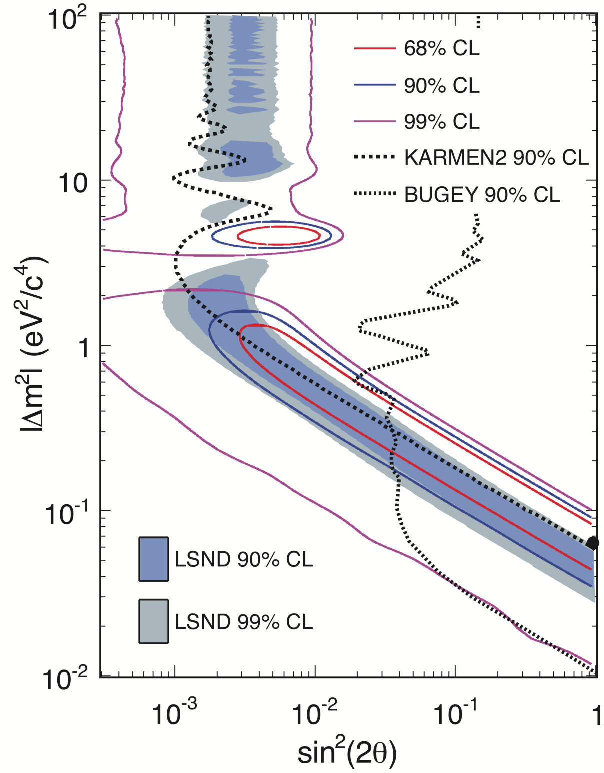


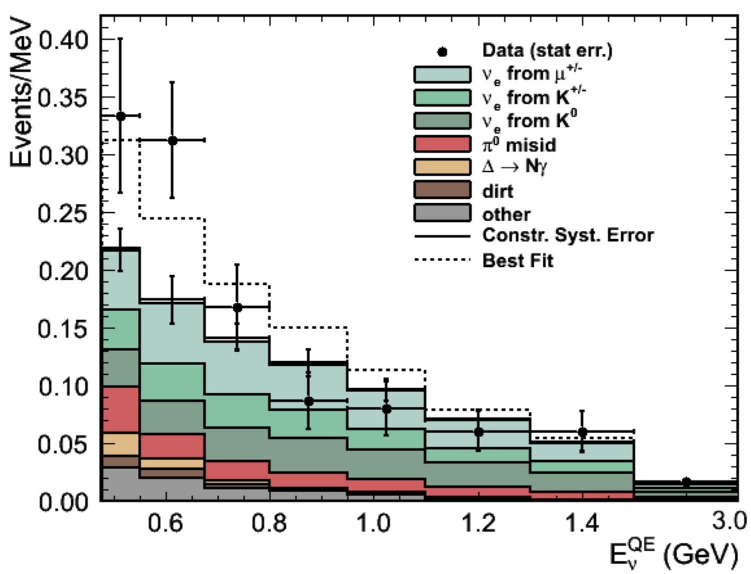
Number of Excess Events

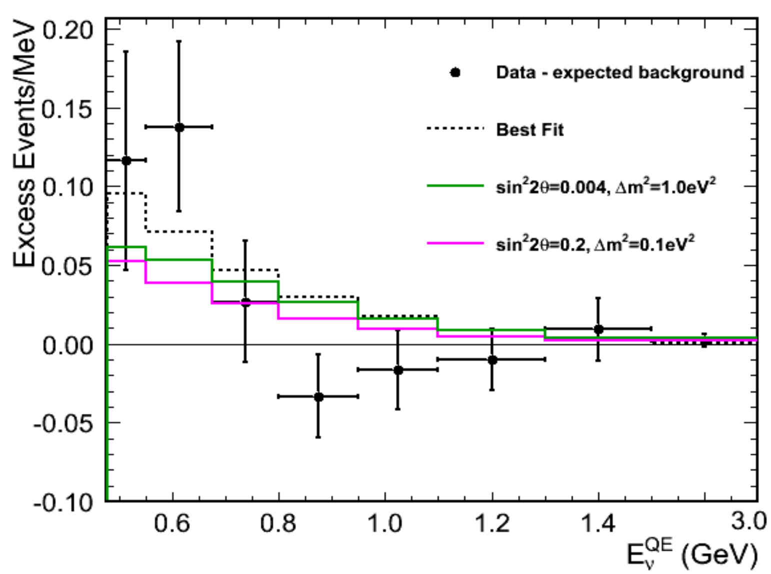
Energy (MeV)	Data	Background	Excess	$\#\sigma_{tot}$ $(\#\sigma_{stat})$
200-475	119	100.5+-14.3	18.5+-10.0+-10.2	1.3 (1.9)
475-675	64	38.3+-7.2	25.7+-6.2+-3.7	3.6 (4.1)
475-1250	120	99.1+-14.0	20.9+-10.0+-9.8	1.5 (2.1)
475-3000	158	133.3+-18.0	24.7+-11.5+-13.8	1.4 (2.1)
200-3000	277	233.8+-22.5	43.2+-15.3+-16.5	1.9 (2.8)

MiniBooNE Oscillation Fit E>475

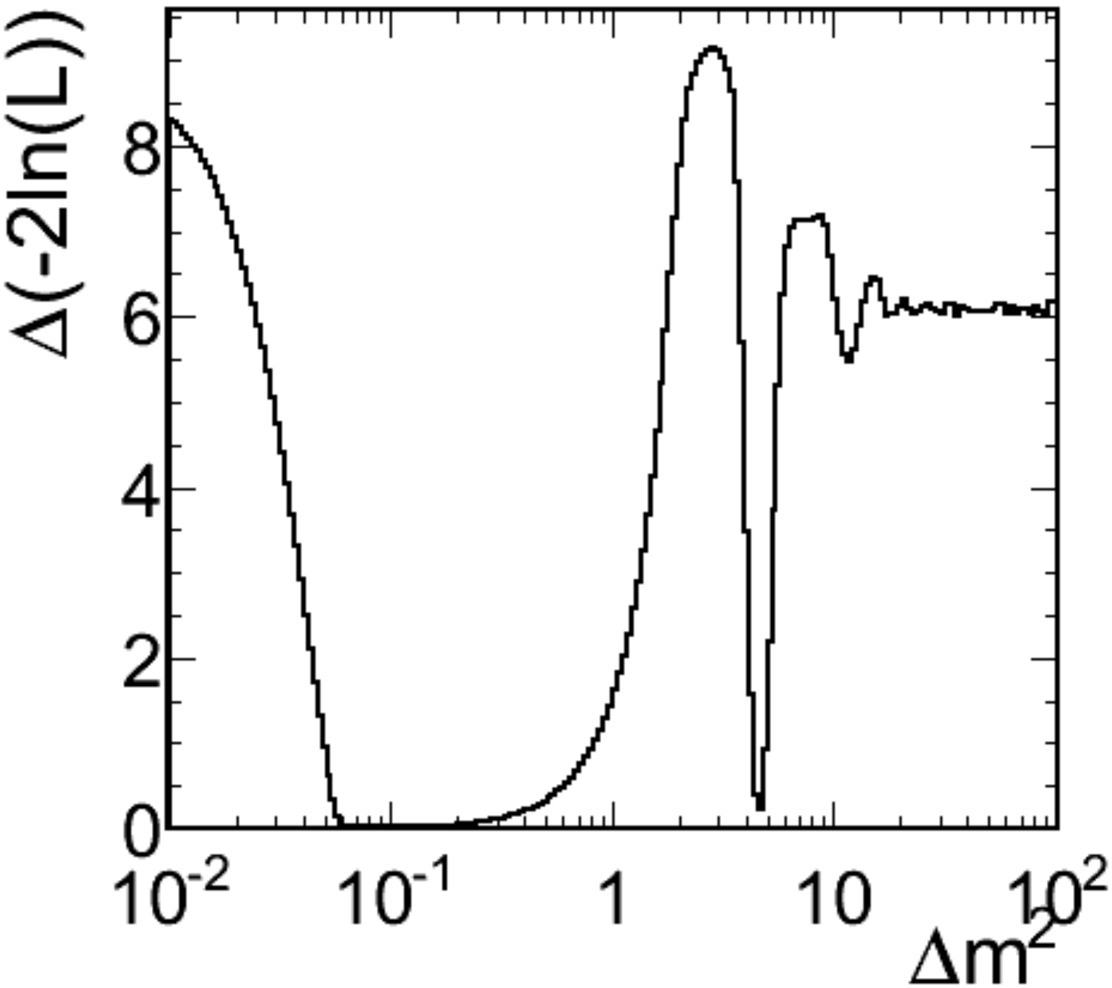
- 5.66E20 POT
- E>475 is signal region for LSND type osc.
- Oscillations favored over background only hypotheses at 99.4% CL (model dependent)
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.9584, 0.064 eV^2)
  χ^2/NDF = 8.0/4; Prob. = 8.7% (475-1250 MeV)





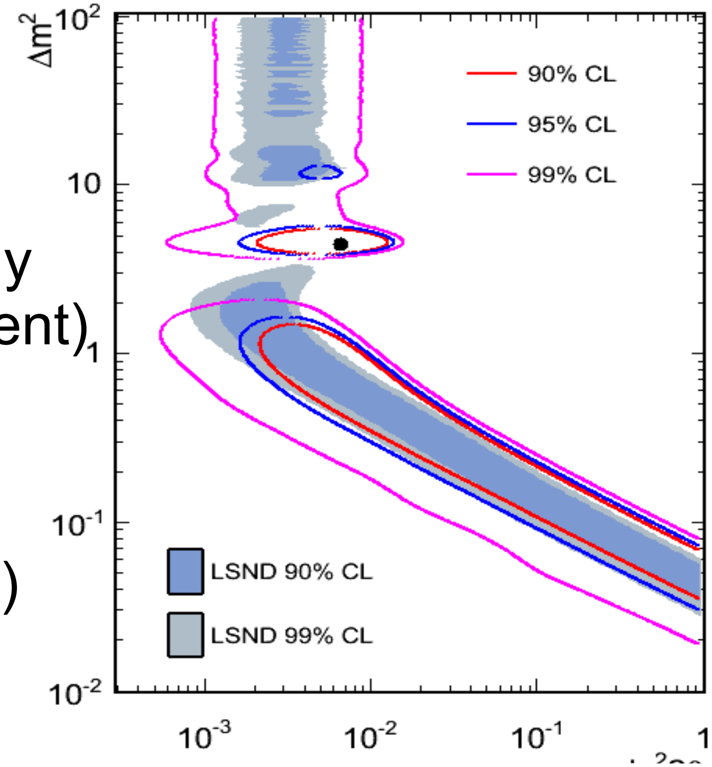


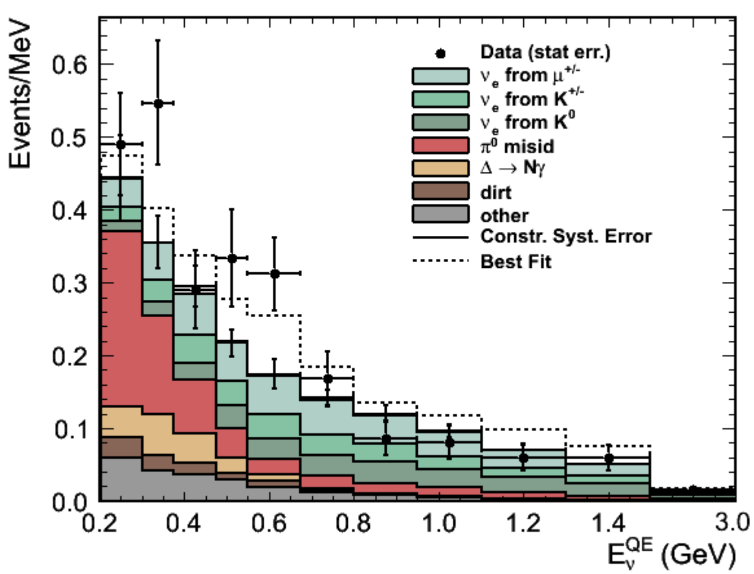
$\Delta\chi^2$ vs Δm^2

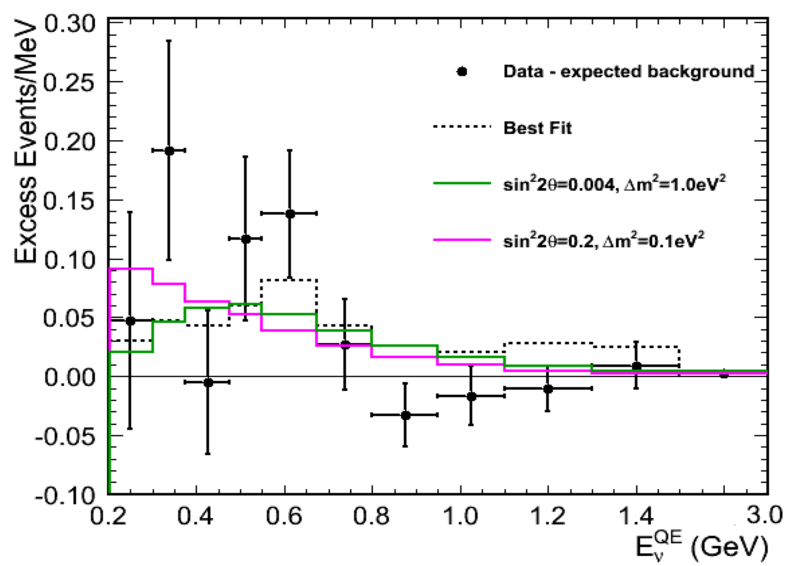


E>200MeV

- 5.66E20 POT
- Oscillations favored over background only hypotheses at 99.6% CL (model dependent)
- No assumption made about low energy excess
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.0066, 4.42 eV^2) χ^2/NDF = 11.6/7; Prob.=10.9%



