MiniBooNE Antineutrino Oscillation Results and Implications for the Future

W.C. Louis

Los Alamos National Laboratory

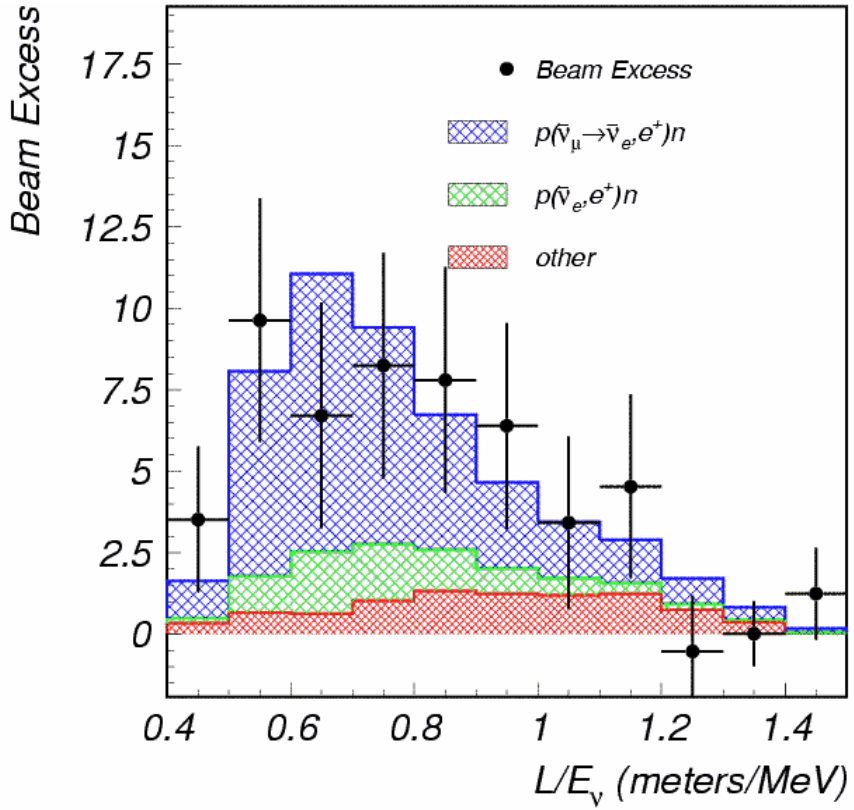
November 4, 2010

Outline

- 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
- Conclusion

LSND Signal

- LSND experiment
- Stopped pion beam
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- 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)

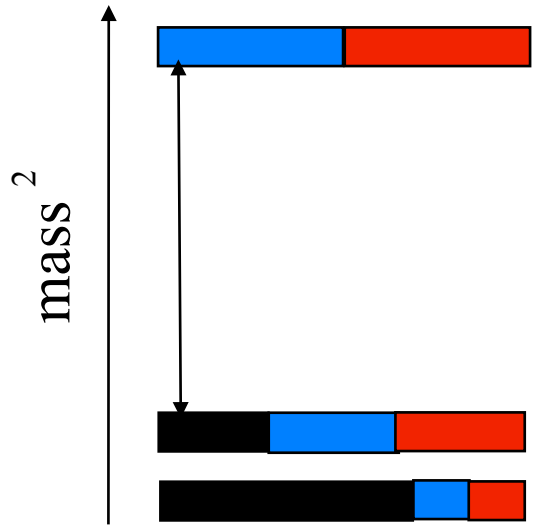


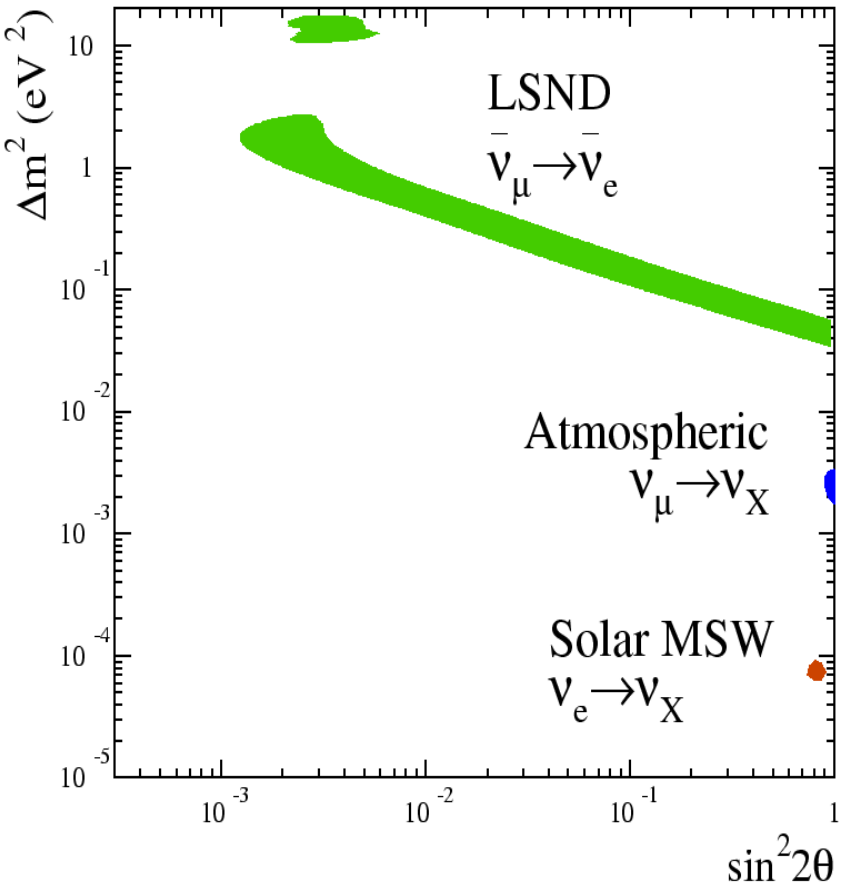
LSND Signal

- Assuming two neutrino oscillations

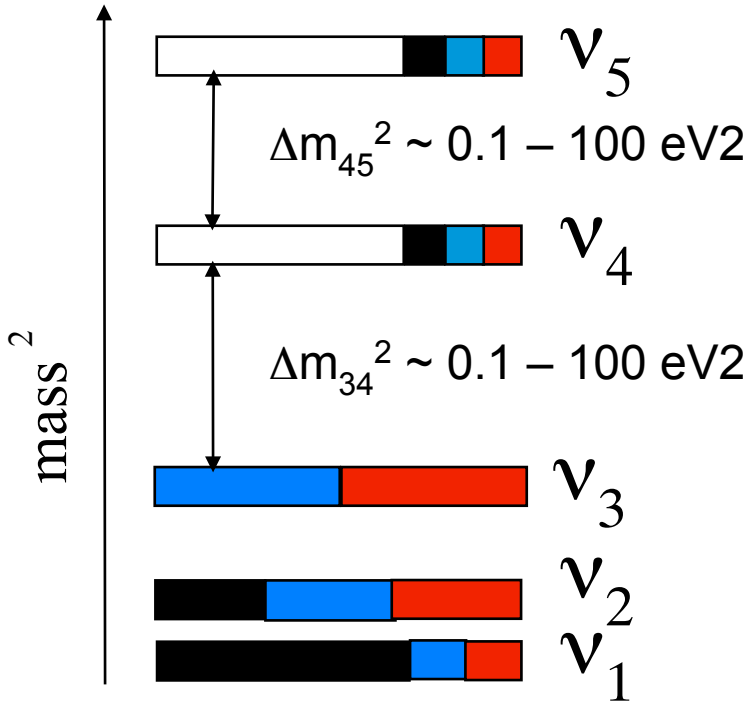
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

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



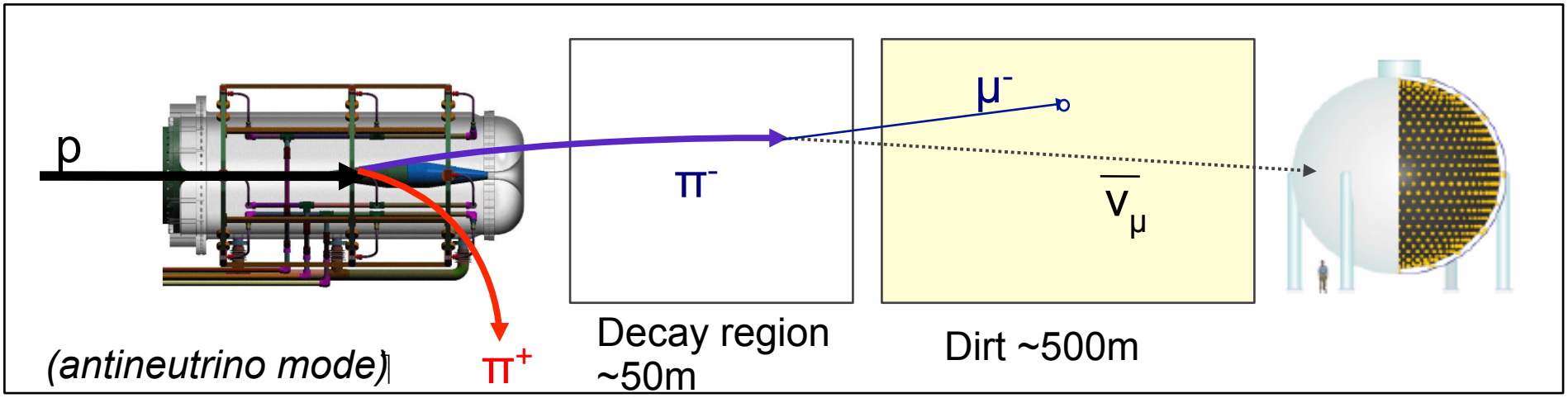


Sterile Neutrinos



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

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

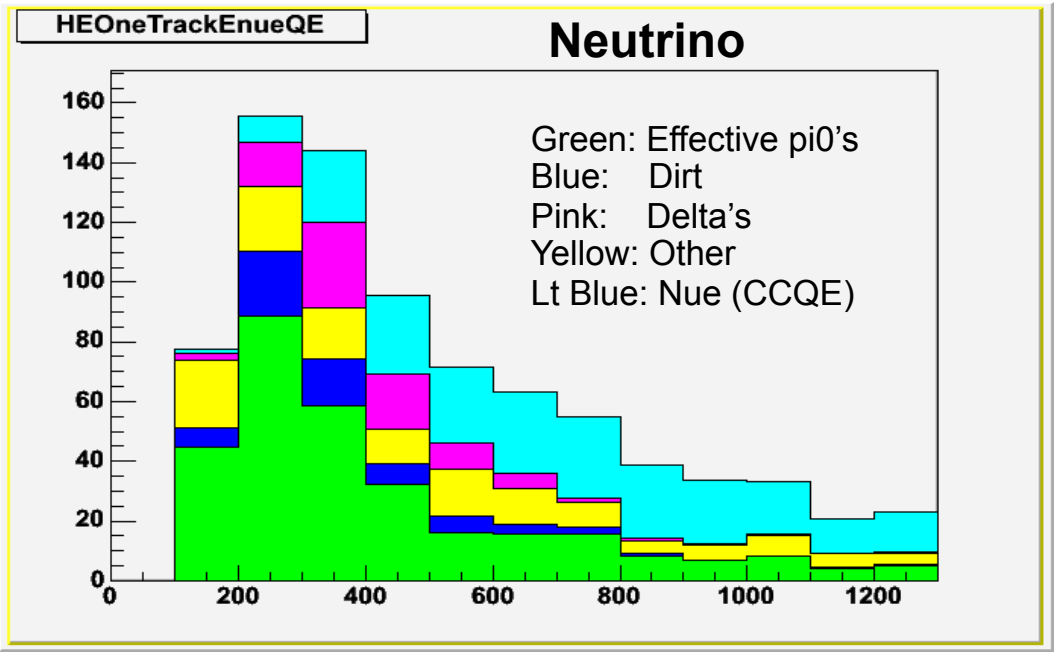
ν_e Event Rate Predictions

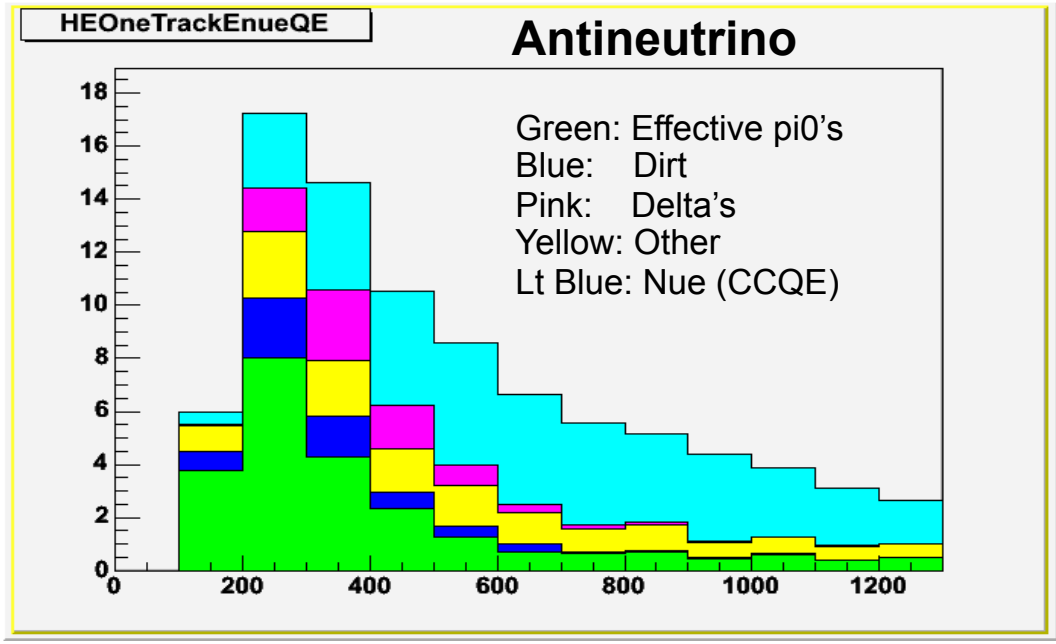
#Events = Flux x Cross-sections x Detector response

External measurements (HARP, E910, etc) ν_μ rate constrained by neutrino data

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

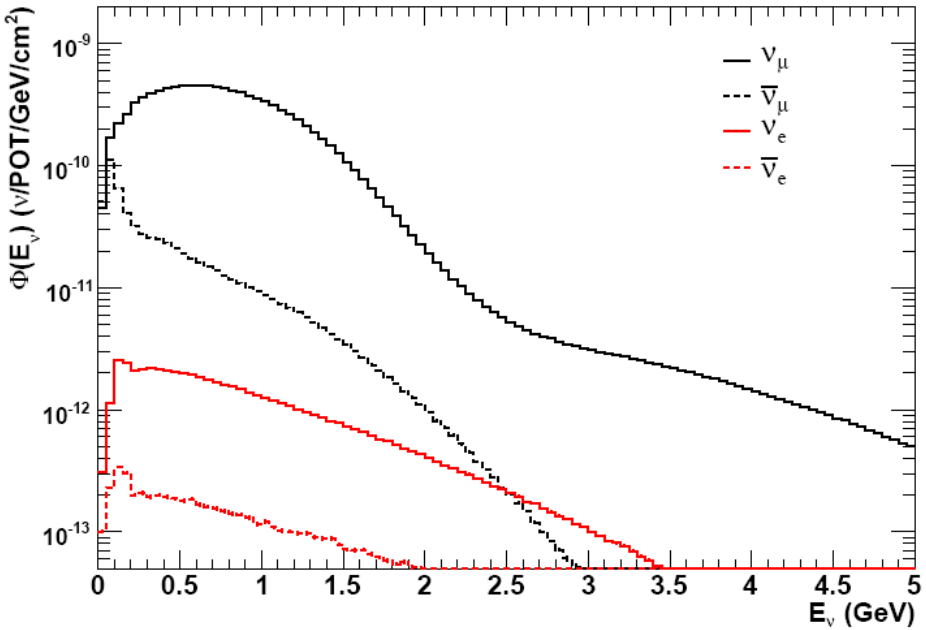
Detailed detector simulations checked with neutrino data and calibration sources.