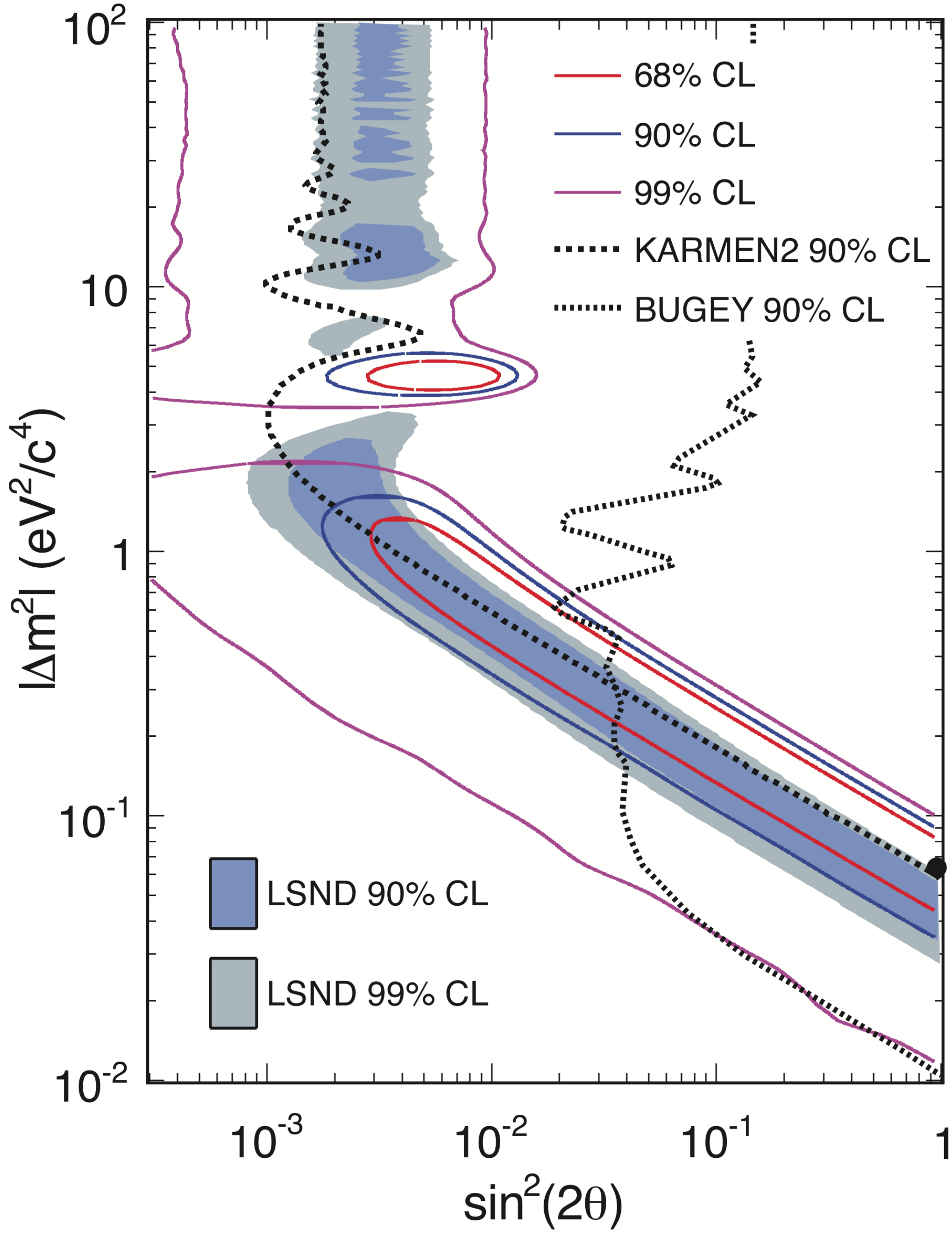




MiniBooNE Oscillation Fit

E>475 MeV

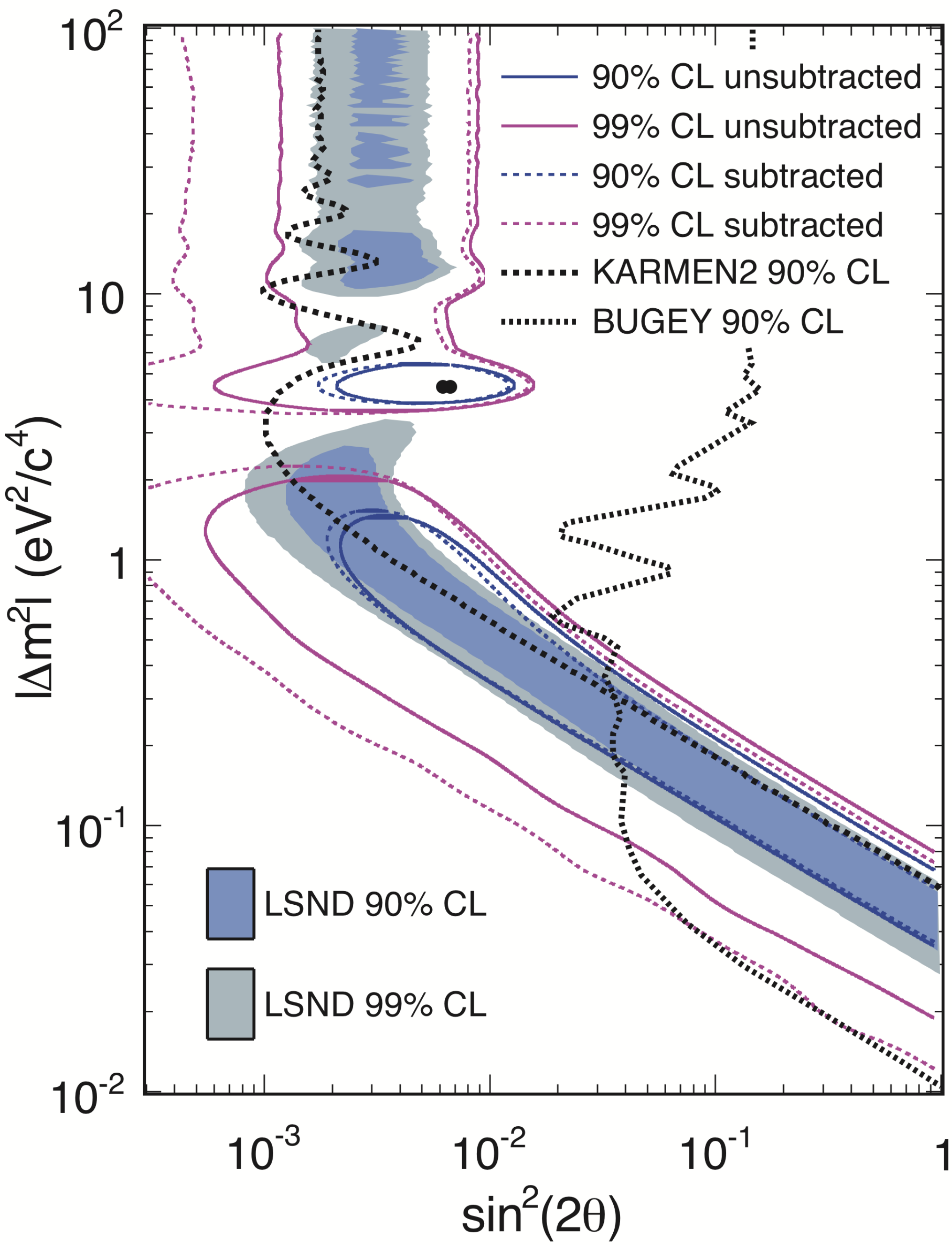
$\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed



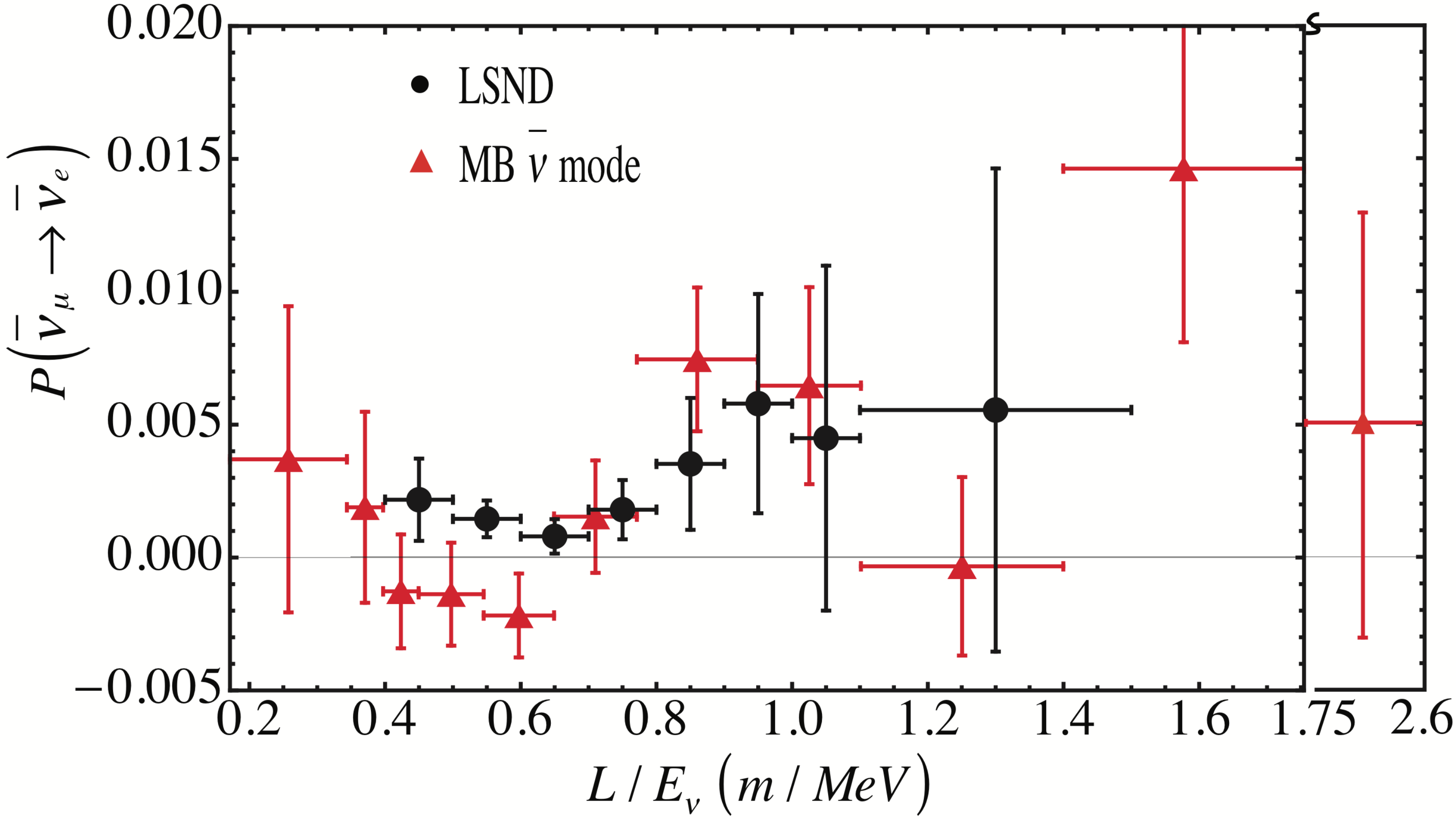
MiniBooNE Oscillation Fit

E>200 MeV

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed

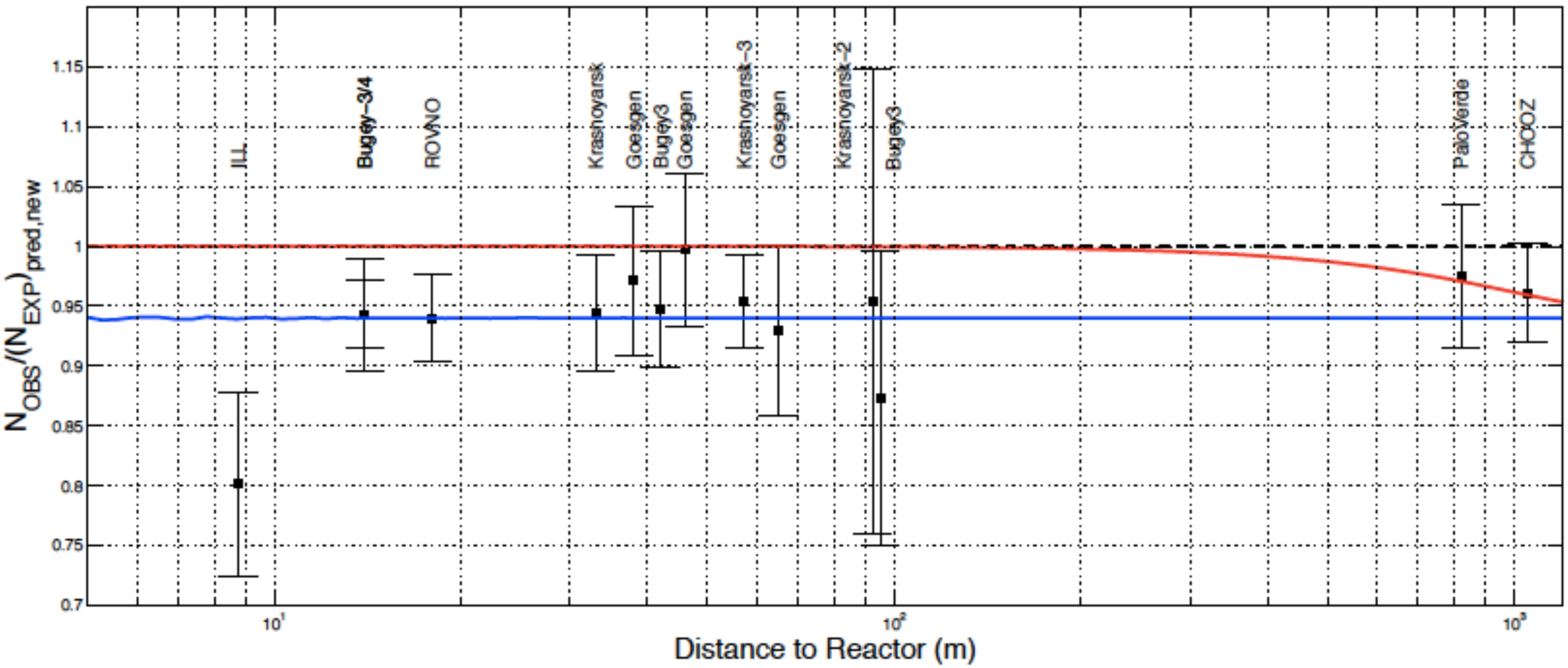


LSND & MiniBooNE Data



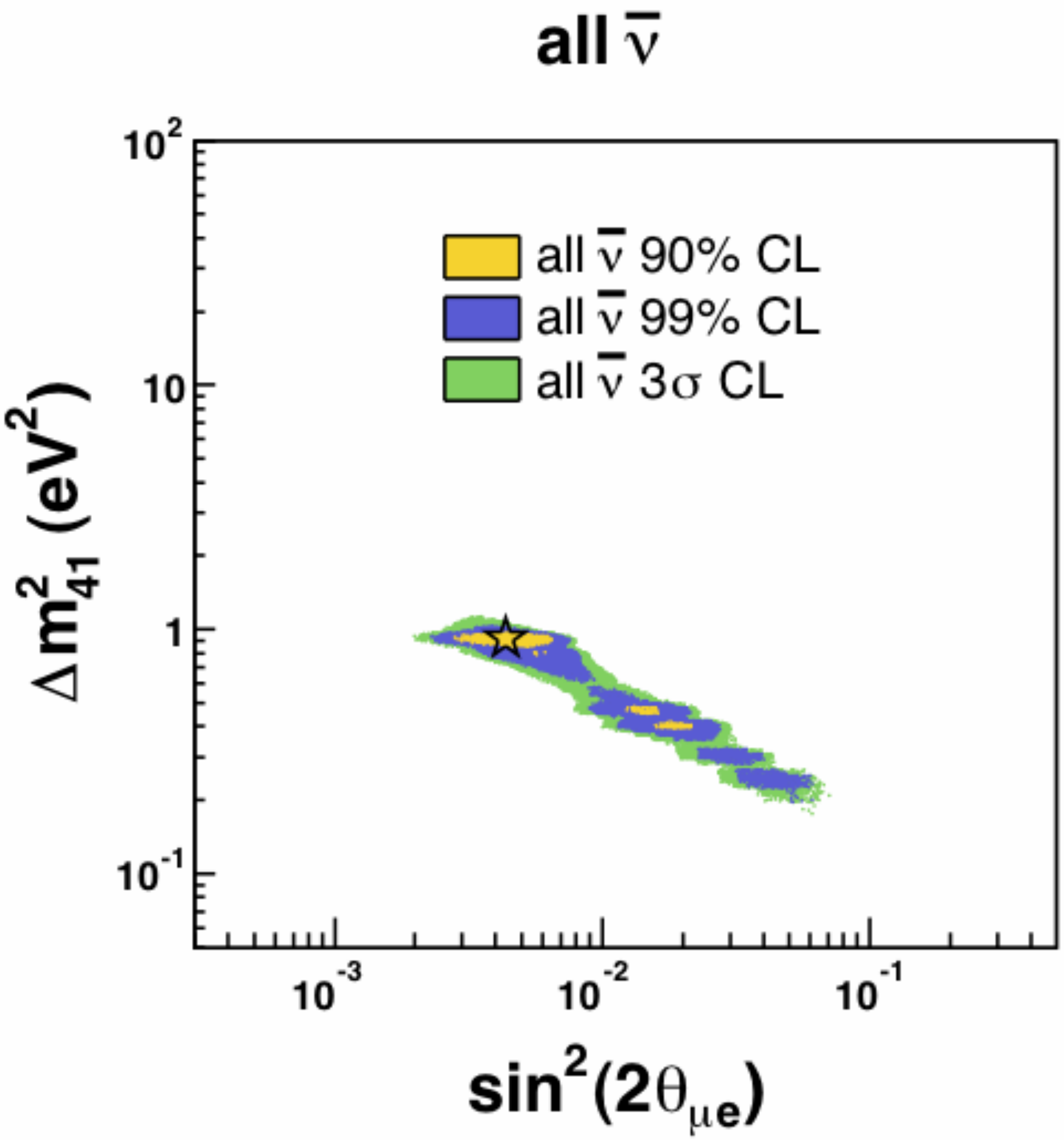
Reactor Neutrino Anomaly?

arXiv: 1101.2755



Reactor neutrino data consistent with oscillations to sterile neutrinos.

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

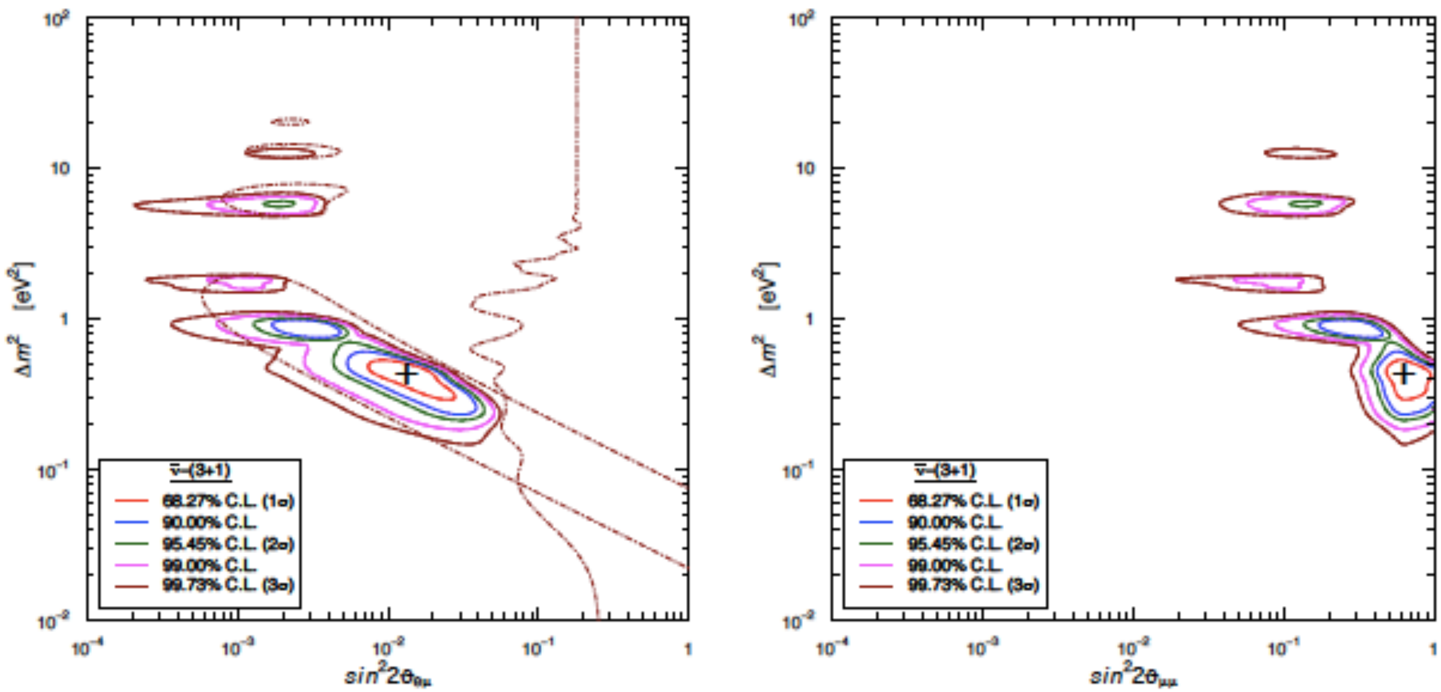


Updated from G. Karagiorgi et al., PRD80, 073001 (2009)

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

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

Antineutrino Oscillations in 3+1 Schemes



$\chi^2_{\rm min} = 77.5$ NdF $= 82$ GoF $= 62\%$

$\Delta m^2 = 0.43\,{\rm eV}^2$ $\sin^2 2\vartheta_{e\mu} = 0.013$

$\sin^2 2\vartheta_{ee} = 0.017$ $\sin^2 2\vartheta_{\mu\mu} = 0.63$

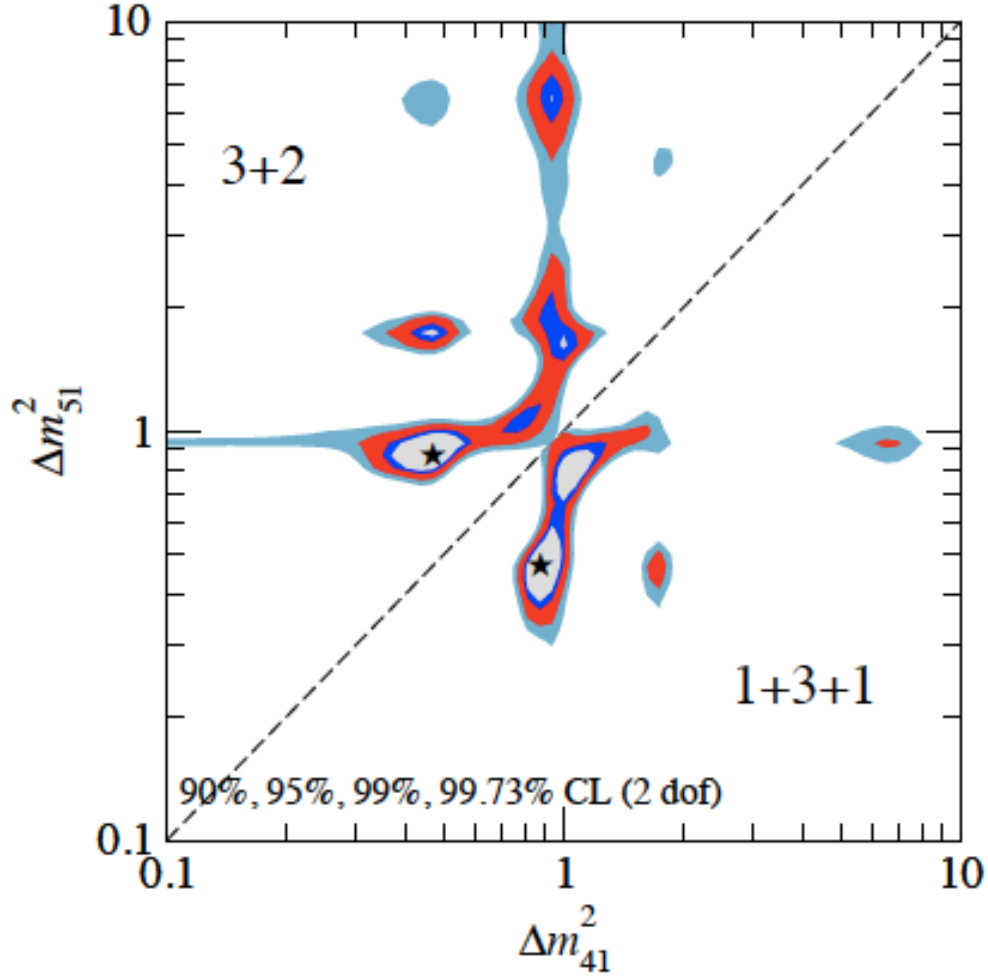
Prediction: large SBL $\bar{\nu}_\mu$ disappearance at $0.1 \lesssim \Delta m^2 \lesssim 1\,{\rm eV}^2$

arXiv:1012.0267

Global 3+2 Fit to World Neutrino & Antineutrino Data

Kopp, Maltoni, & Schwetz, arXiv:1103.4570

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



However, in 3+2 models there is some tension between appearance and disappearance experiments.

3+N Models Requires Large $\bar{\nu}$ Disappearance!

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

Reactor Experiments: $P(\bar{\nu}_e \to \bar{\nu}_x) \sim 10\%$?

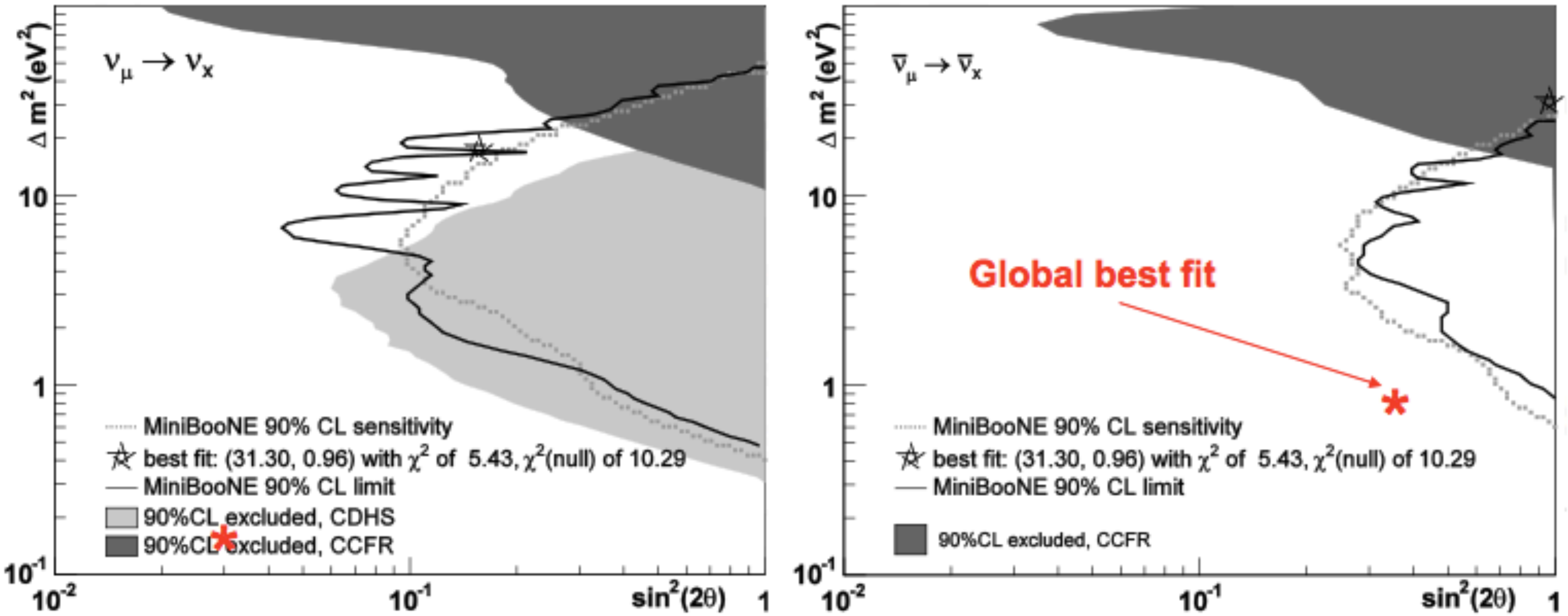
LSND/MiniBooNE: $P(\bar{\nu}_\mu \to \bar{\nu}_e) \sim 0.25\%$

Therefore: **$P(\bar{\nu}_\mu \to \bar{\nu}_x) > 10\%$**

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

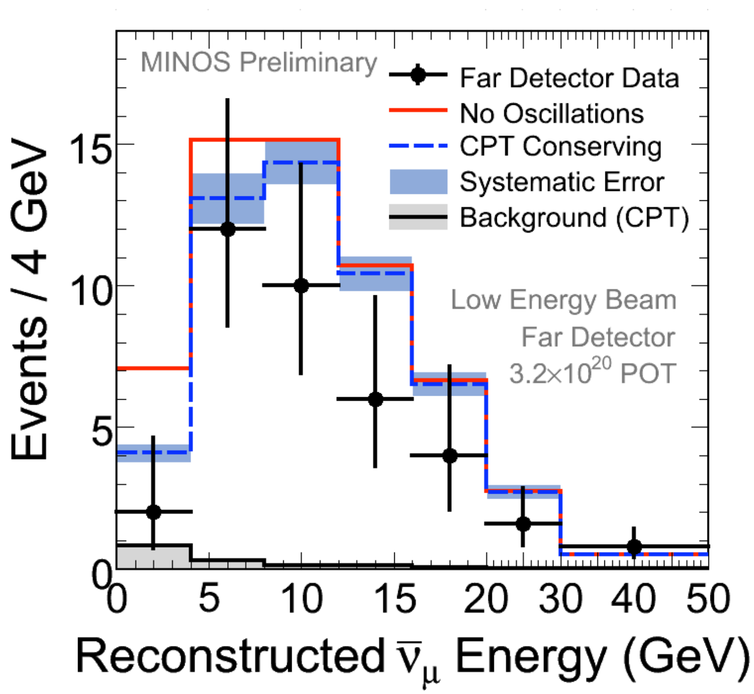
MiniBooNE Neutrino & Antineutrino Disappearance Limits

A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

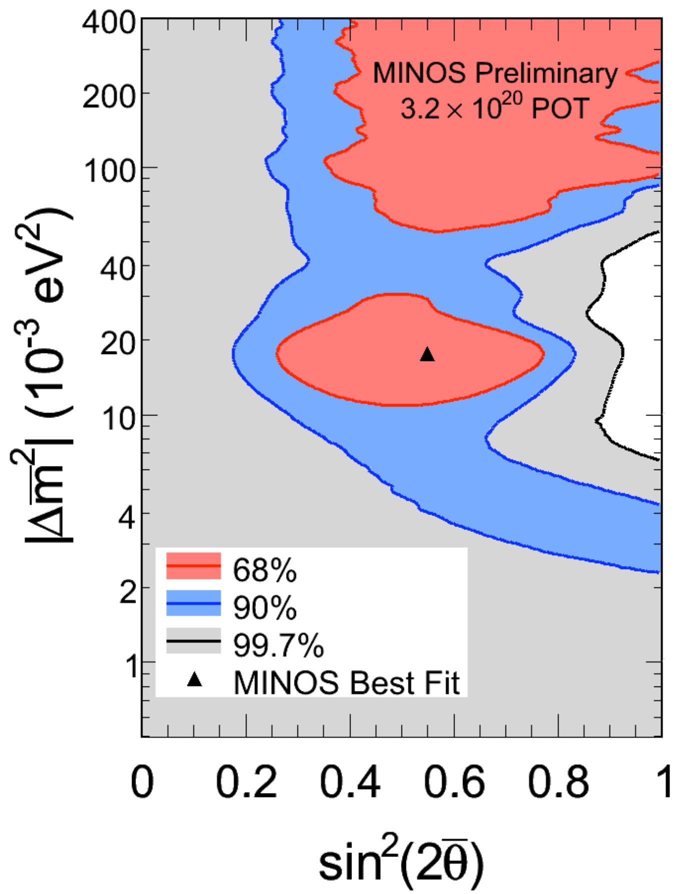


Improved results soon from MiniBooNE/SciBooNE Joint Analysis!

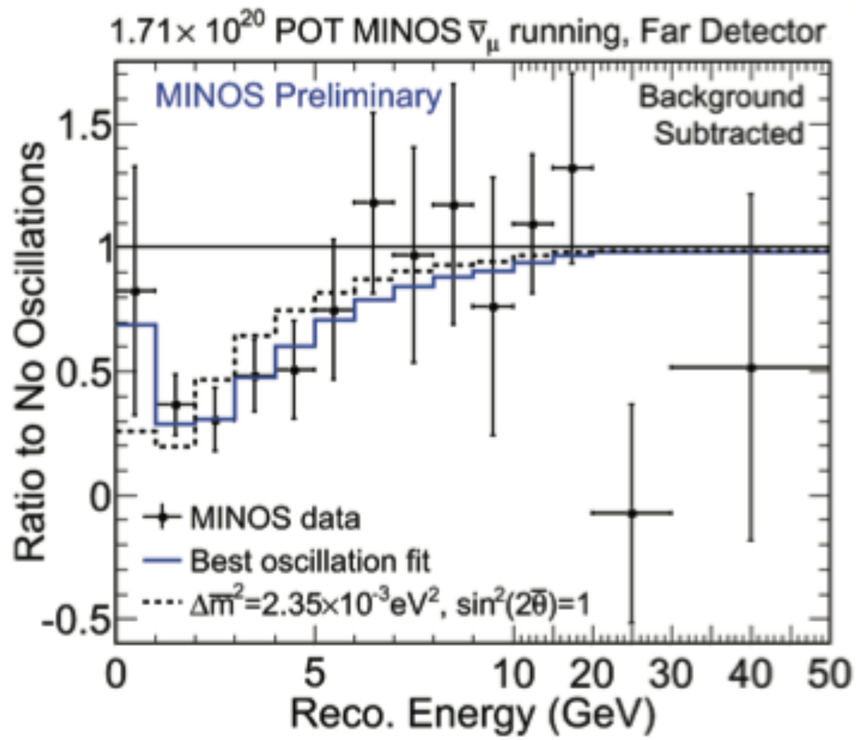
Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in ν Mode

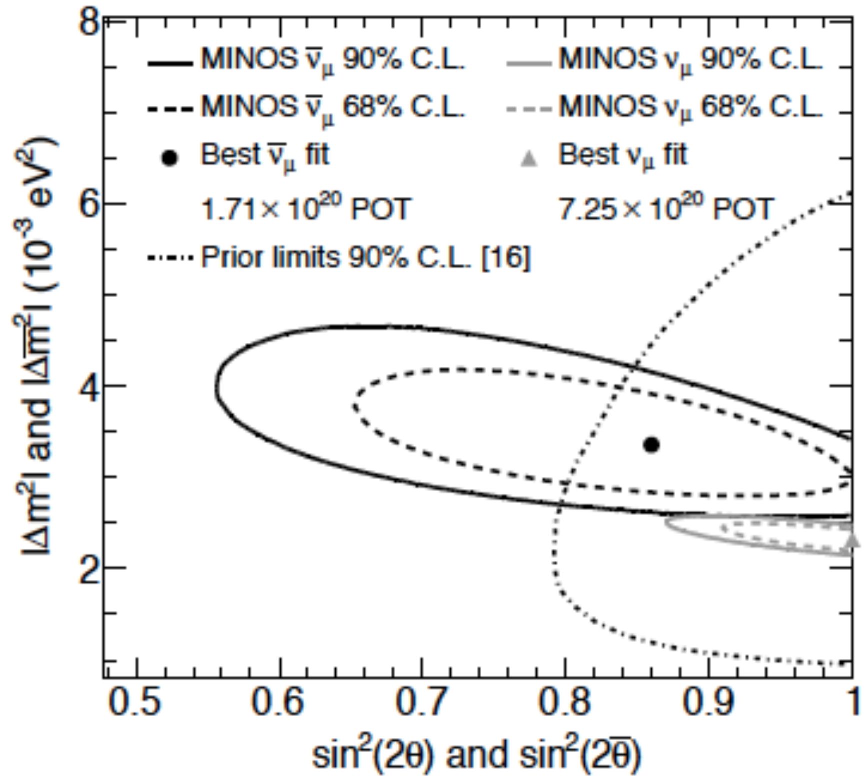


Expect $\bar{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.



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





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

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

IceCube Atmospheric Neutrino Angular Distribution

arXiv:1010.3980 (40 strings; 12 months of data)

IceCube covers the range of 0.001 < L/E < 100 m/MeV !

+ Matter Effects can enhance Oscillations

70% neutrino + 30% antineutrino

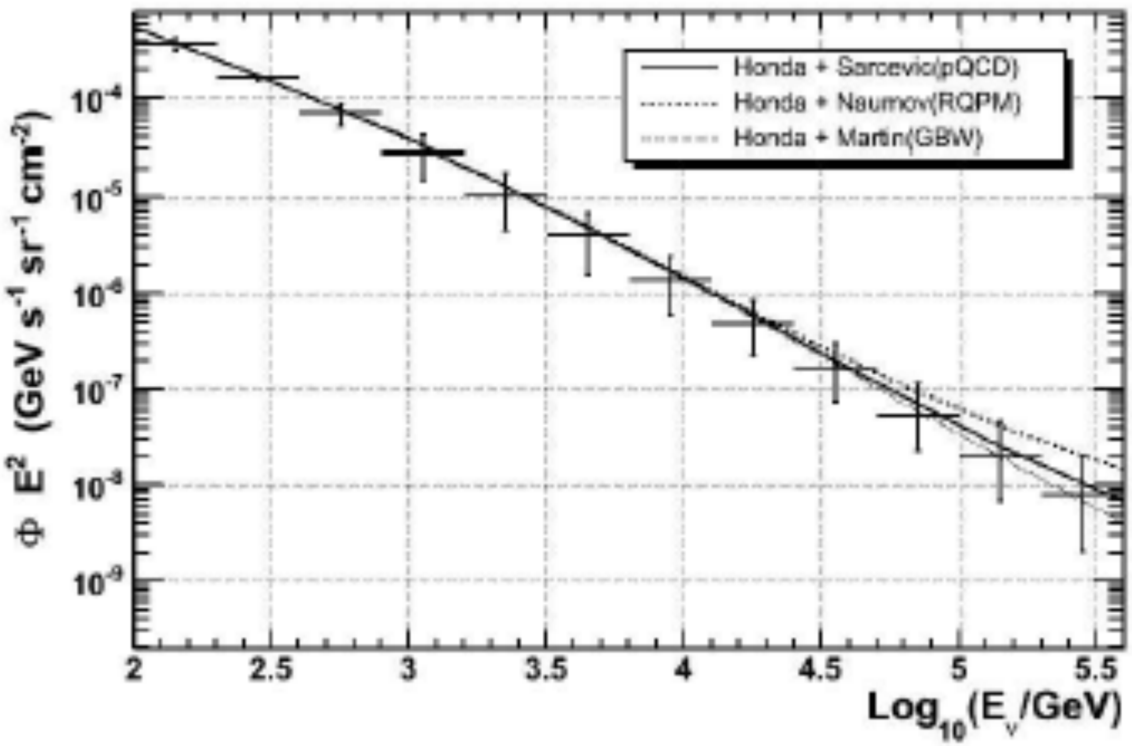


FIG. 24: Comparison of various prompt flux models to the unfolded result. The models shown are the sum of the Honda flux [2], plus one of Sarcevic [8], Naumov [10], or Martin [9].