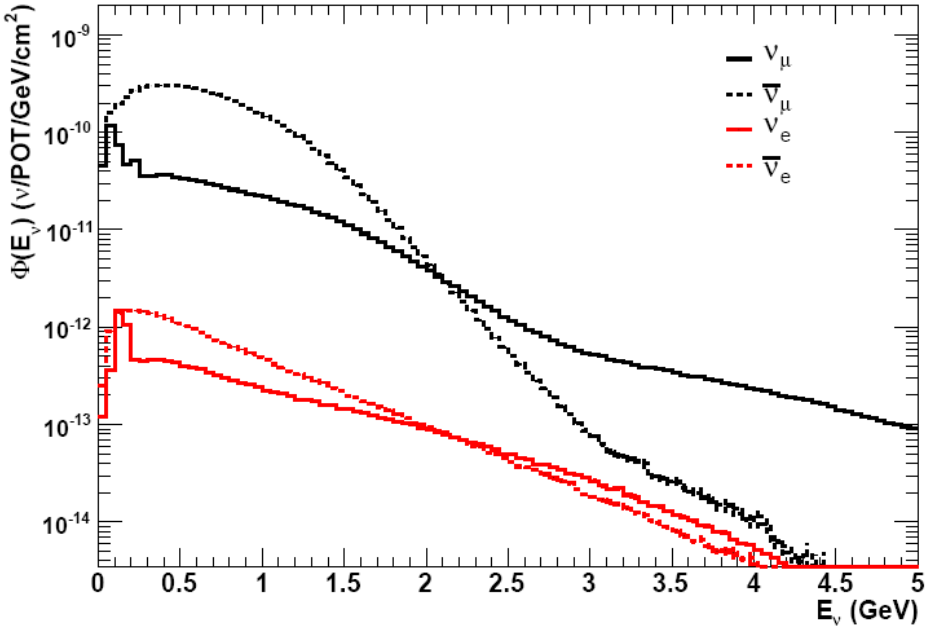


Neutrino Flux from GEANT4 Simulation

Neutrino-Mode Flux

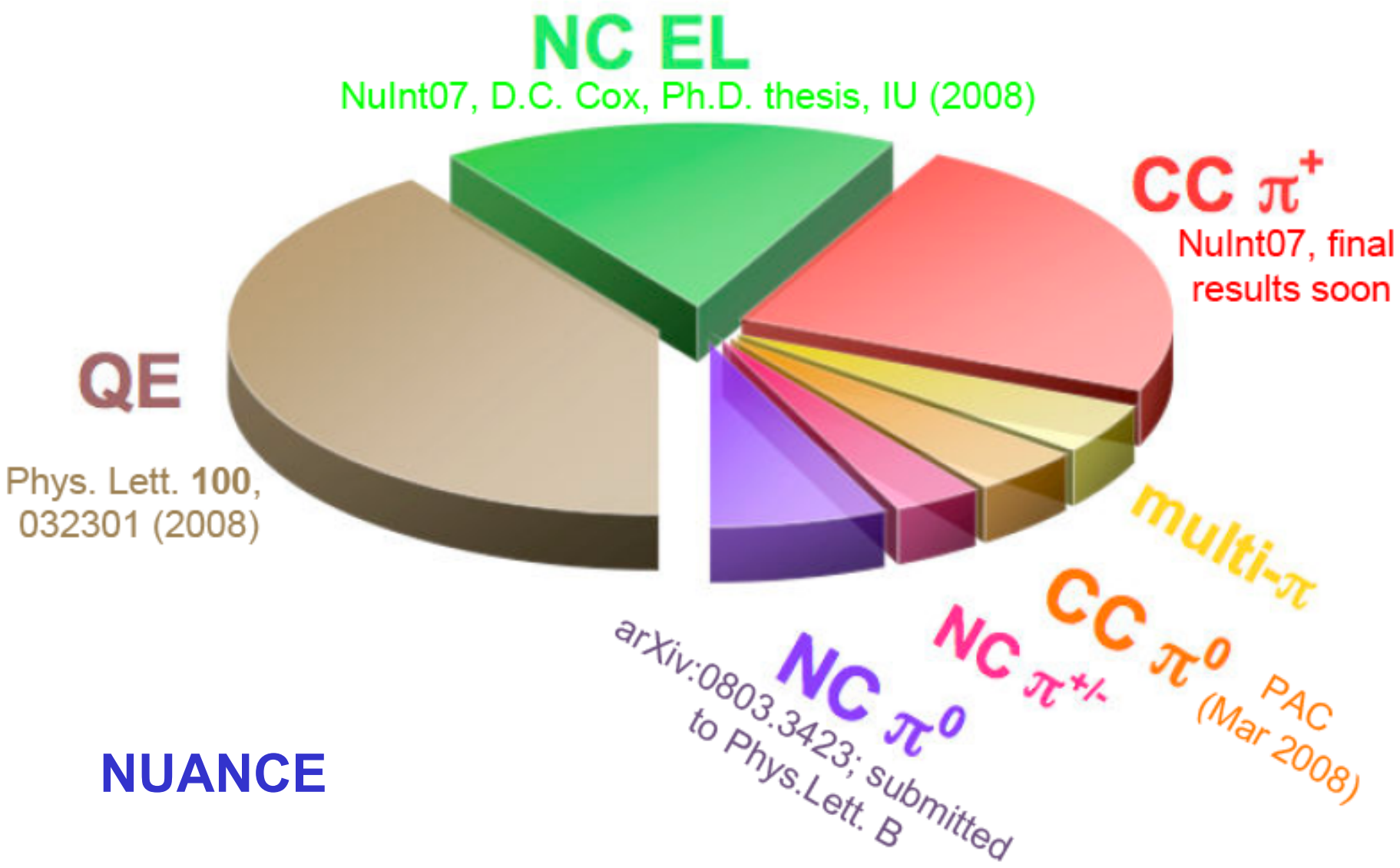


Antineutrino-Mode Flux



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

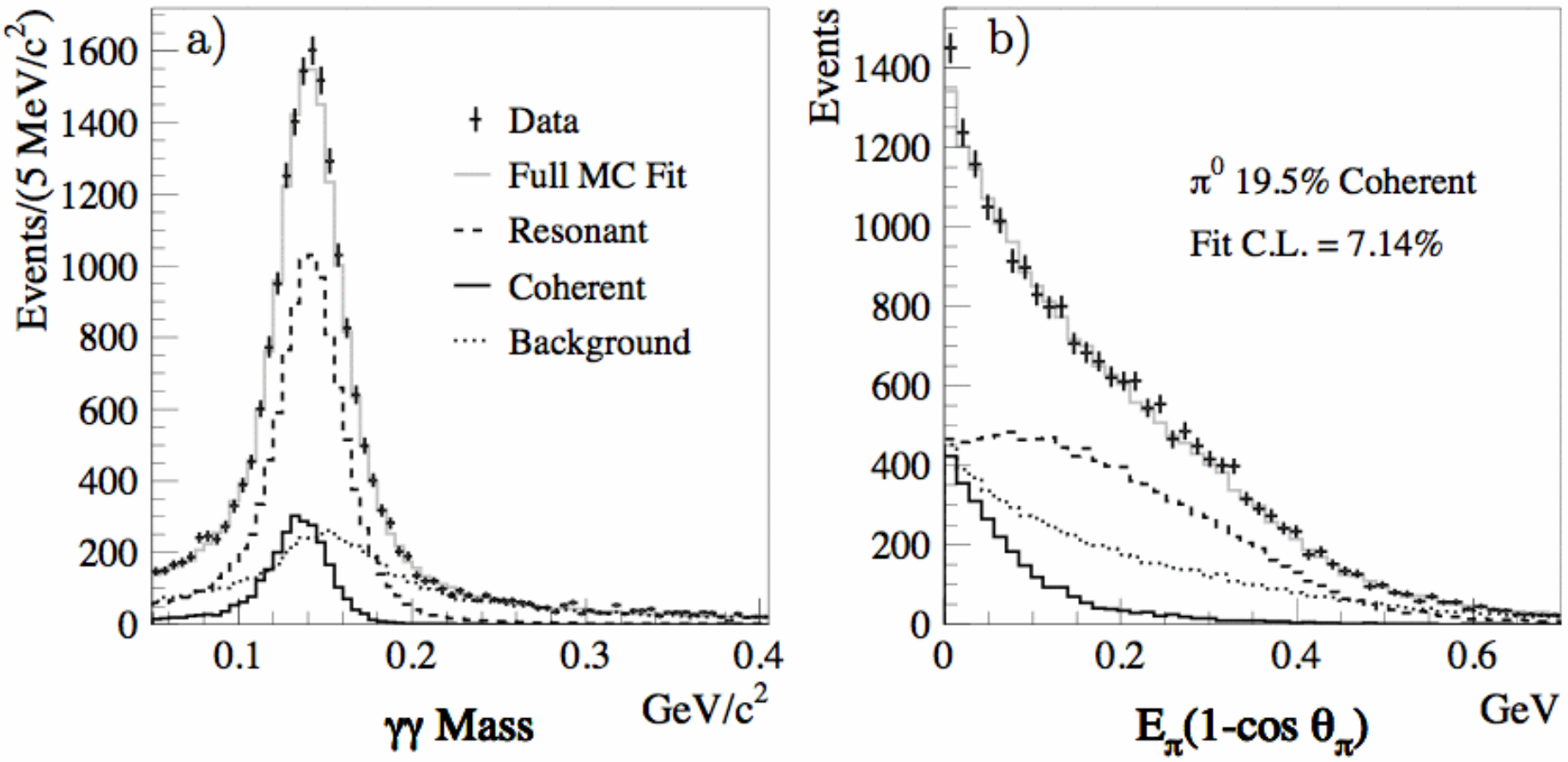
Neutrino Cross Sections



NCπ^0 Scattering

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

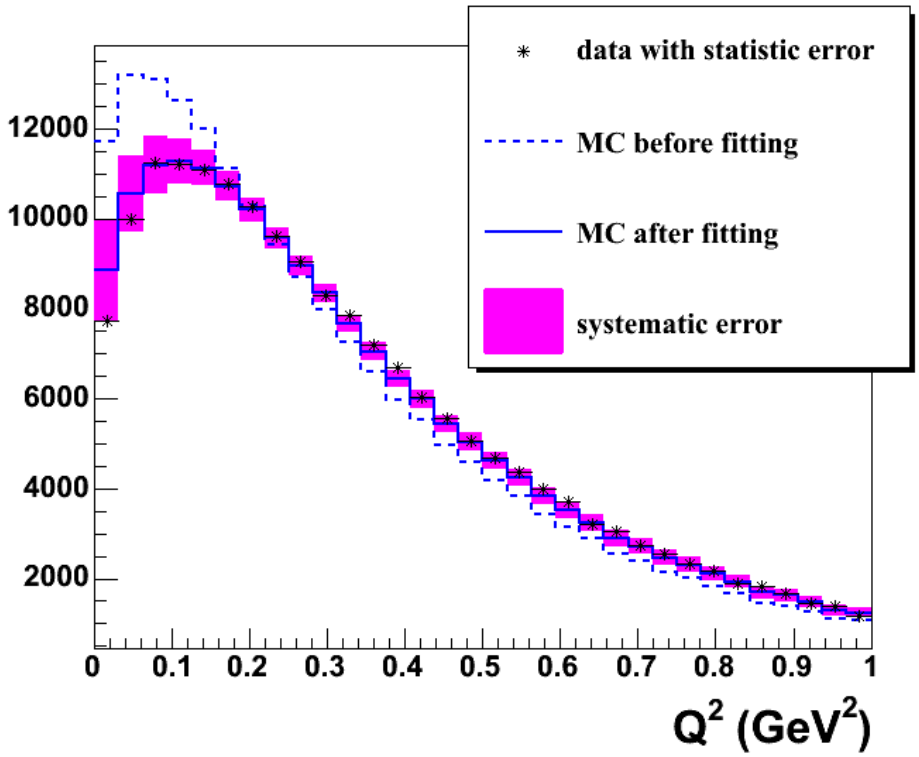
coherent fraction=19.5+-1.1+-2.5%



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

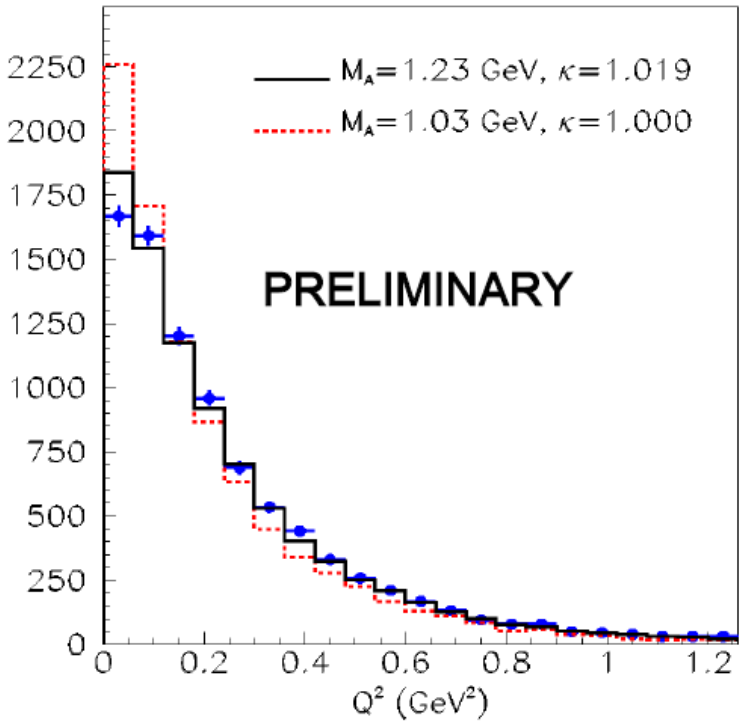
$\varkappa$ -- Pauli Blocking parameter

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

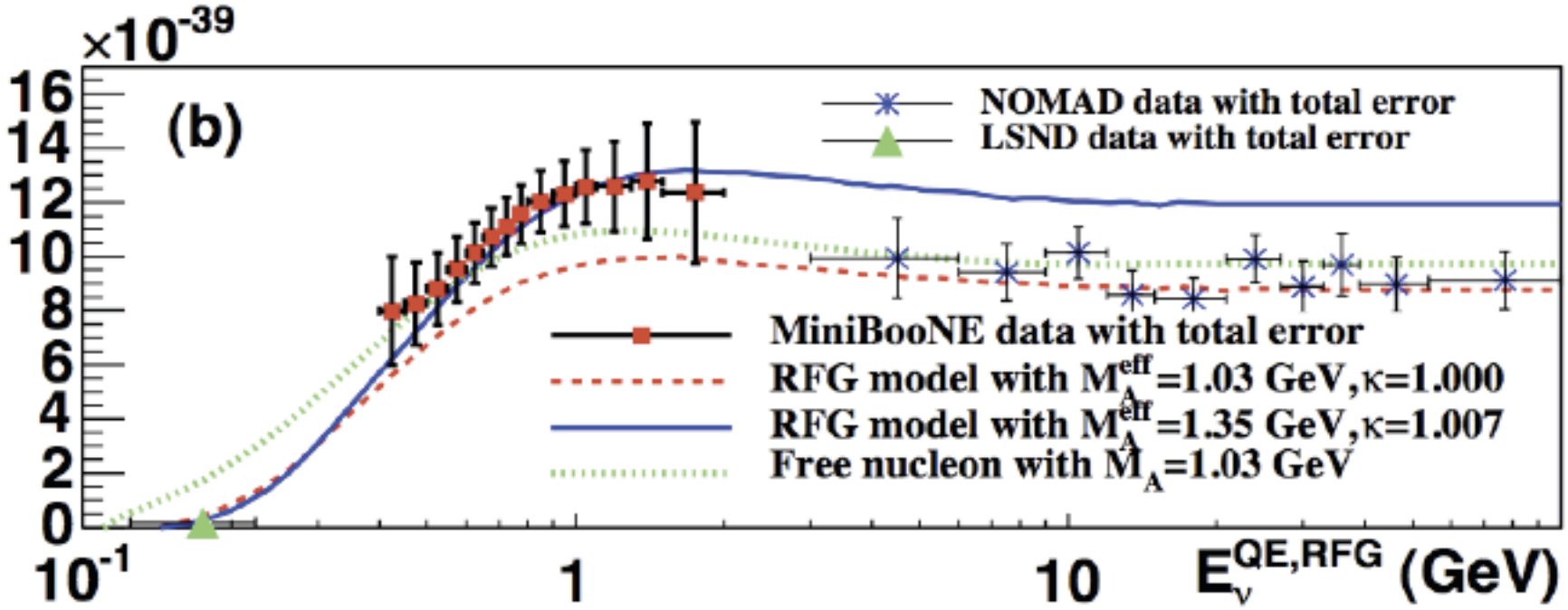
$M_A = 1.23+-0.20$ GeV

$\varkappa = 1.019+-0.011$

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 $\sigma_{\nu\mu}(^{12}C)>6\ \sigma_{\nu\mu}(n)$