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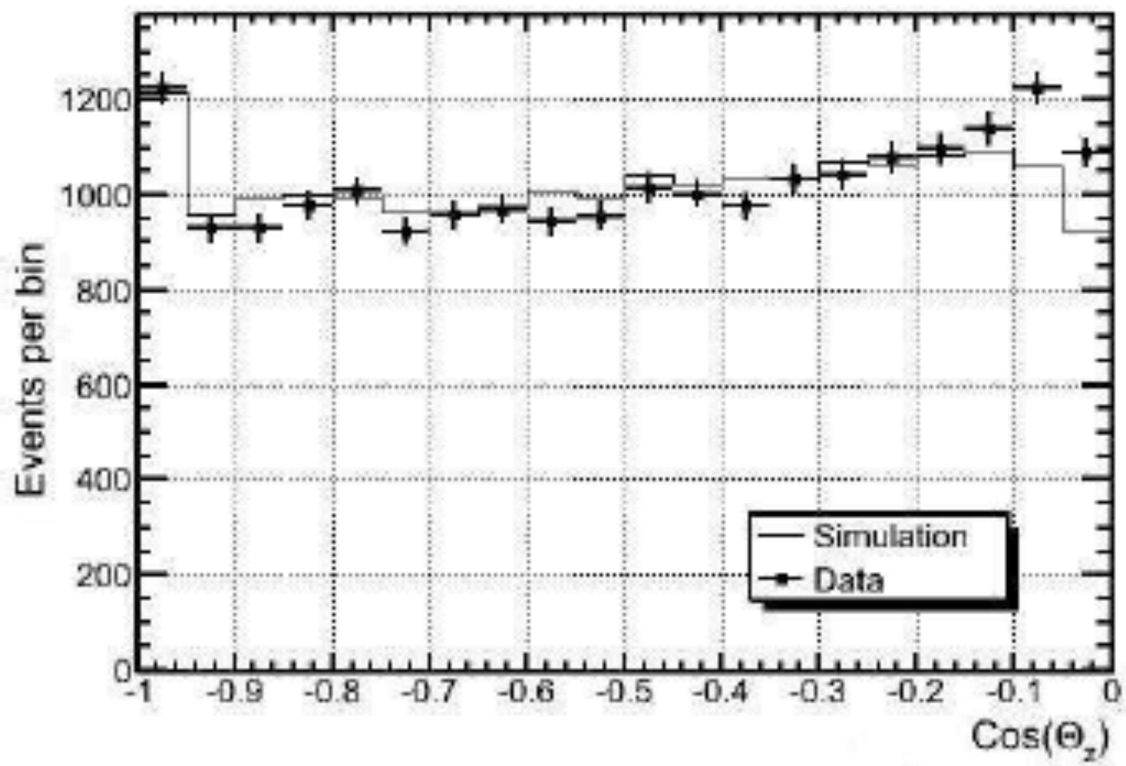
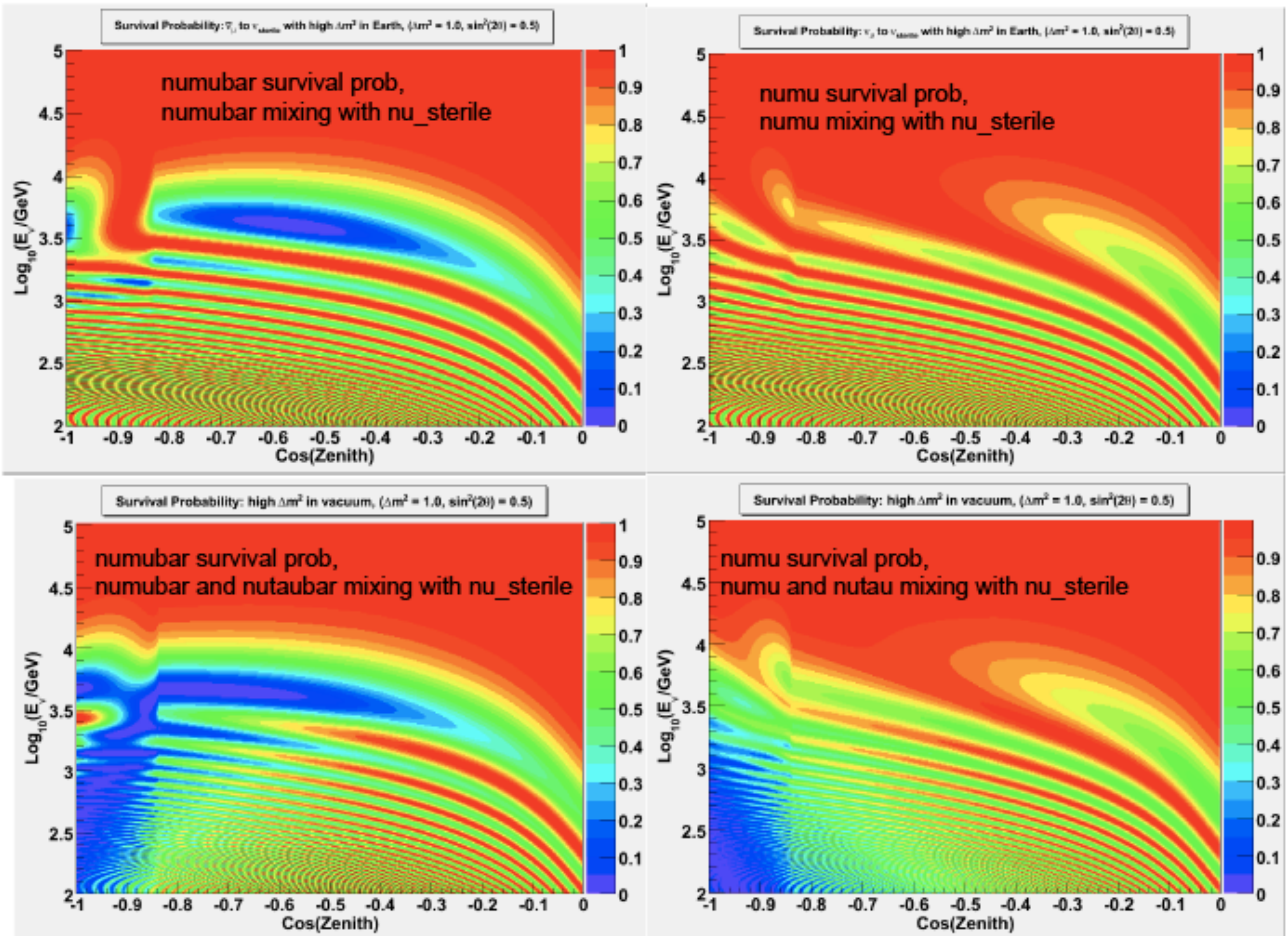


FIG. 19: Cosine(θ_Z) distributions for data and for simulation, using zenith angle from the MPE fit. Simulation has been normalized to the data. Error bars for data are statistical only.

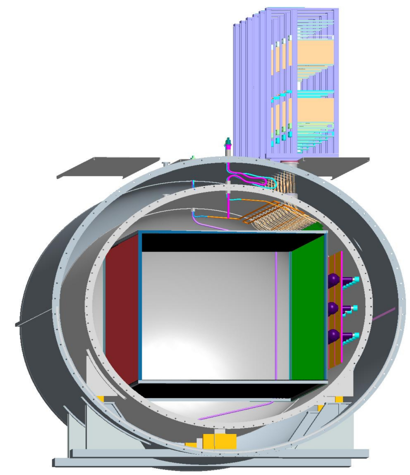
$\overline{\nu}_\mu$ & ν_μ Survival Probability in IceCube for Δm^2=1 eV^2, $\sin^2 2\theta$=0.5

(Warren Huelsnitz)



Future Experiments

- More MiniBooNE $\bar{\nu}$ Data (15E20 POT)
- MicroBooNE
  - Address low energy excess
- NOvA: 2 near detectors?
- LBNE: Look at high energy!
- Few ideas under consideration:
  - Build a MiniBooNE like detector (or a 2nd MicroBooNE detector at 200m) (LOI arXiv:0910.2698)
  - A new search for anomalous neutrino oscillations at the CERN-PS (arxiv:0909.0355v3)
  - Redoing a stopped pion source at ORNL (OscSNS - http://physics.calumet.purdue.edu/~oscsns/)



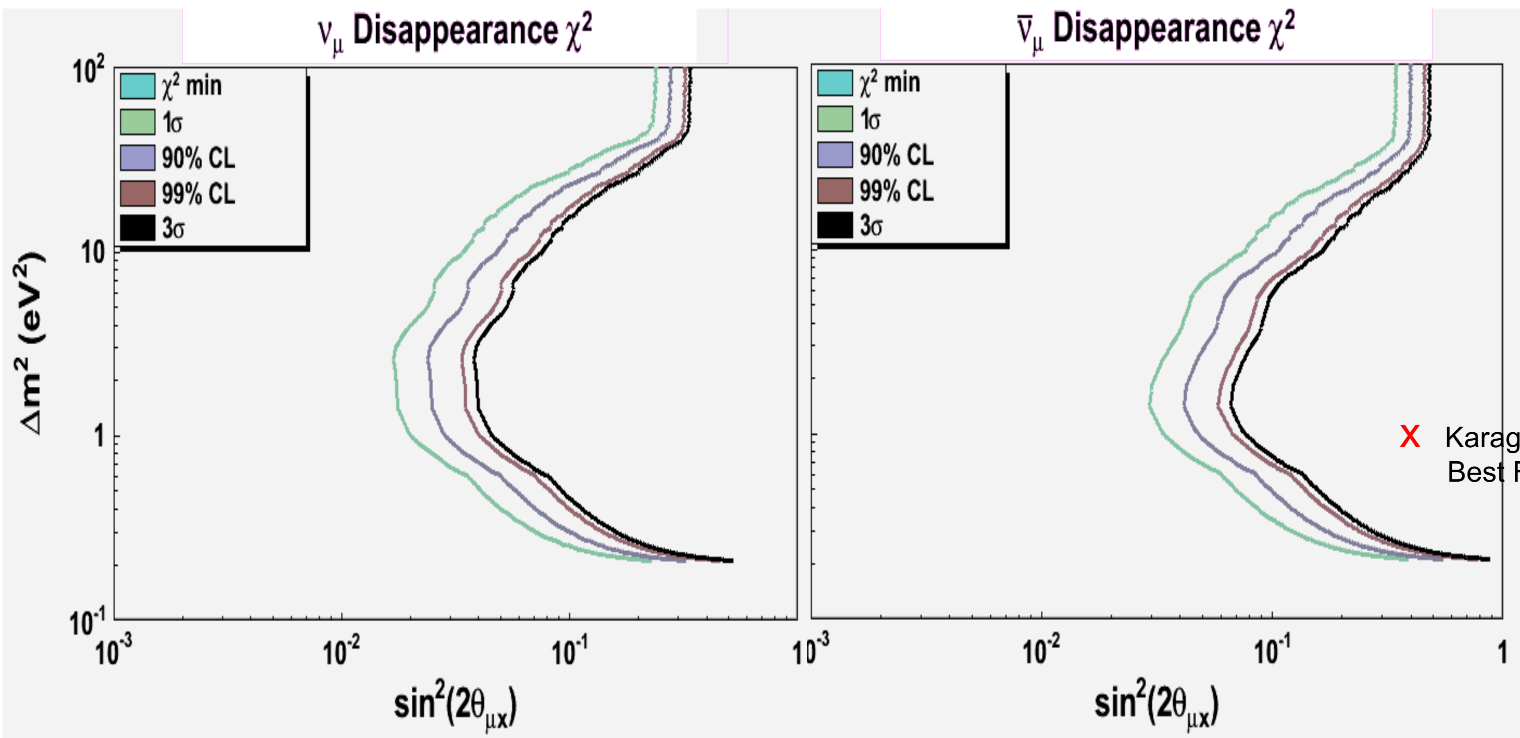
BooNE: Near Detector at ~200 m

BooNE

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

6.5e20 Far/1e20 Near POT

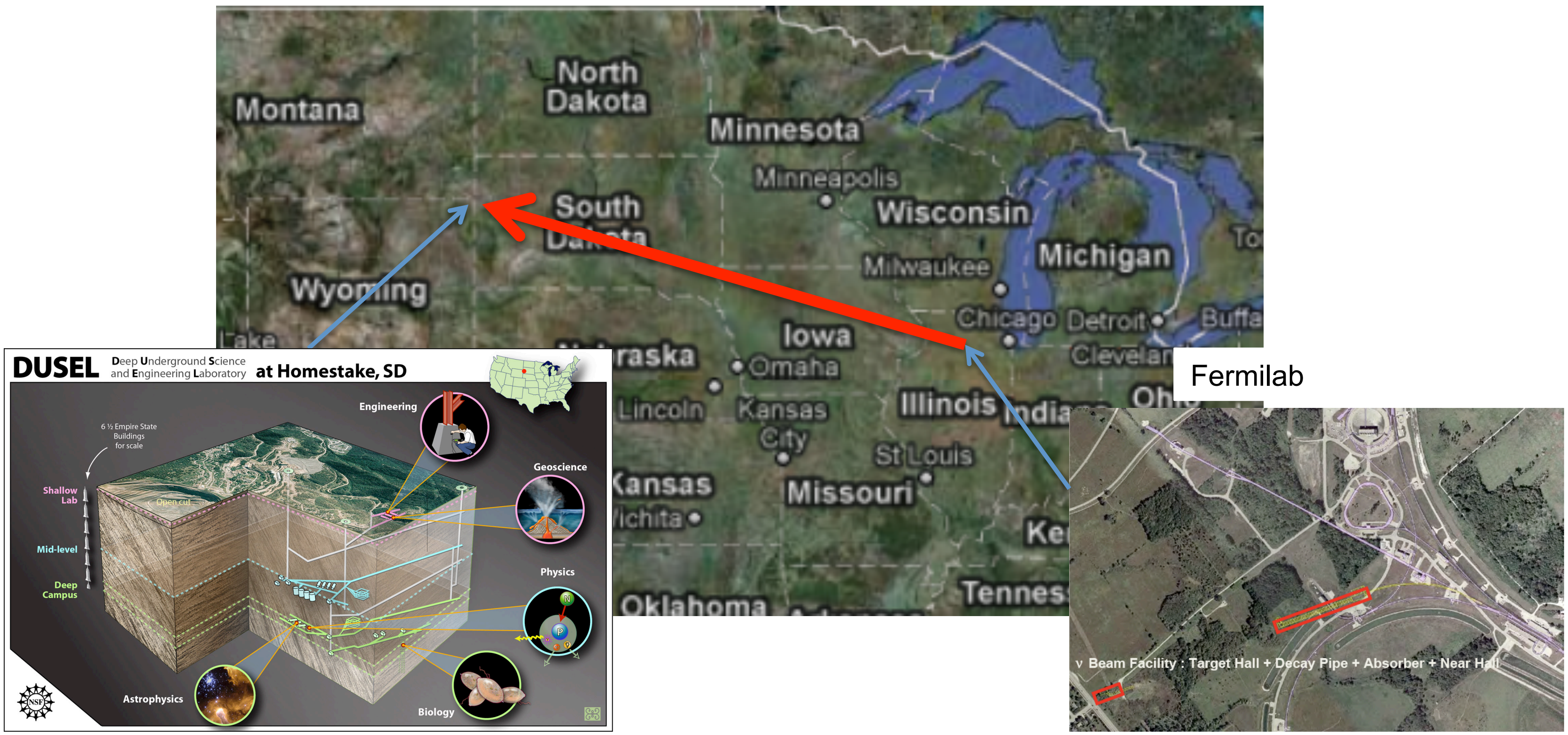
1e21 Far/1e20 Near POT



X Karagiorgi et al.
Best Fit

LBNE (~1300 km)

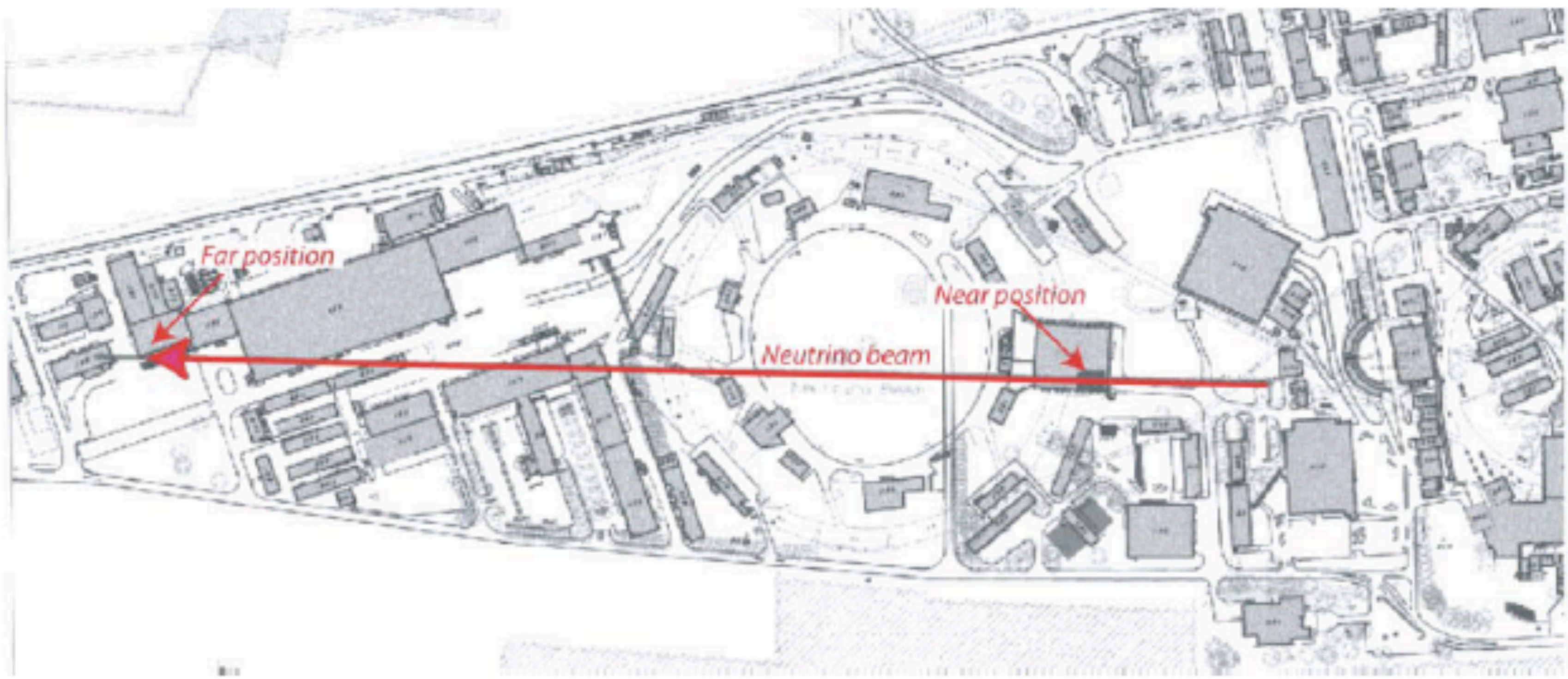
Low Energy (~2 GeV): $\Delta m^2 \sim 0.002\ eV^2$
High Energy (>10 GeV): $\Delta m^2 \sim 1\ eV^2$