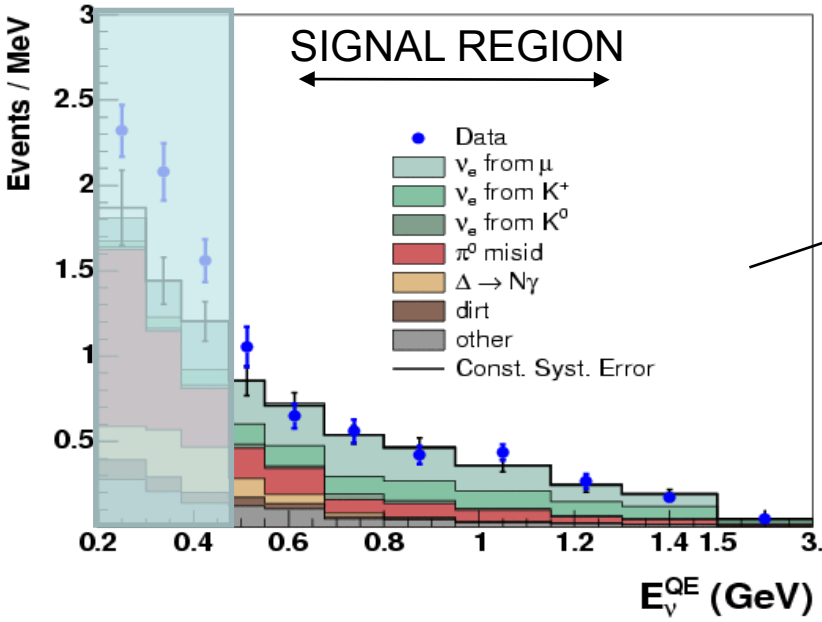
How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

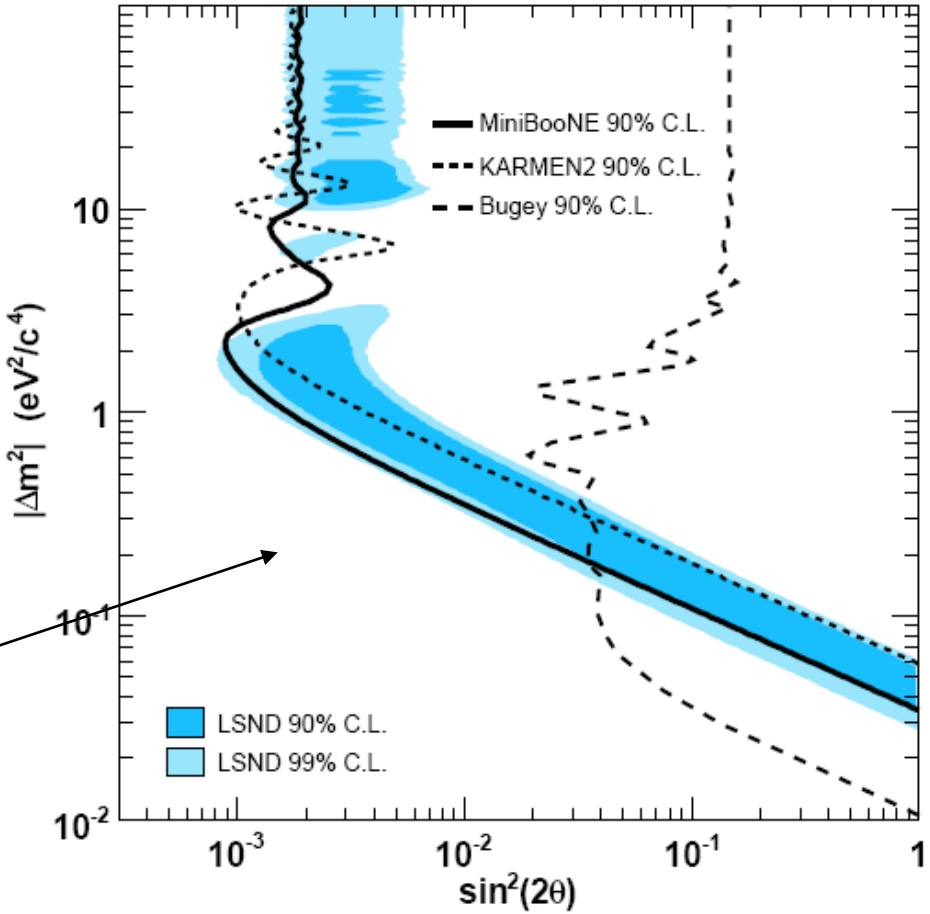
A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys.Rev.**C65,** 024002 (2002) ; Gerry Garvey.

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)
- Inconsistent with simple 2ν oscillations as explanation of LSND (assuming no CP violation)





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

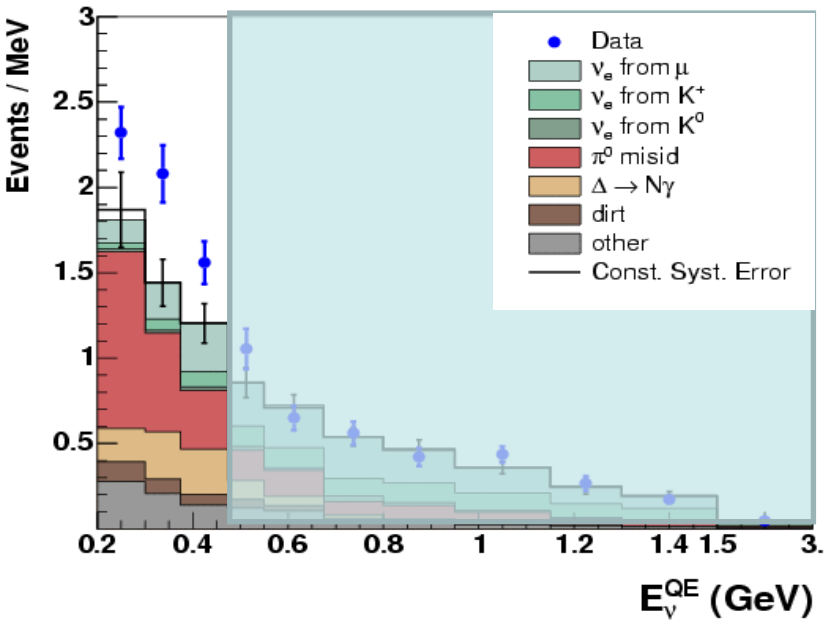
MiniBooNE Neutrino Oscillation Results

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

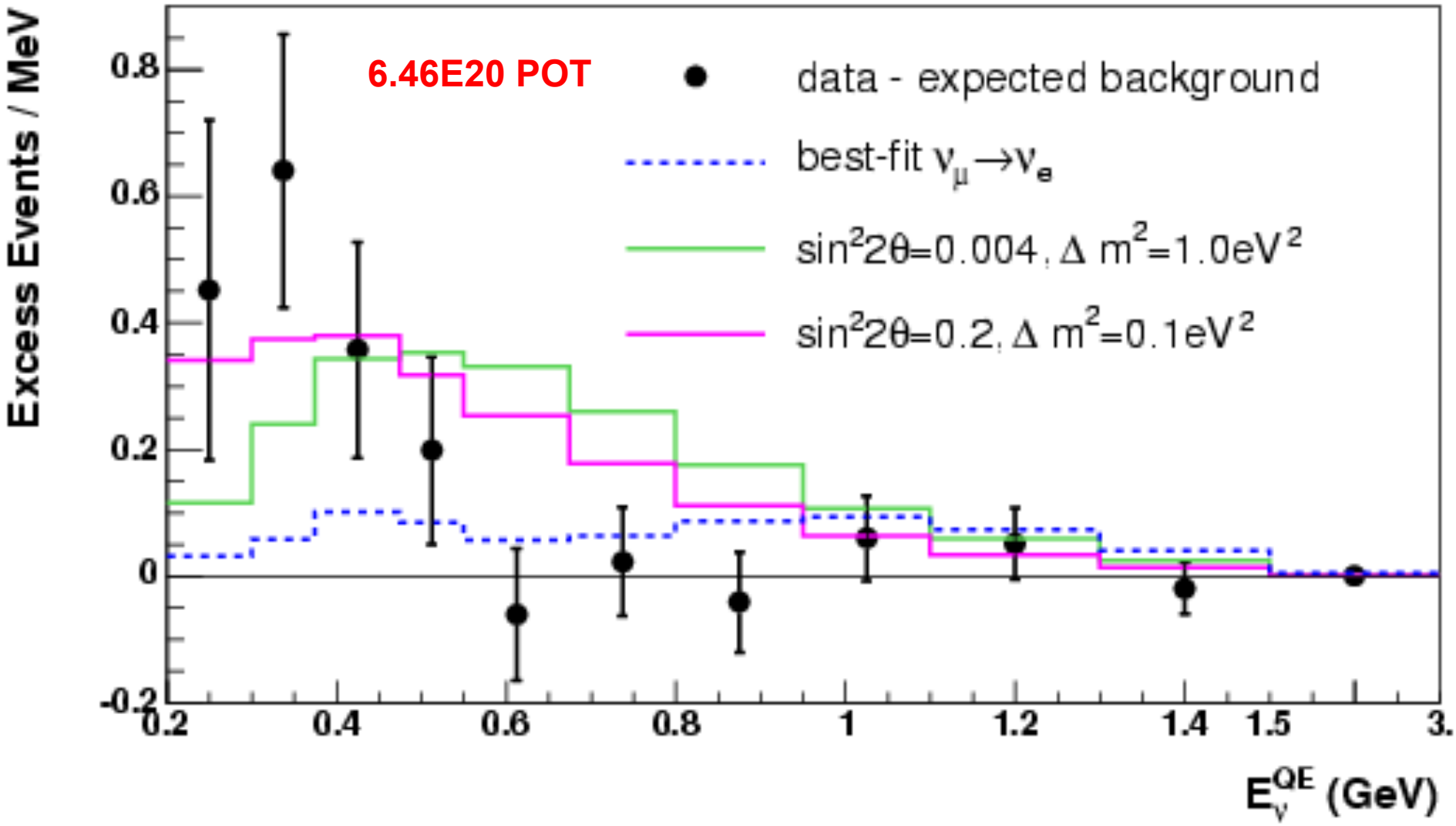
CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