ICARUS at the CERN PS

A new search for anomalous neutrino oscillations at the CERN-PS

B. Baibussinov[a], E. Calligarich[b] S. Centro[a], D. Gibin[a], A. Guglielmi[a],
F. Pietropaolo[a], C. Rubbia[c,*] and P. Sala[d]



ICARUS at the CERN PS

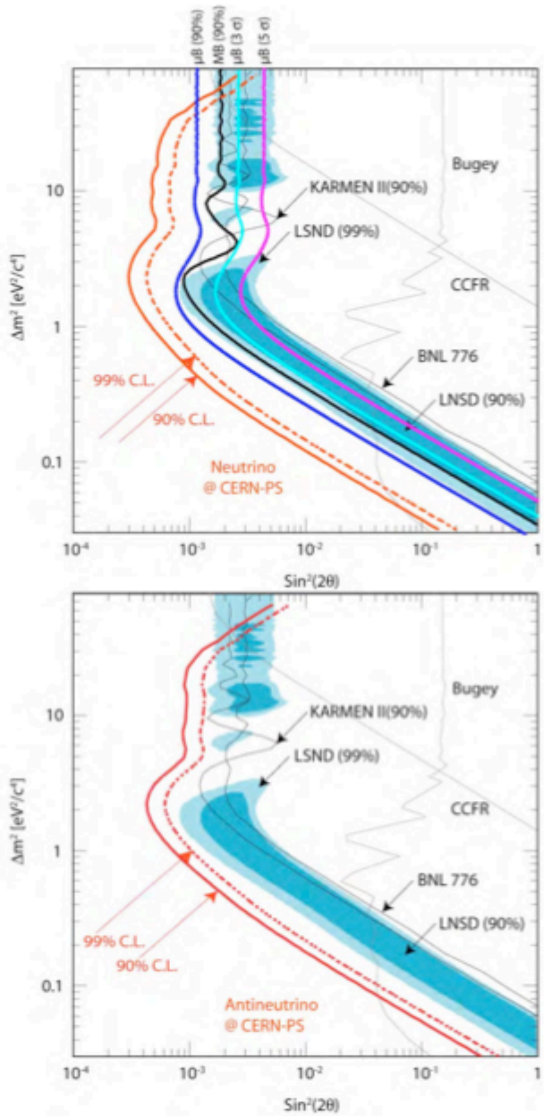


Figure 25. Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (top) and anti-neutrino (bottom) for 2.5 10^{20} pot and 5.0 10^{20} pot respectively. The LSND allowed region is fully explored in both cases.

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

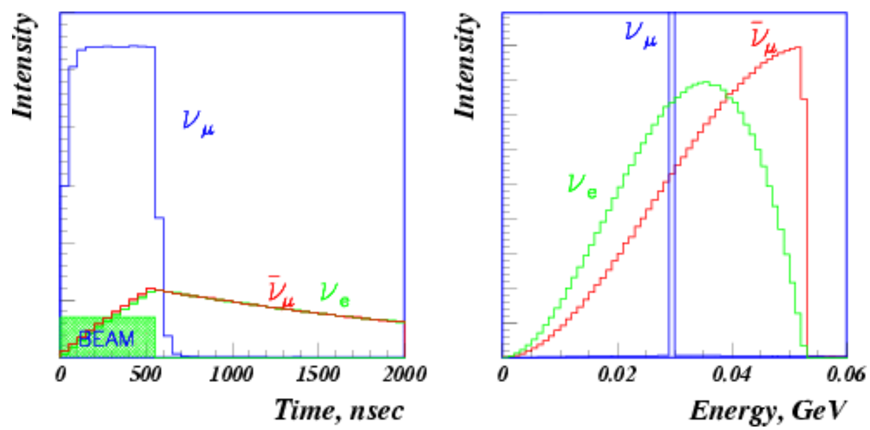
600 ton ICARUS at 850 m

150 ton LAr at 127 m

OscSNS

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

OscSNS



$\bar{\nu}_\mu \to \bar{\nu}_e$ $\Delta(L/E) \sim 3\%$; $\bar{\nu}_e\, p \to e^+ n$

$\nu_\mu \to \nu_e$ $\Delta(L/E) \sim 3\%$; $\nu_e\, C \to e^+ N_{gs}$

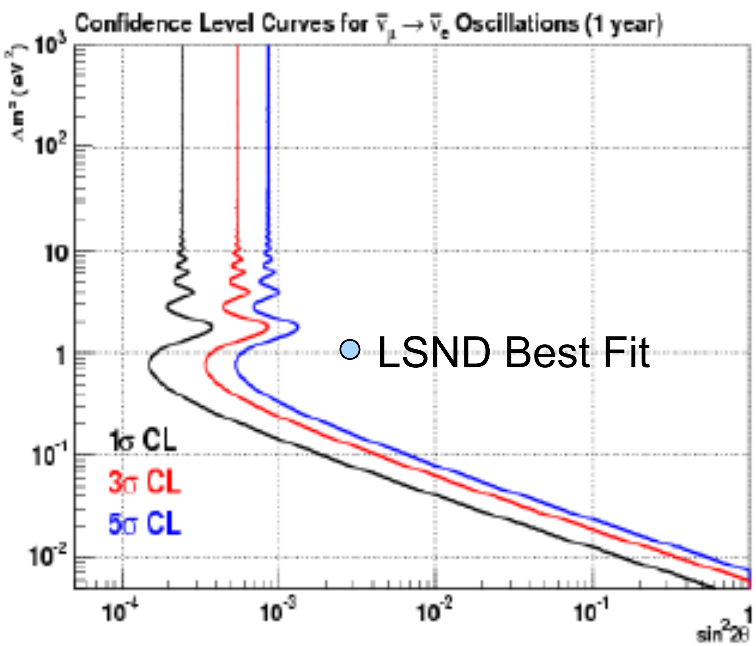
$\nu_\mu \to \nu_s$ $\Delta(L/E) < 1\%$; **Monoenergetic ν_μ** !; $\nu_\mu\, C \to \nu_\mu\, C^*(15.11)$

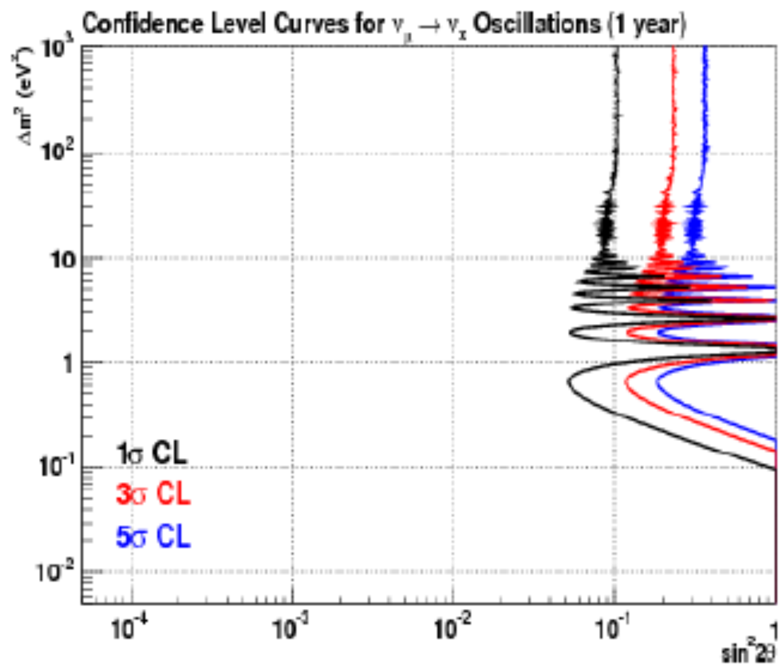
$\bar{\nu}_\mu \to \bar{\nu}_s$; $\bar{\nu}_\mu\, C \to \bar{\nu}_\mu\, C^*(15.11)$

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

OscSNS

- $\bar{\nu}_e$ appearance (left) and ν_μ disappearance sensitivity (right) for 1 year of running (for 60m)





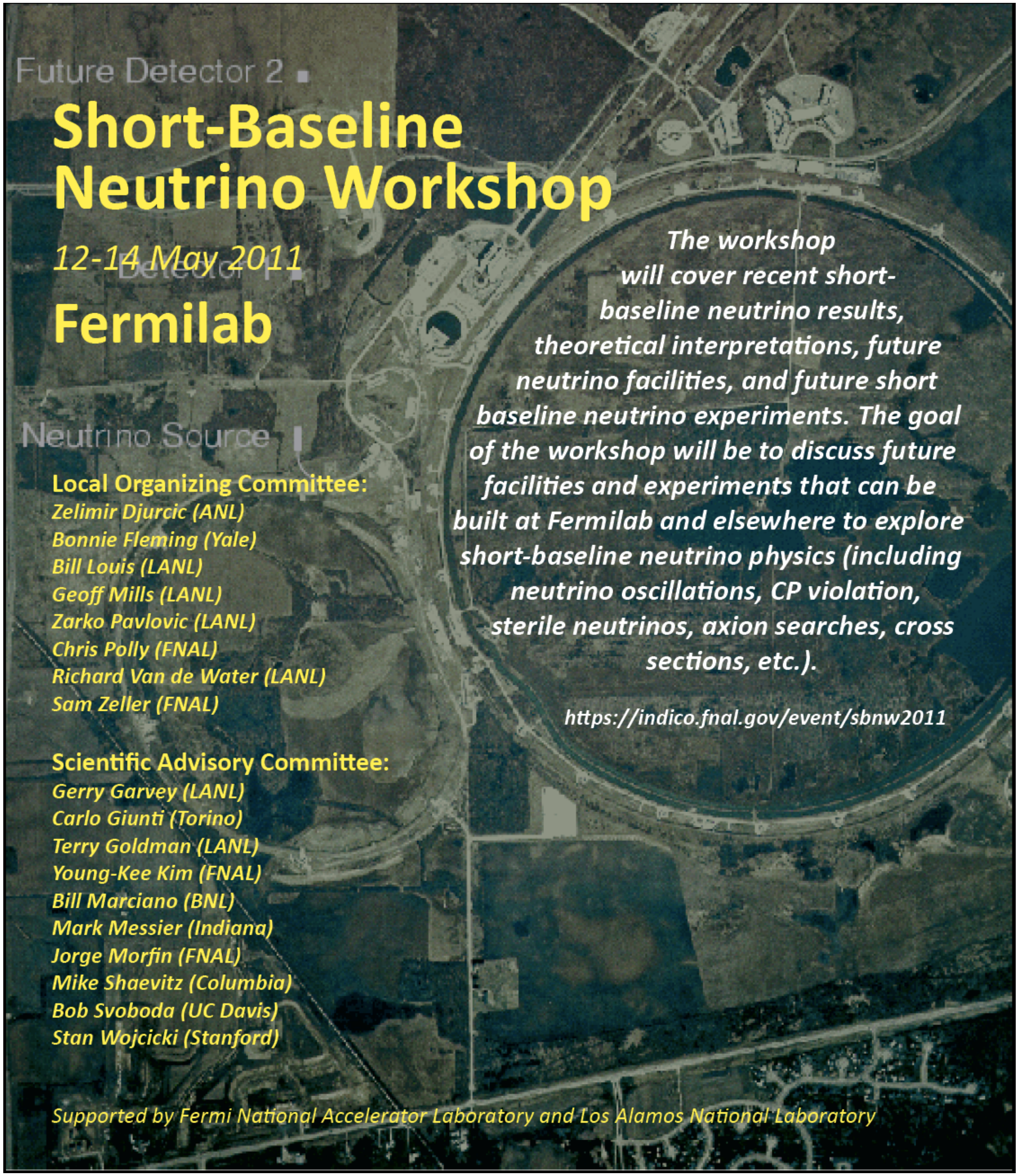
Conclusions

• The MiniBooNE data are consistent with $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillations at $\Delta m^2 \sim 1$ eV^2 and consistent with the evidence for antineutrino oscillations from LSND.

• The MiniBooNE $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillation allowed region appears to be different from the ν_μ -> ν_e oscillation allowed region. (CP Violation?)

• The world antineutrino data fit well to a 3+1 oscillation model with $\Delta m^2 \sim 1$ eV^2. This model predicts large $\bar{\nu}$ disappearance. (Other possibilities include, e.g., sterile ν decay and Lorentz Violation.)

• MINOS, IceCube, NOvA (two detectors), LBNE, BooNE at FNAL (two oil Detectors or two LAr detectors), ICARUS at CERN, or OscSNS at ORNL could measure neutrino oscillations with high significance (>5σ) and prove that sterile neutrinos exist!



Future Detector 2
Short-Baseline Neutrino Workshop
12-14 May 2011
Fermilab
Neutrino Source
Local Organizing Committee:
Zelimir Djurcic (ANL)
Bonnie Fleming (Yale)
Bill Louis (LANL)
Geoff Mills (LANL)
Zarko Pavlovic (LANL)
Chris Polly (FNAL)
Richard Van de Water (LANL)
Sam Zeller (FNAL)
Scientific Advisory Committee:
Gerry Garvey (LANL)
Carlo Giunti (Torino)
Terry Goldman (LANL)
Young-Kee Kim (FNAL)
Bill Marciano (BNL)
Mark Messier (Indiana)
Jorge Morfin (FNAL)
Mike Shaevitz (Columbia)
Bob Svoboda (UC Davis)
Stan Wojcicki (Stanford)
The workshop will cover recent short-baseline neutrino results, theoretical interpretations, future neutrino facilities, and future short baseline neutrino experiments. The goal of the workshop will be to discuss future facilities and experiments that can be built at Fermilab and elsewhere to explore short-baseline neutrino physics (including neutrino oscillations, CP violation, sterile neutrinos, axion searches, cross sections, etc.).
https://indico.fnal.gov/event/sbnw2011
Supported by Fermi National Accelerator Laboratory and Los Alamos National Laboratory

Backup

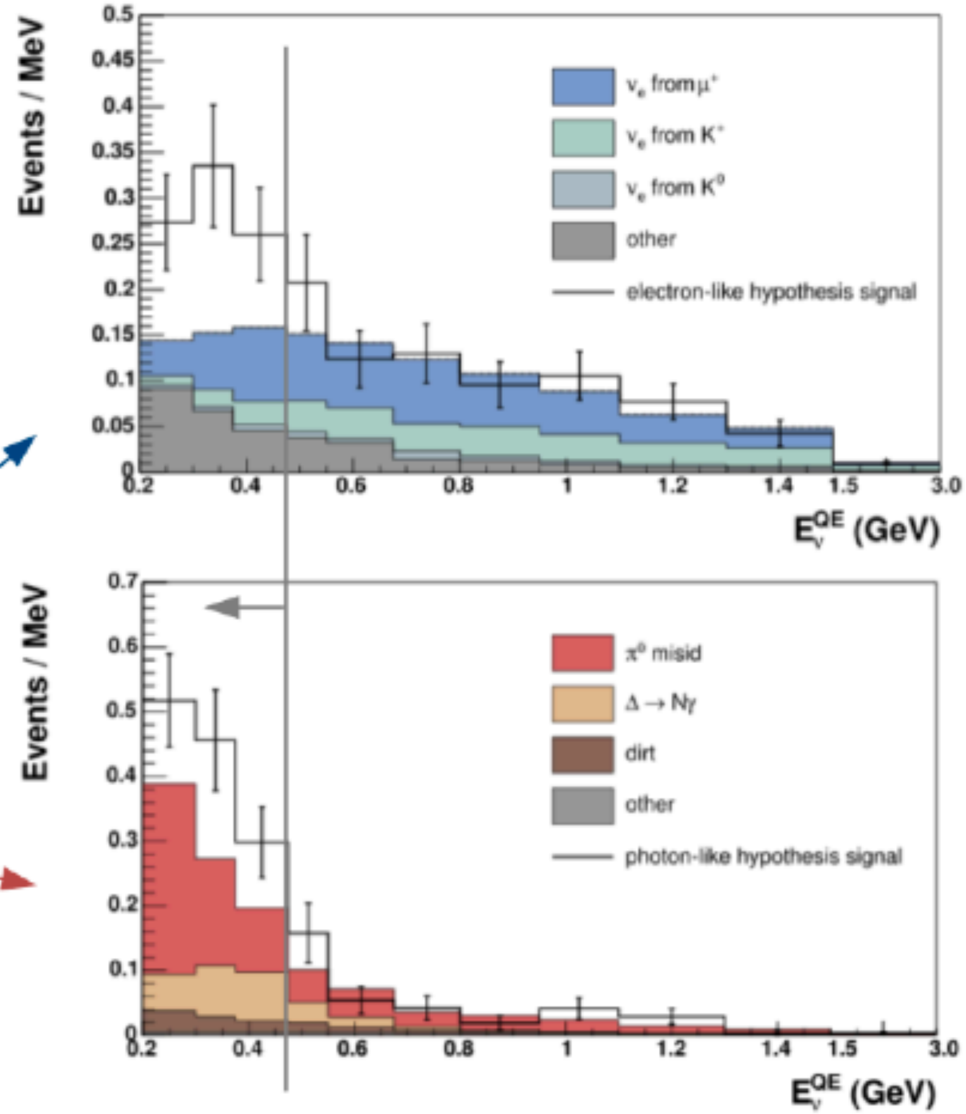
MicroBooNE

MicroBooNE sensitivity to low energy excess:

(neutrino running,
70 ton fiducial volume,
x2 higher PID efficiency than MiniBooNE,
3% mis-ID,
6.0e20 POT)

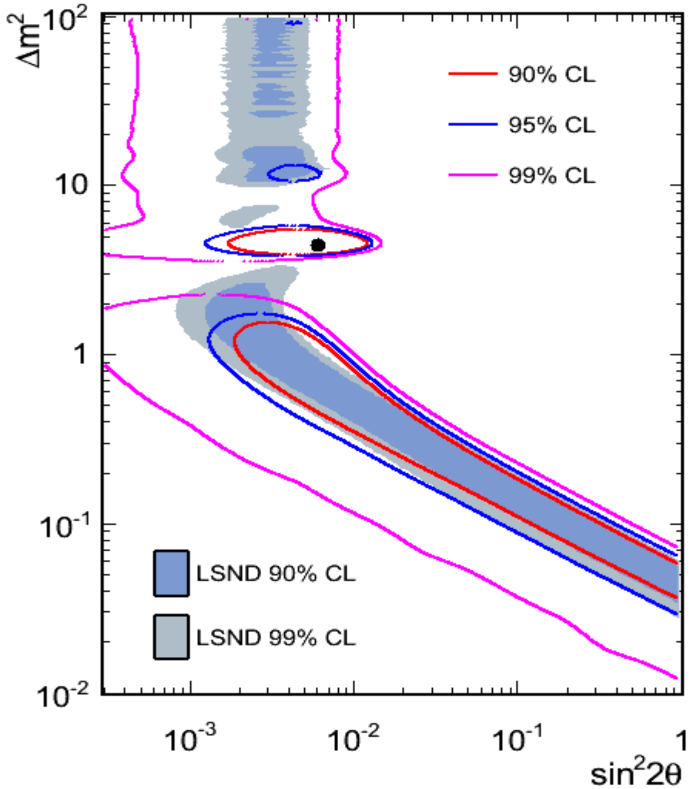
Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7σ stat. significance

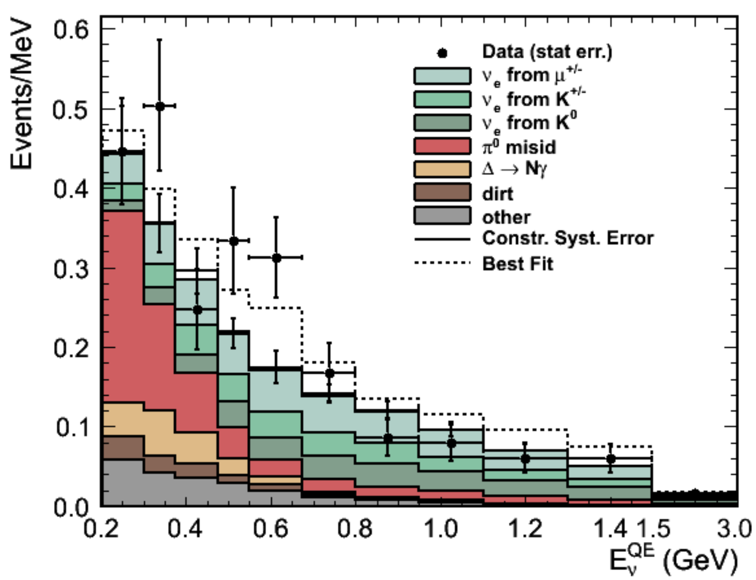
Photon-like hypothesis:
36.8 excess events
78.9 background events
4.1σ stat. significance

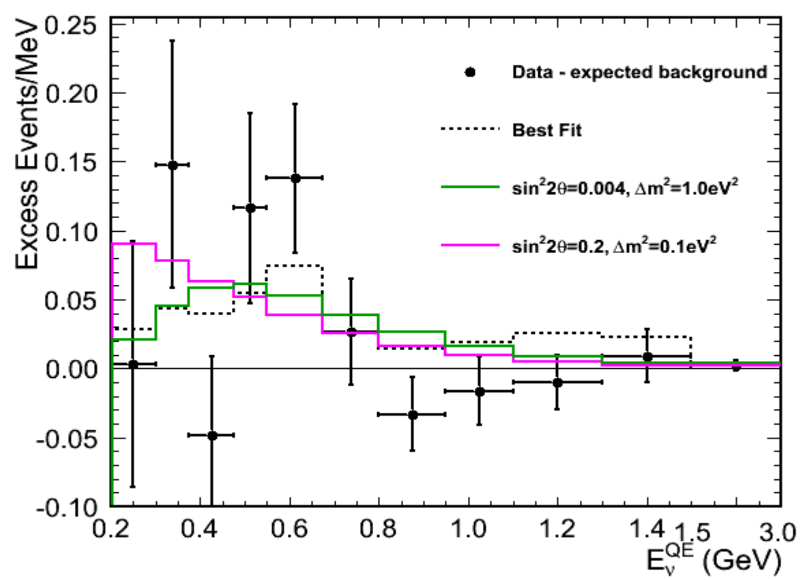


E>200MeV

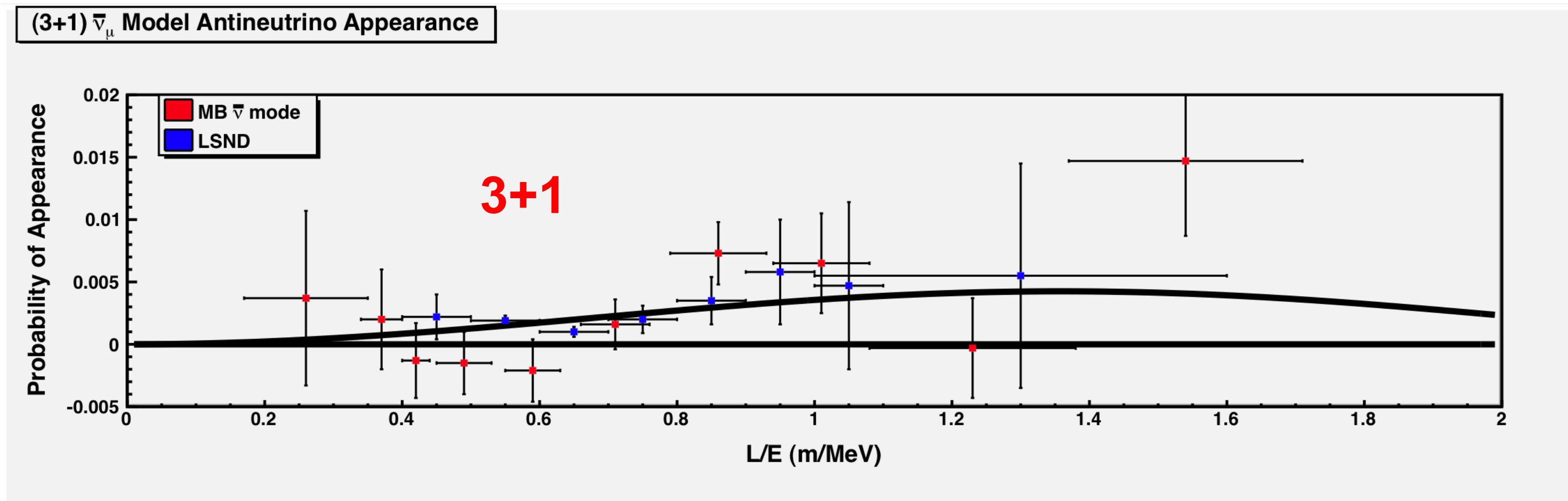
- Subtract excess produced by neutrinos in $\bar{\nu}$ mode (11.6 events)
- Best fit $(\sin^2 2\theta, \Delta m^2) = (0.0061, 4.42\ eV^2)$ $\chi^2/NDF = 12.6/7$; Prob.=7.5%