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

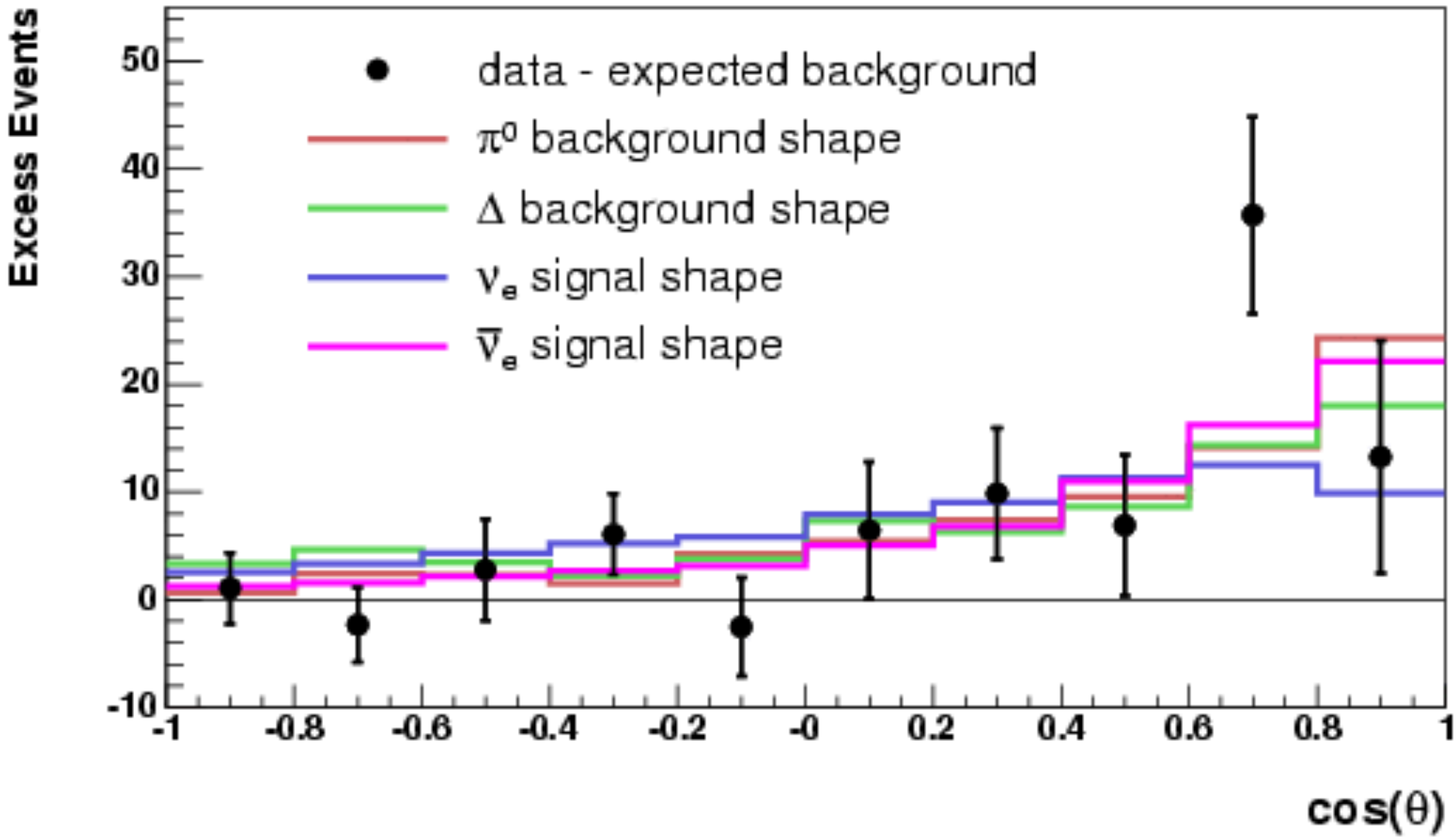
MiniBooNE Data Show a Low-Energy Excess

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

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



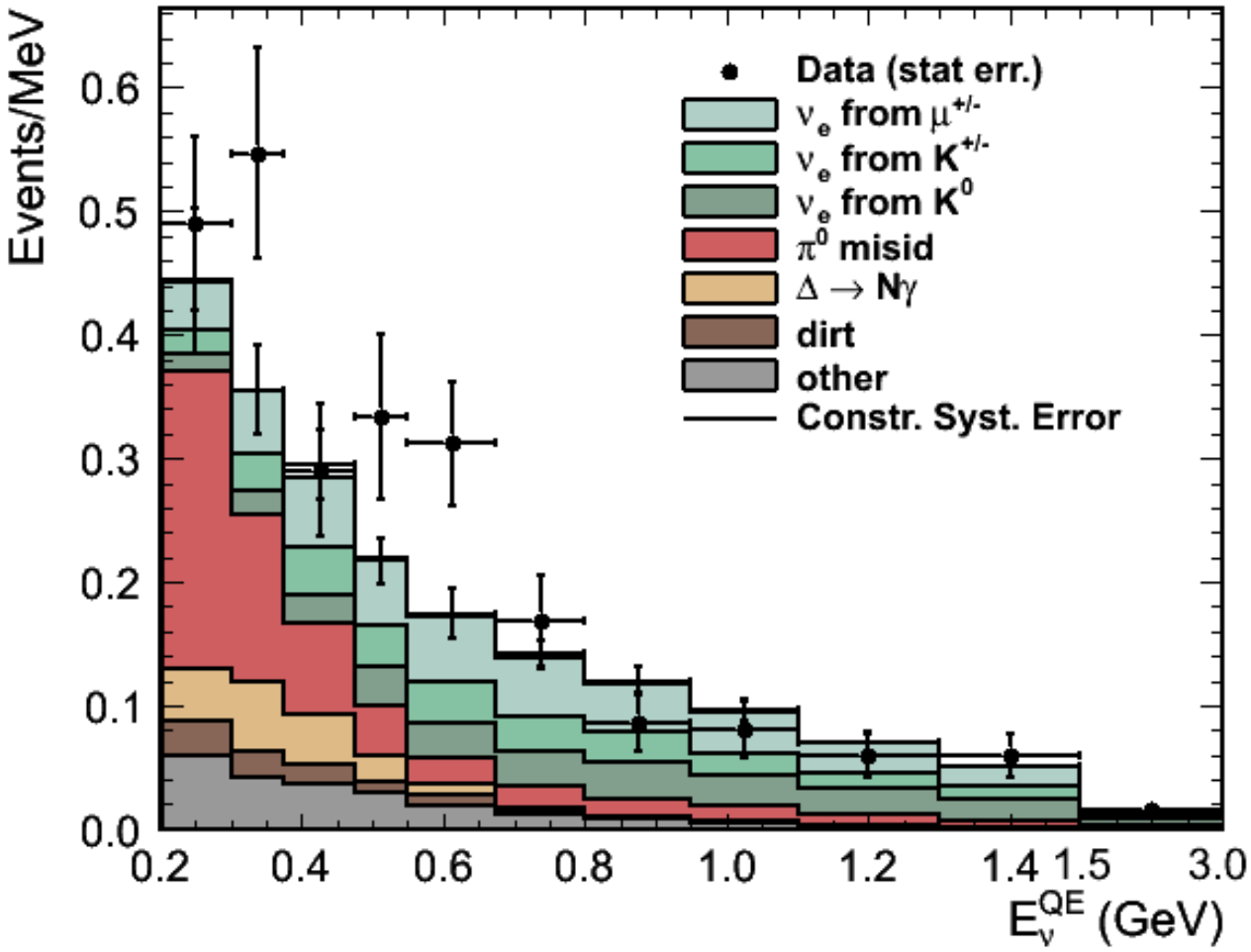
Low-Energy Excess vs cosθ



MiniBooNE Antineutrino Oscillation Results

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

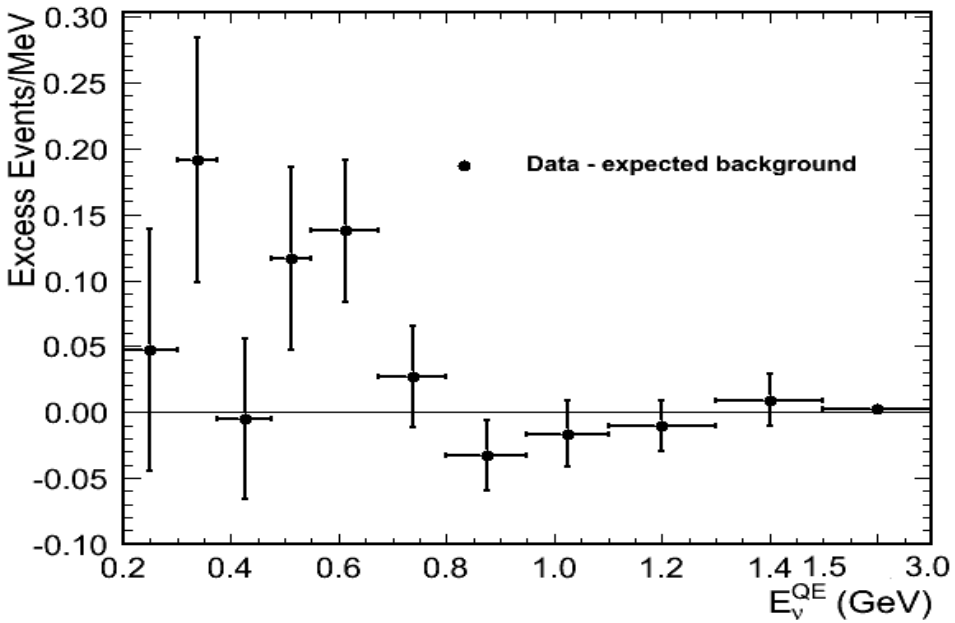
- 5.66e20 POT



MiniBooNE Antineutrino Null Probability

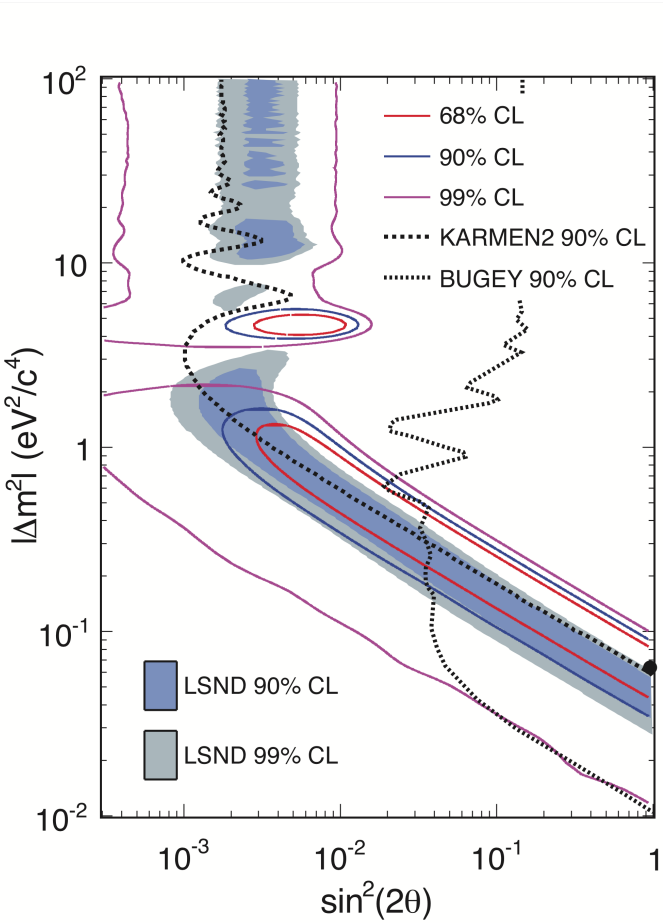
- Absolute χ^2 probability of null point (background only) - model independent
- Frequentist approach

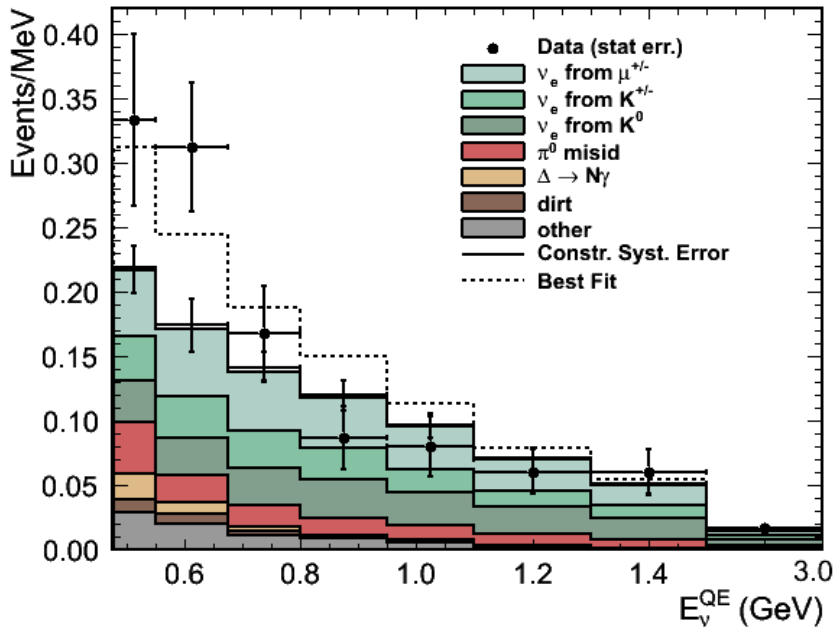
475-1250 MeV	chi2/NDF	probability
ν_μ -> ν_e	6.1/6	40%
$\bar{\nu}_\mu$ -> $\bar{\nu}_e$	18.5/6	0.5%

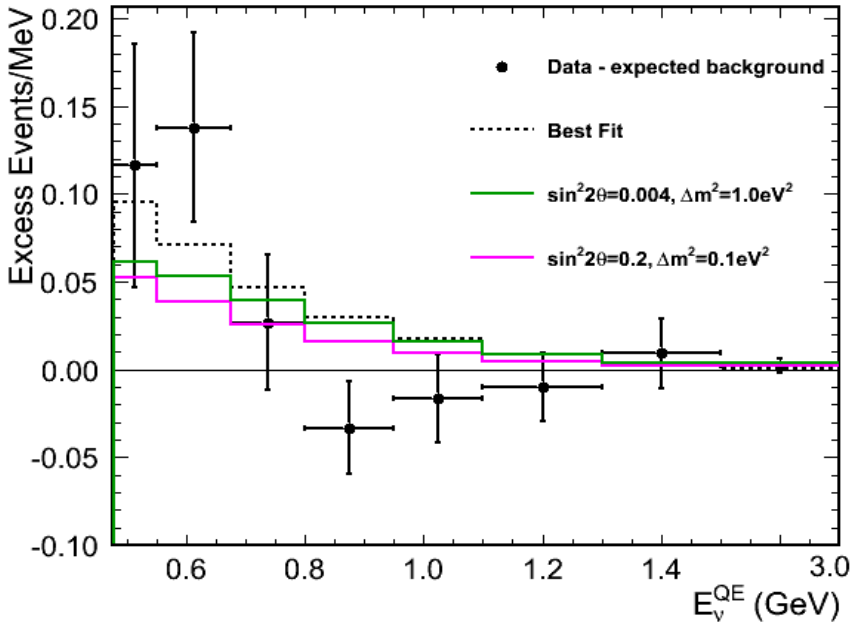


MiniBooNE Oscillation Fit E>475

- 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)