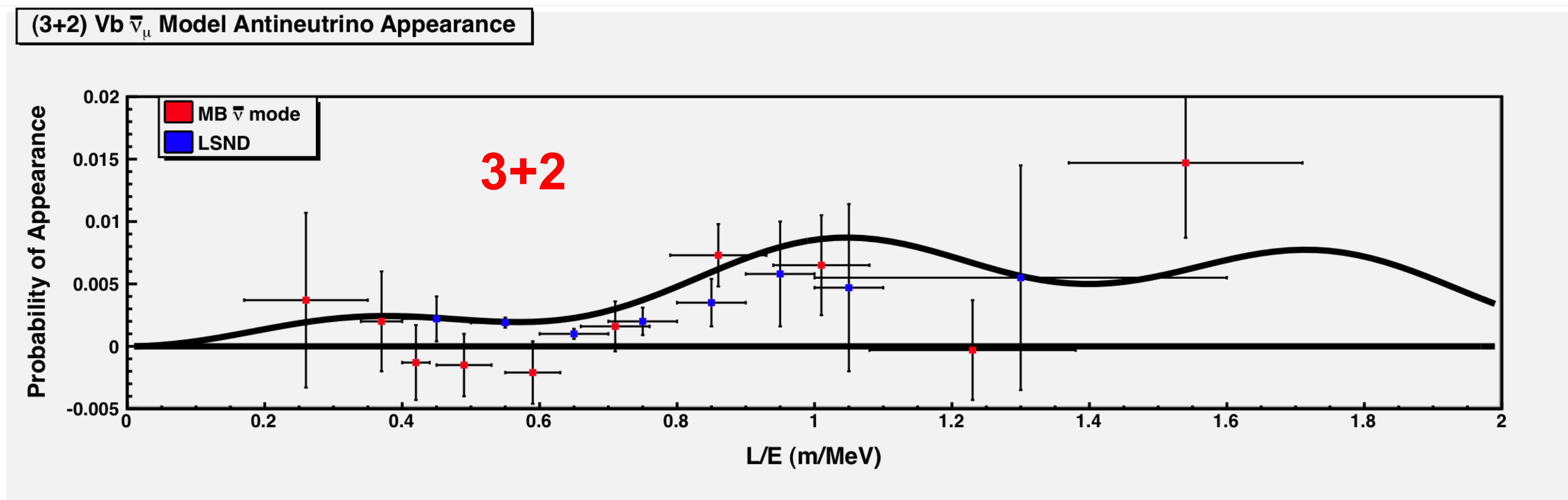




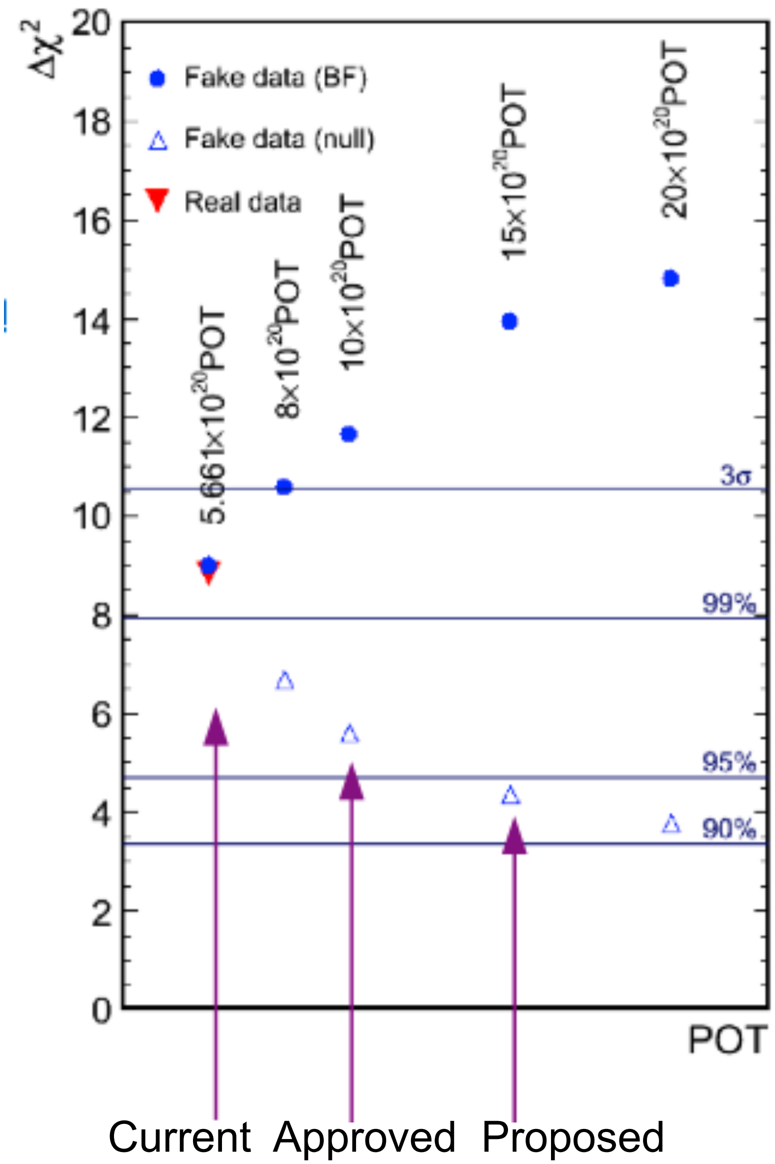


LSND/MiniBooNE Data Compared to 3+N Global Fits

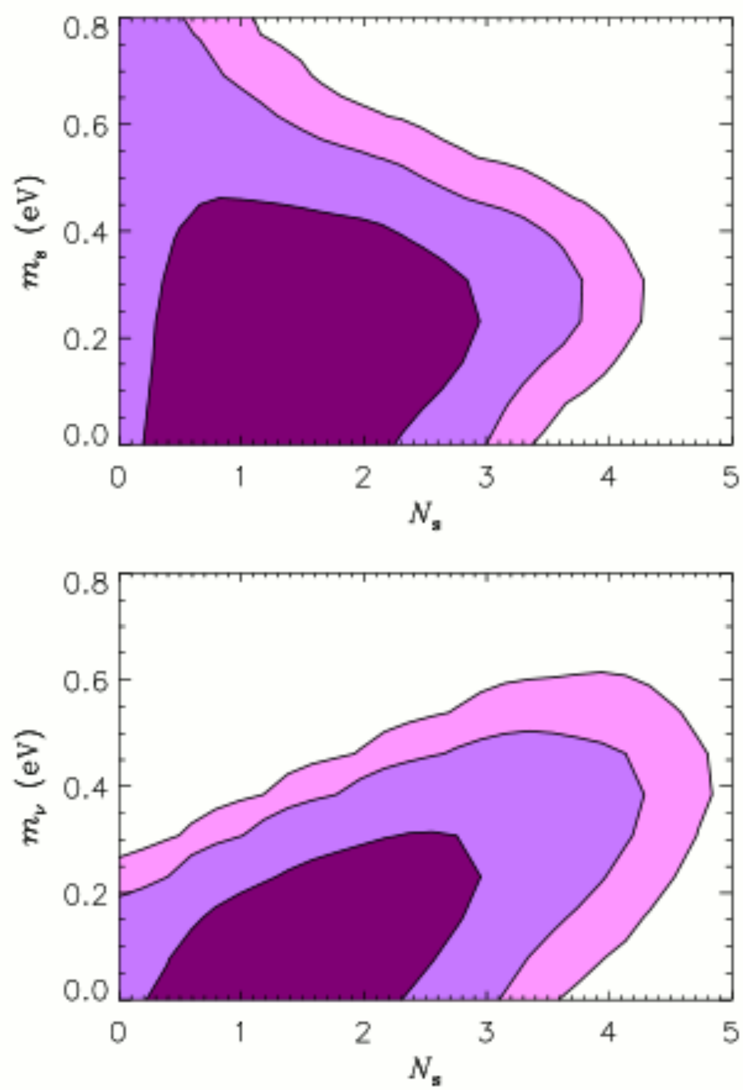




More MiniBooNE Antineutrino Running



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



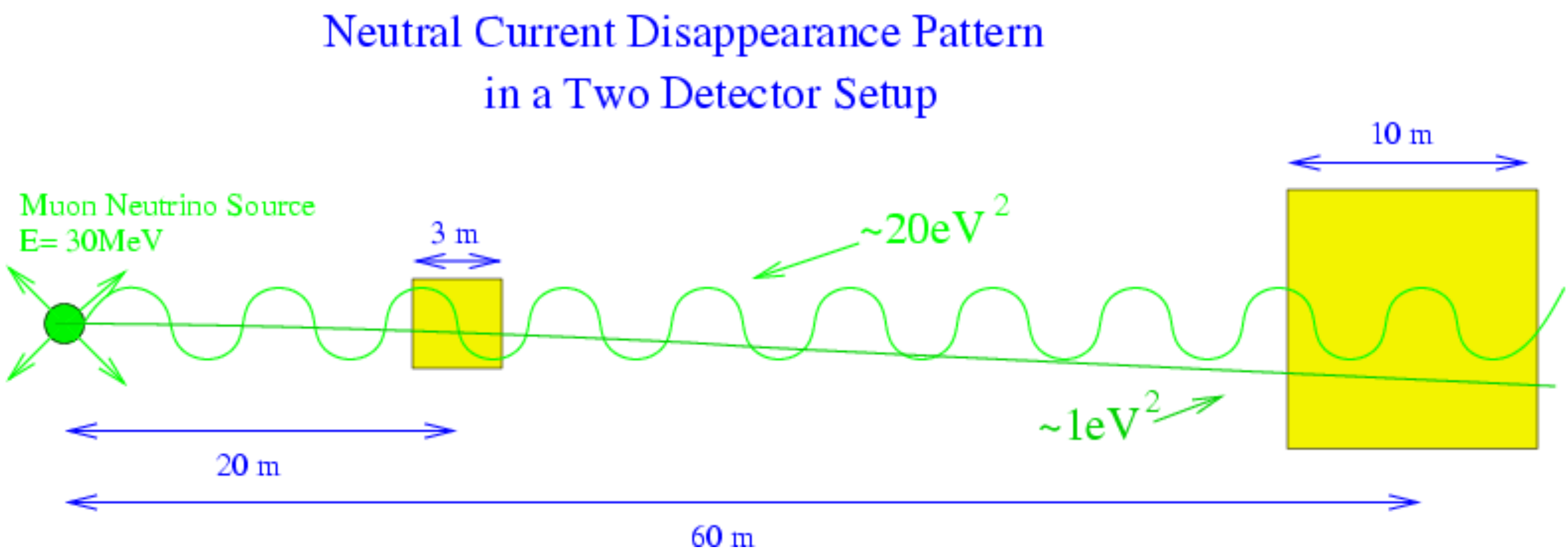
$3 + N_s$
$m_\nu = 0$

$3 + N_s$
$m_s = 0$

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

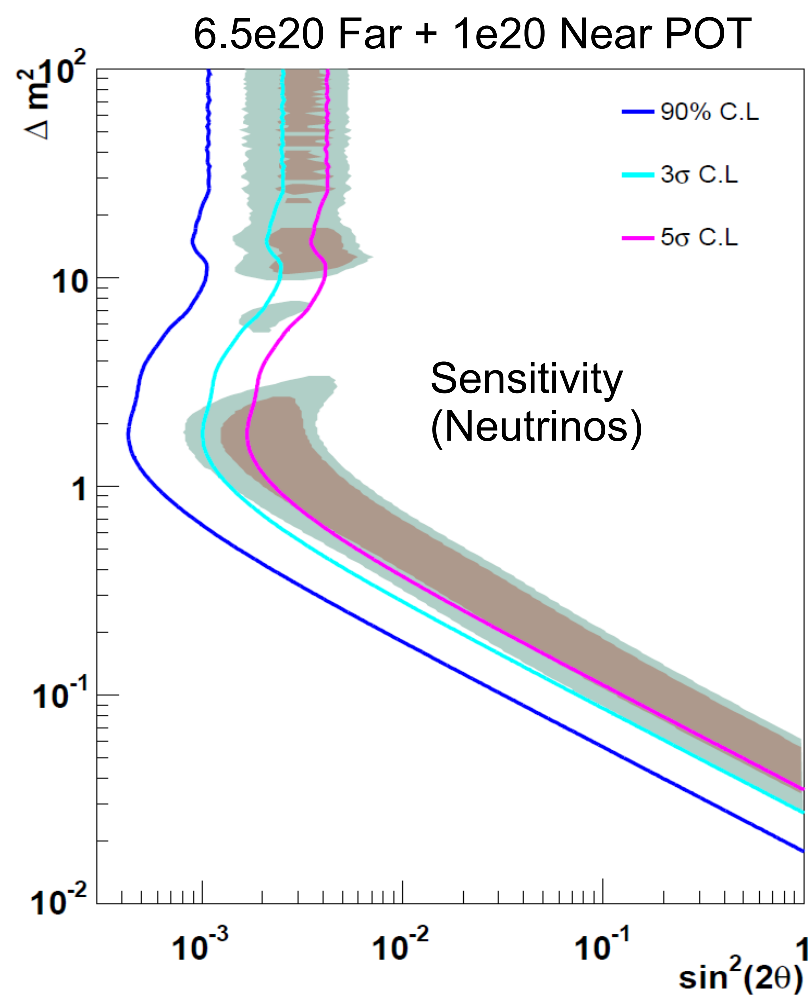
ν_μ C -> ν_μ C*(15.11)

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



BooNE

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and CP violation



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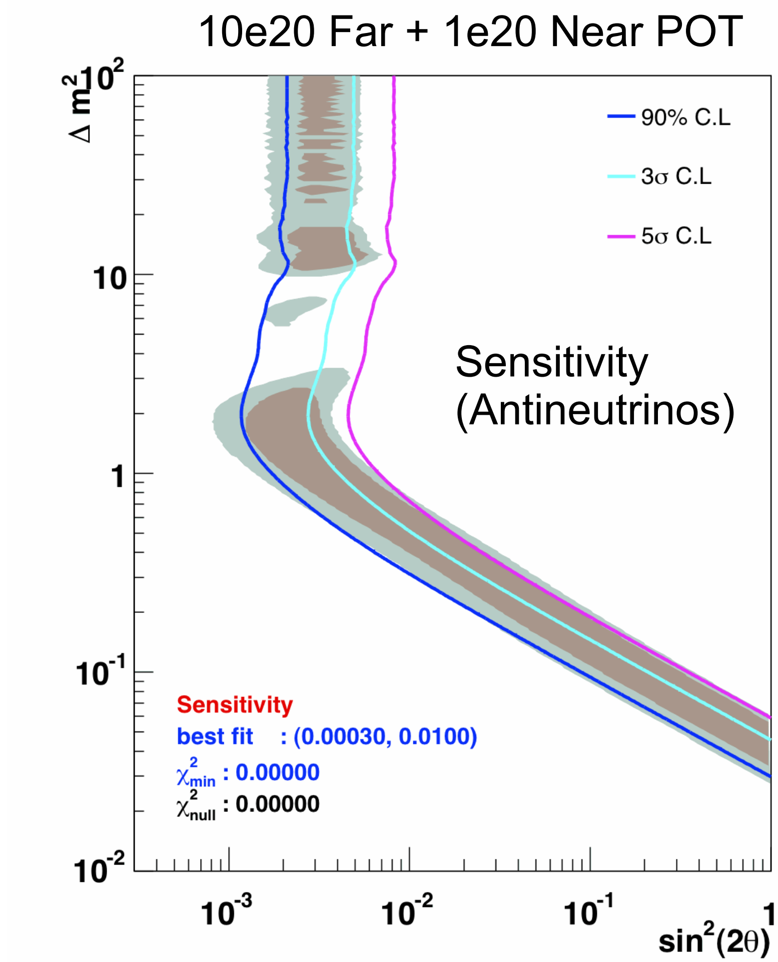
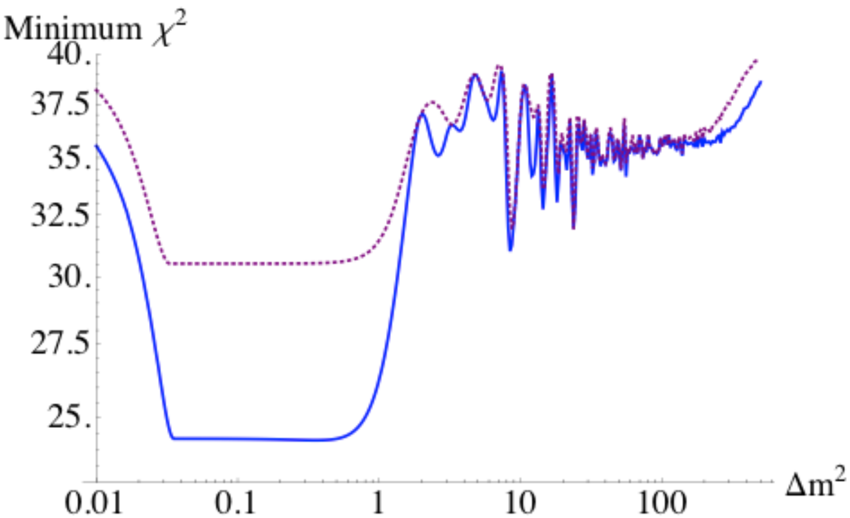
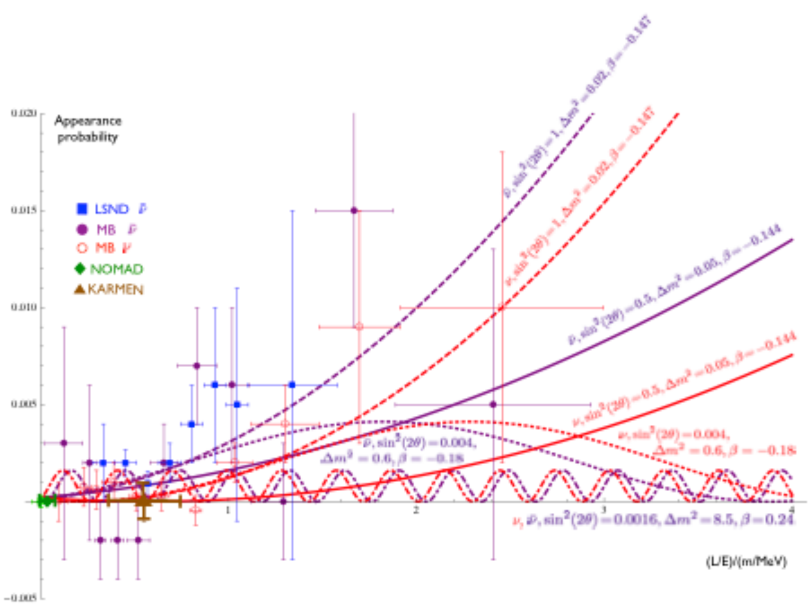
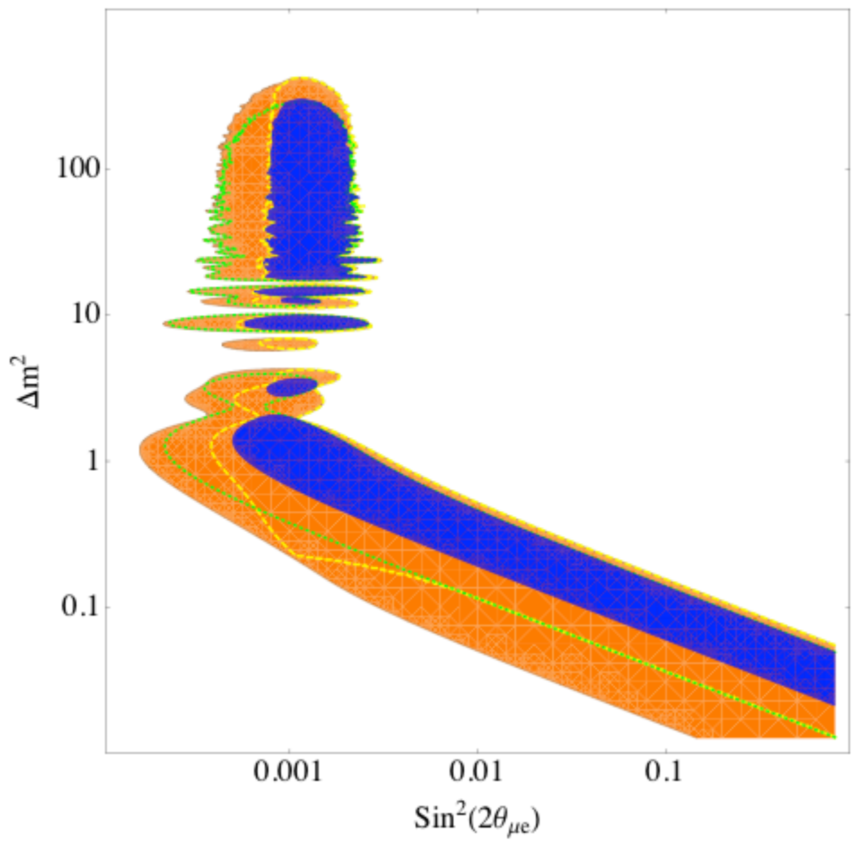


3+2 Global Fit to the World ν & ν Data

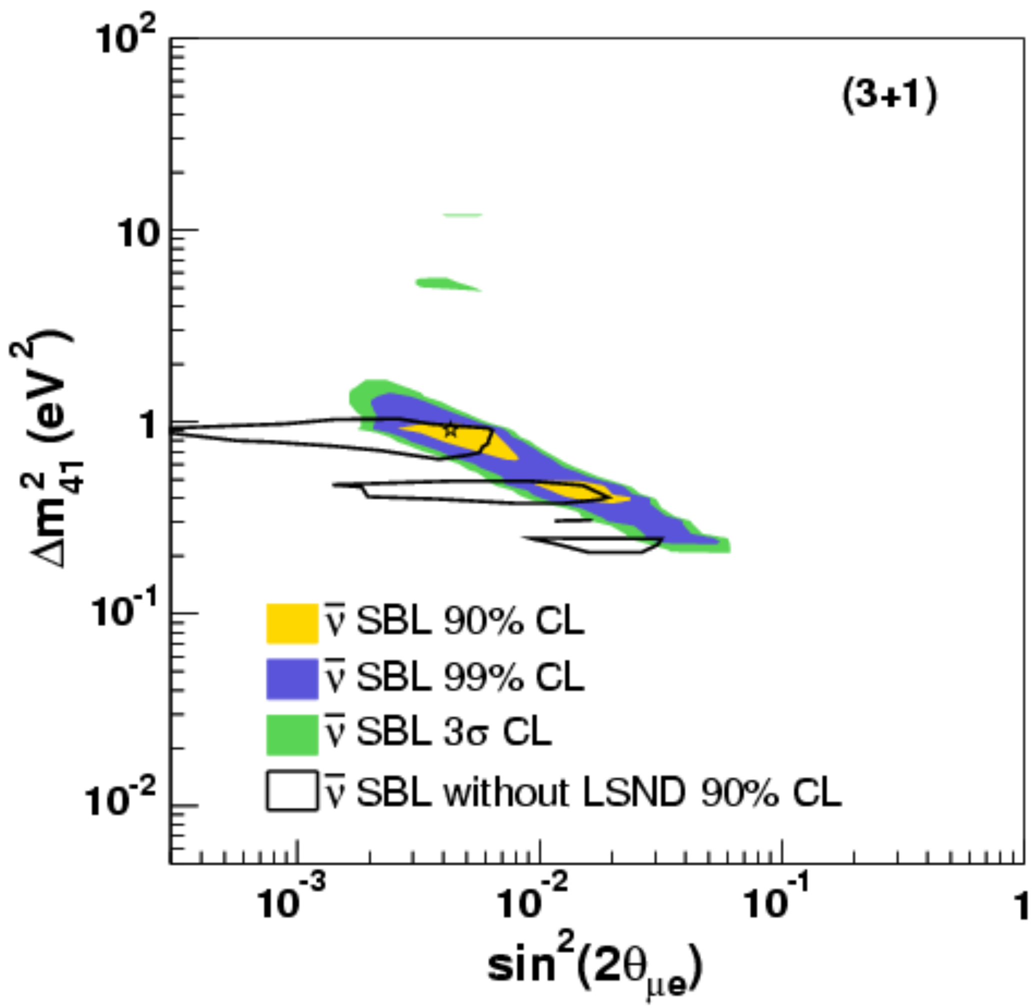




Ann Nelson, arXiv: 1010.3970
One light sterile ν (0.1 - 20 eV) &
one heavy sterile ν (33 eV – 40 GeV)



3+1 Global Fit to World Antineutrino Data (with old MiniBooNE data set)

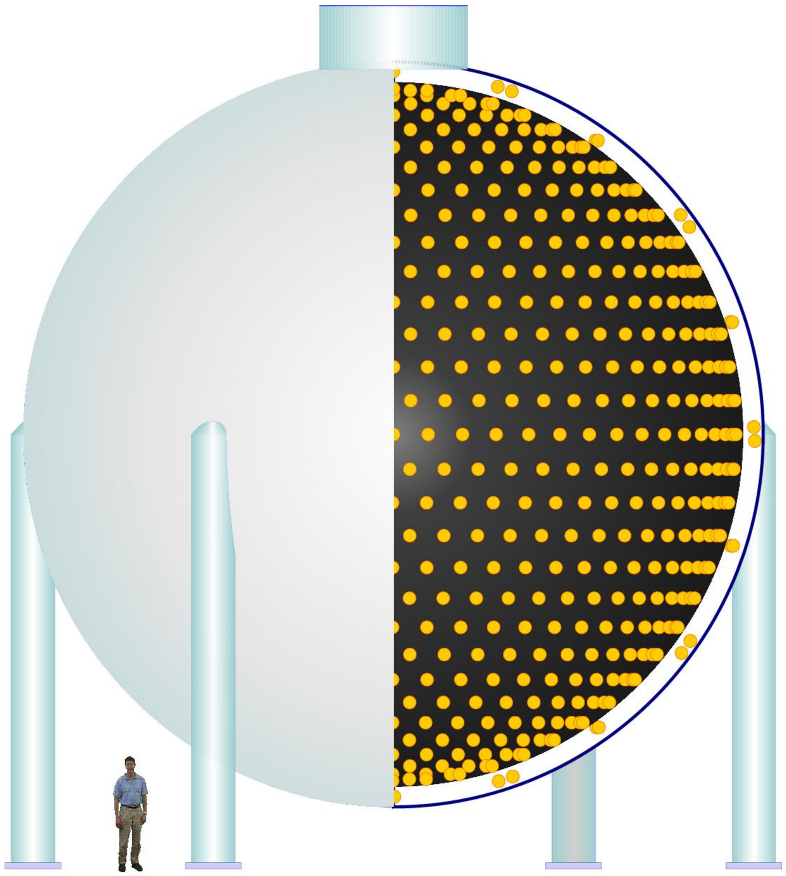


G. Karagiorgi et al., PRD80, 073001 (2009)

Best 3+1 Fit:
$\Delta m_{41}^2 = 0.915$ eV^2
$\sin^2 2\theta_{\mu e} = 0.0043$
$\chi^2 = 87.9/103$ DOF
Prob. = 86%

Predicts $\overline{\nu_\mu}$ & $\overline{\nu_e}$ disappearance of $\sin^2 2\theta_{\mu\mu} \sim 35\%$ and $\sin^2 2\theta_{ee} \sim 4.3\%$

The MiniBooNE Detector



- 541 meters downstream of target
- 3 meter overburden
- 12.2 meter diameter sphere

  (10 meter "fiducial" volume)

- Filled with 800 t

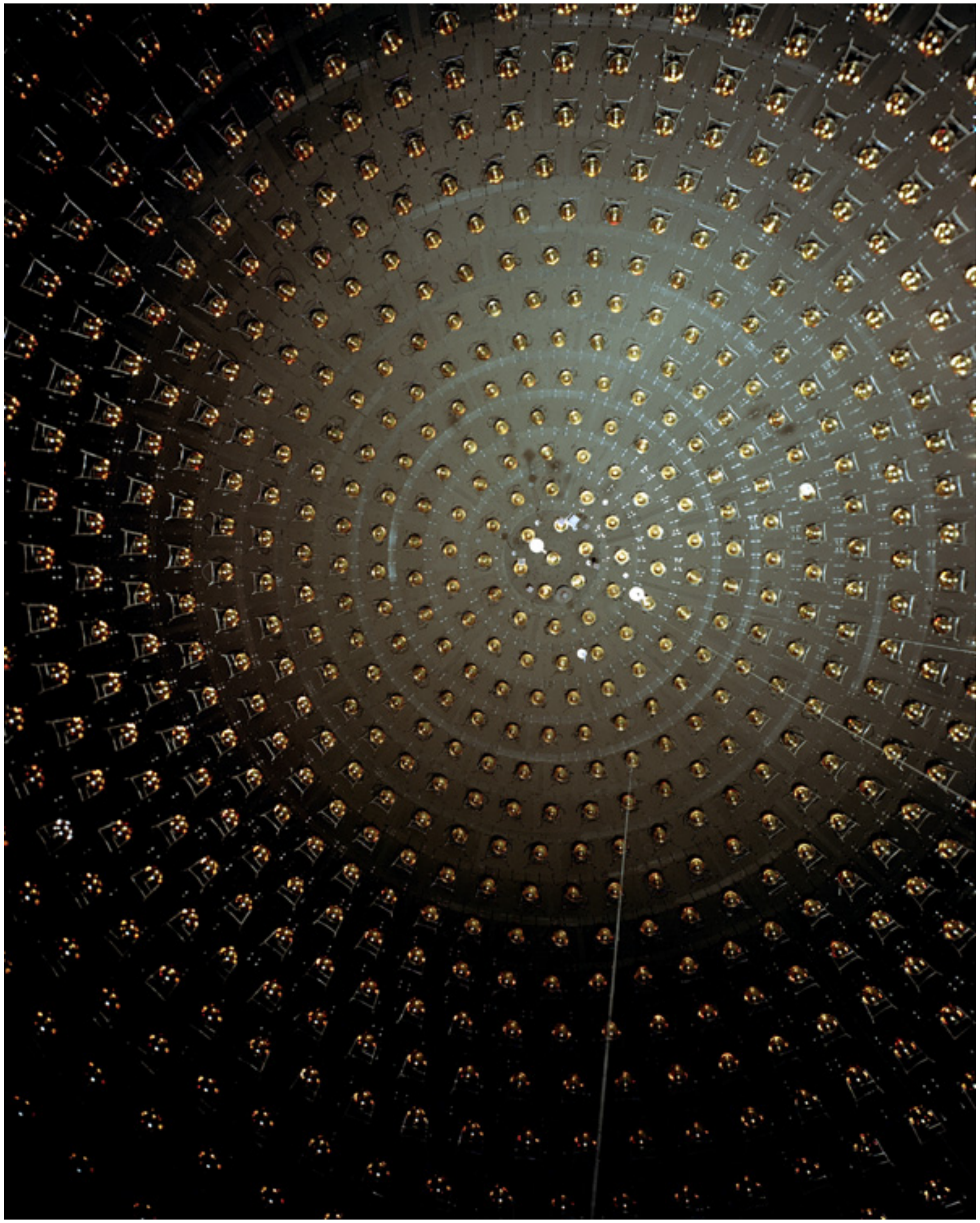
  of pure mineral oil (CH_2)

  (Fiducial volume: 450 t)

- 1280 inner phototubes,

  240 veto phototubes

- Simulated with a GEANT3 Monte Carlo



10% Photocathode coverage

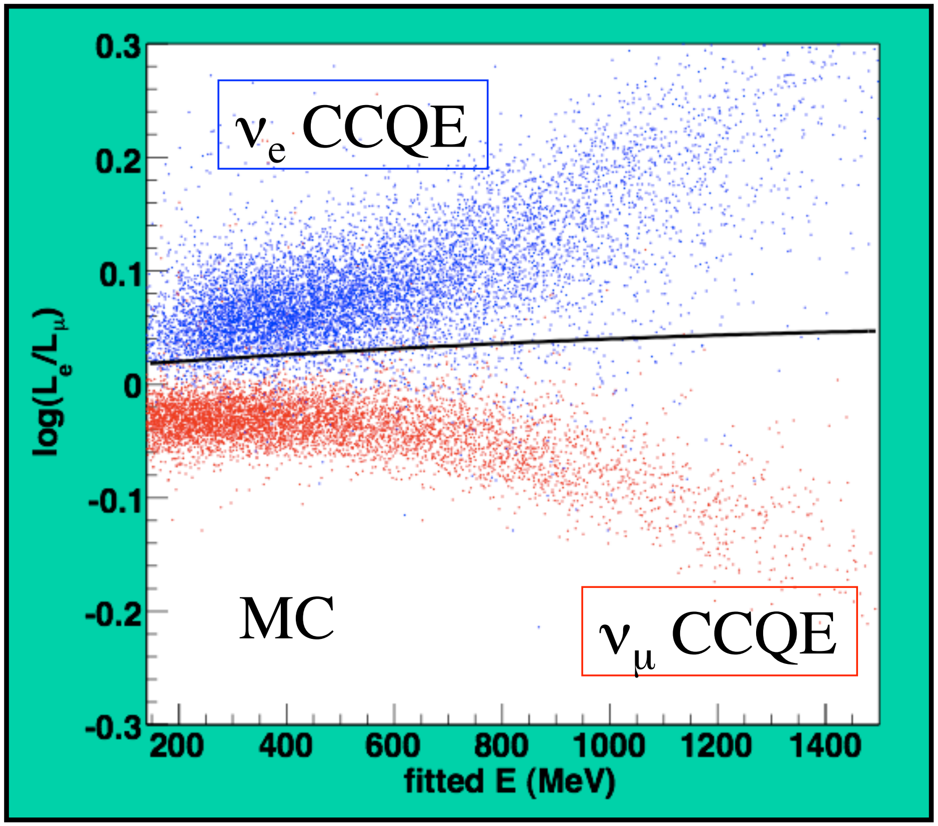
Two types of
Hamamatsu Tubes:
R1408, R5912

Charge Resolution:
1.4 PE, 0.5 PE

Time Resolution
1.7 ns, 1.1ns

Rejecting "muon-like" events Using log(L_e/L_μ)

log(L_e/L_μ)>0 favors electron-like hypothesis



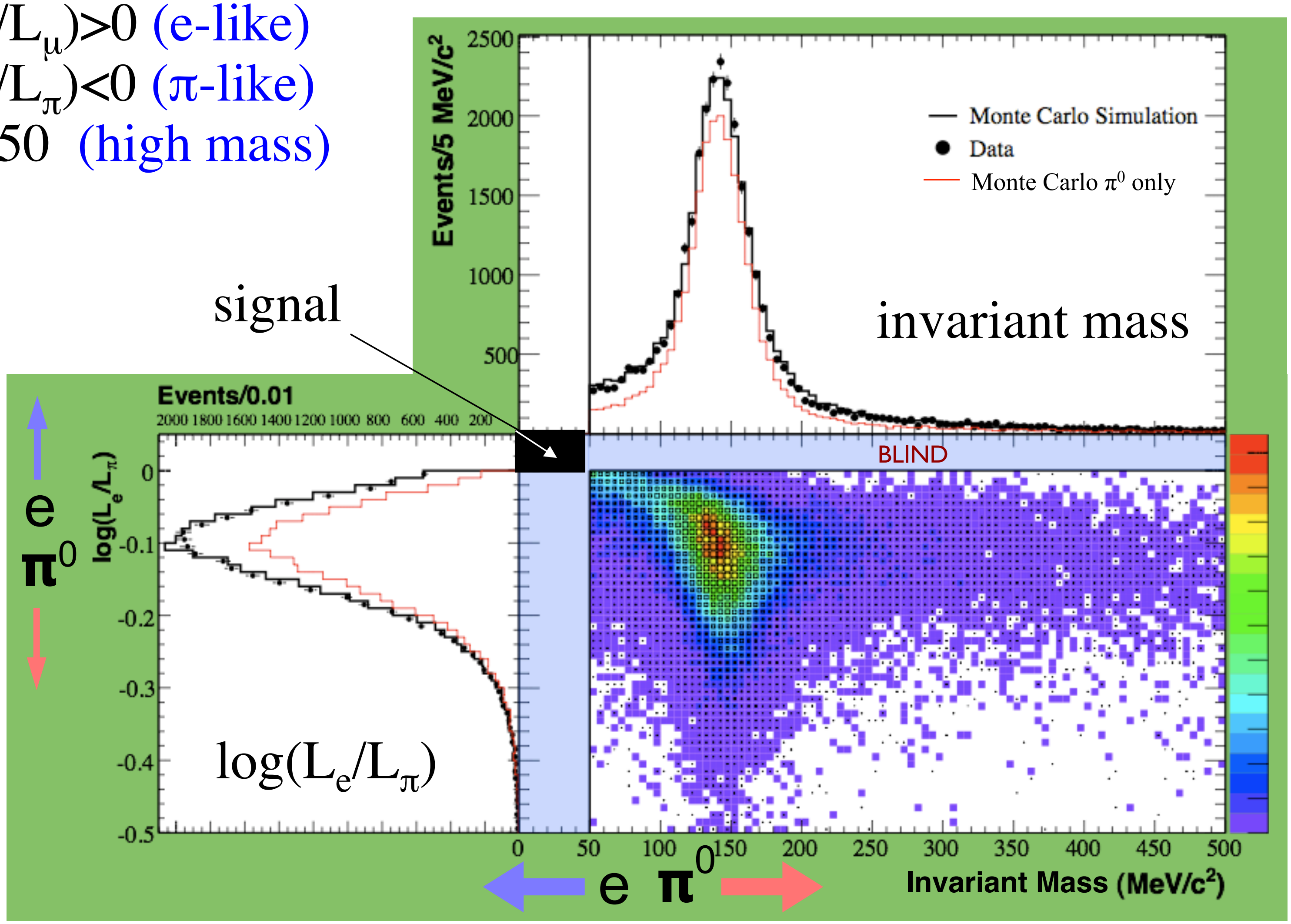
Note: photon conversions are electron-like.
This does not separate e/π^0.

Separation is clean at high energies where muon-like events are long.

Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

Testing e-π^0 separation using data

1 subevent
$\log(L_e/L_\mu)>0$ (e-like)
$\log(L_e/L_\pi)<0$ (π-like)
mass>50 (high mass)

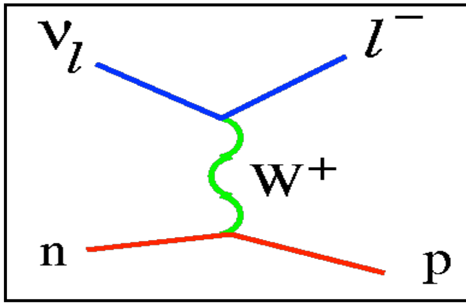


MiniBooNE Detects Cherenkov Light

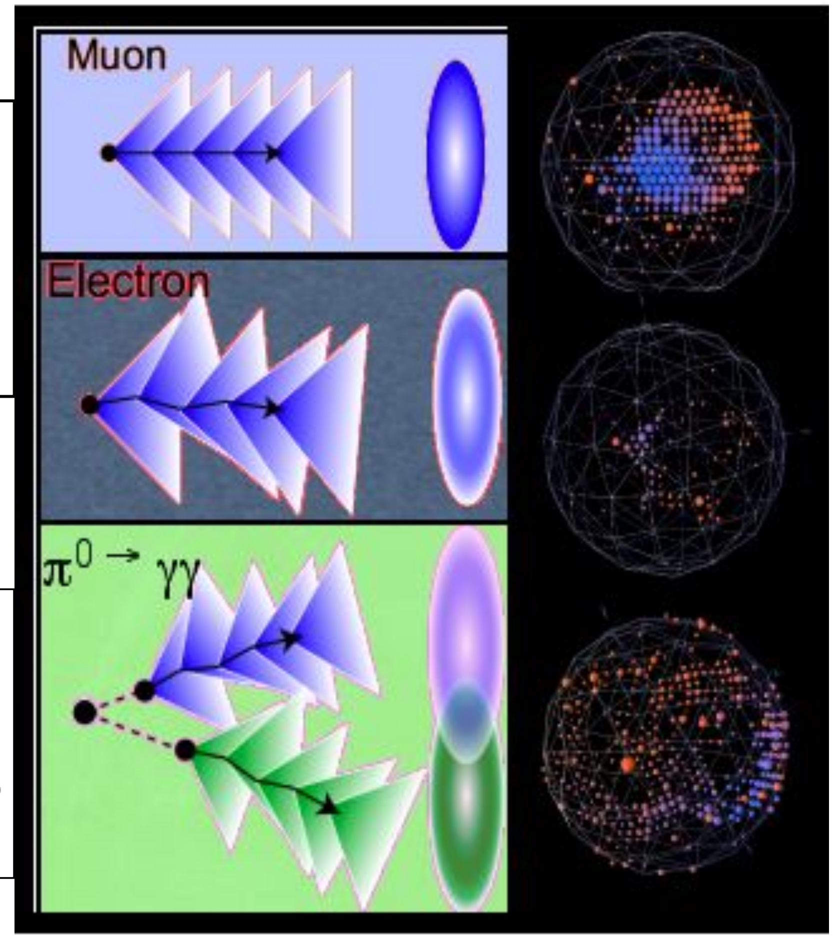
Pattern of Cerenkov Light Gives Event Type

The most important types of neutrino events in the oscillation search:

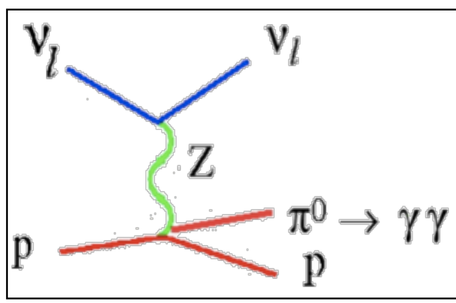
Background Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents
or exiting through veto.



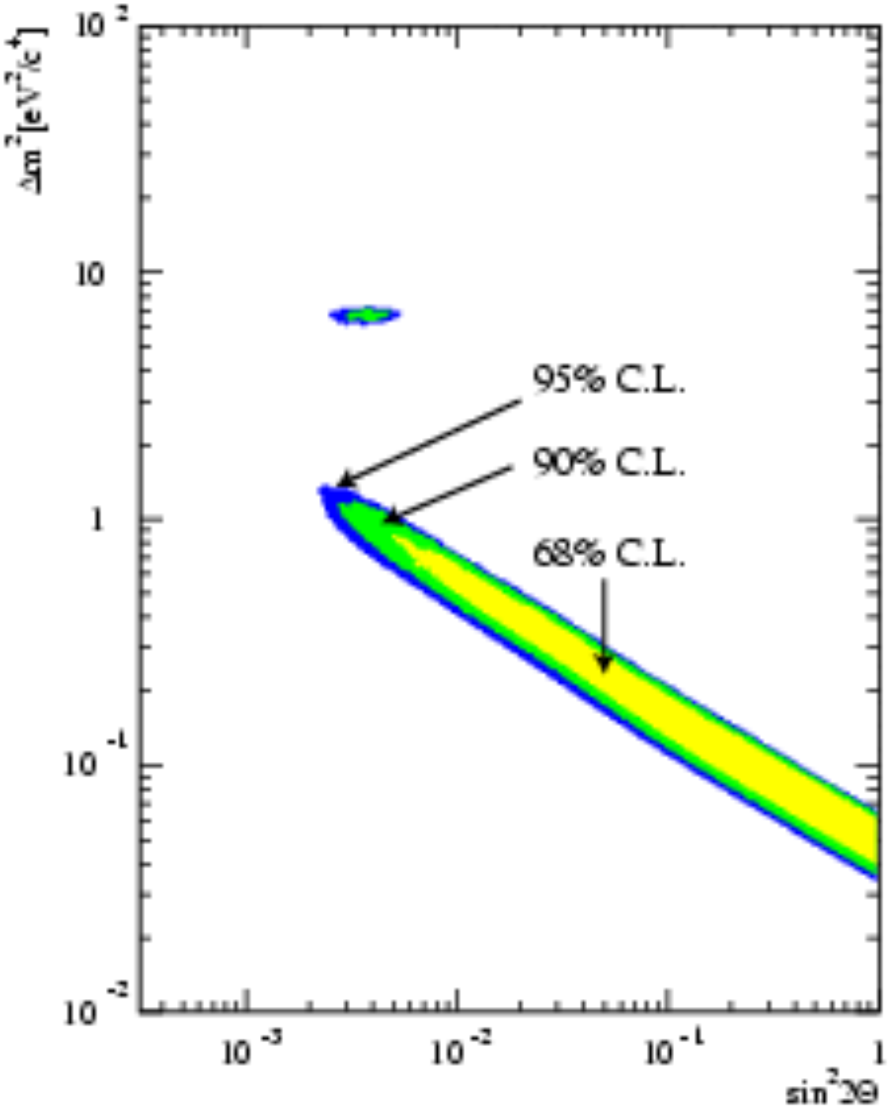
Signal and Background
Electrons (or single photon):
Tag for :$\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_e}$ CCQE signal.
1 subevent



Background π^0s:
Can form a background if one
photon is weak or exits tank.
In NC case, 1 subevent.



Joint LSND/KARMEN Analysis



Joint analysis with
Karmen2: 64% compatible

E. Church, et al., PRD 66, 013001

LSND $\bar{\nu}_e$ Background Estimates

Estimate	$\bar{\nu}_e/\bar{\nu}_\mu$	$\bar{\nu}_e$ Bkgd	LSND Excess
LSND Paper	0.086%	19.5+-3.9	87.9+-22.4+-6.0
Zhemchugov Poster1	0.071%	16.1+-3.2	91.3+-22.4+-5.6
Zhemchugov Poster2	0.092%	20.9+-4.2	86.5+-22.4+-6.2
Zhemchugov Seminar	0.119%	27.0+-5.4	80.4+-22.4+-7.1

All $\bar{\nu}_e$ background estimates assume a 20% error. Note that the $\bar{\nu}_e/\bar{\nu}_\mu$ ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001); (uses **MCNP**)

Zhemchugov Poster1: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Poster2: **GEANT4** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Seminar: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at CERN on September 14, 2010

Although the analysis of Zhemchugov et al. is not fully understood or endorsed, their $\bar{\nu}_e/\bar{\nu}_\mu$ ratios agree reasonably well with the published LSND results.

Note that LSND measures the correct rate of $\bar{\nu}_\mu$ p -> μ^+ n interactions, which confirms the π^- production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV!

GEANT4 Overestimates π^- Production!