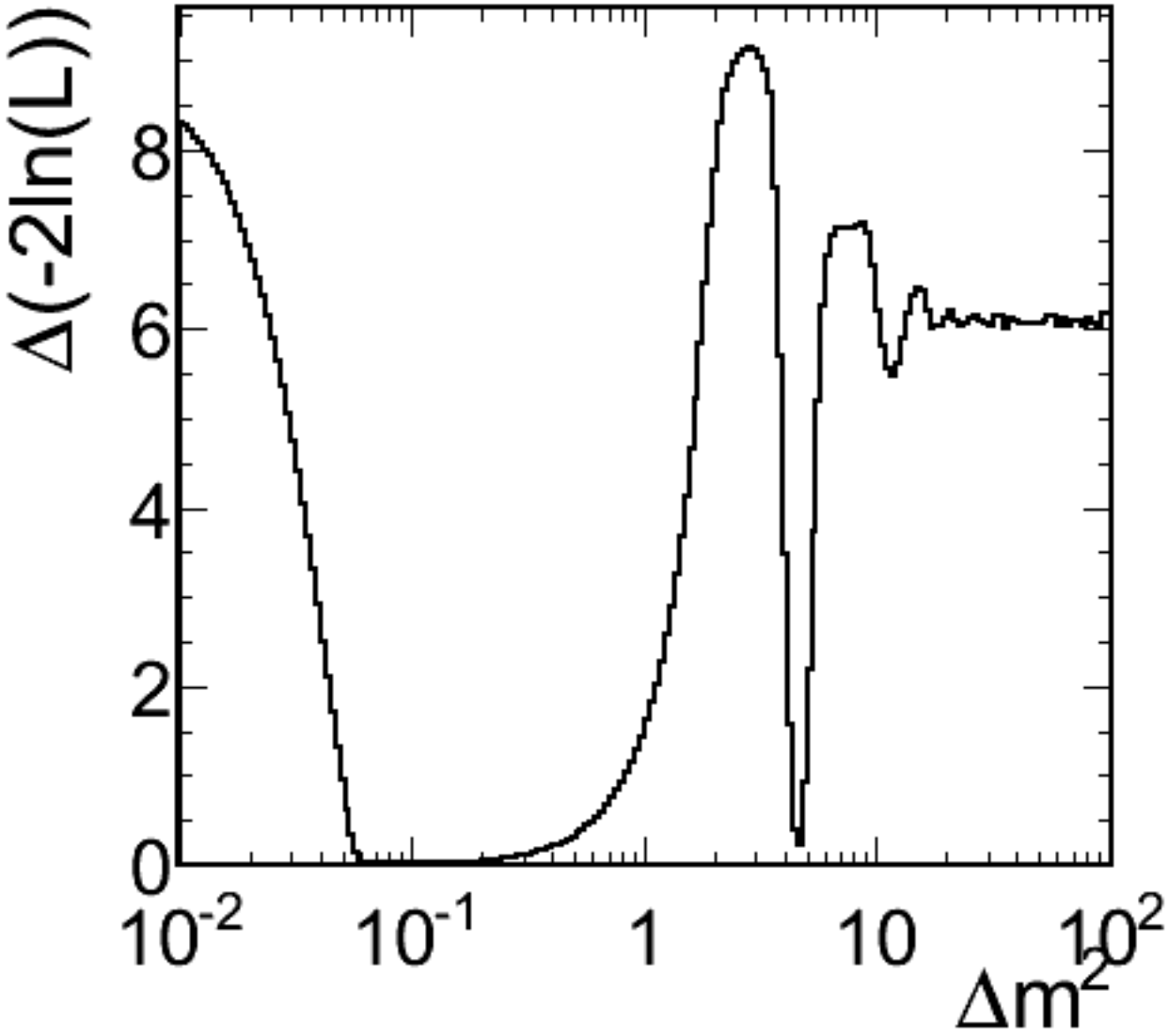






$\Delta\chi^2$ vs Δm^2

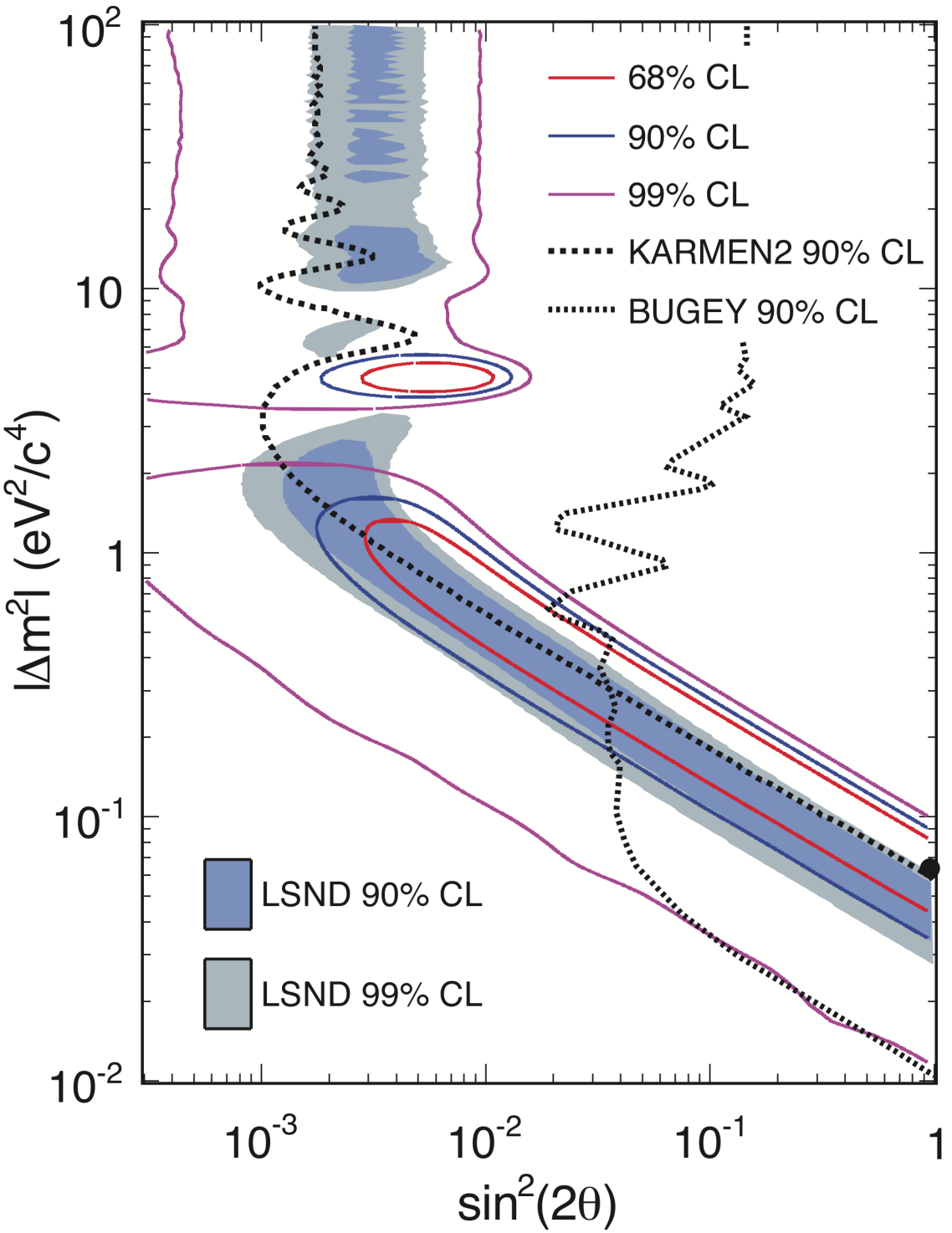
(Best $\Delta\chi^2$ at each Δm^2)



MiniBooNE Oscillation Fit

E>475 MeV

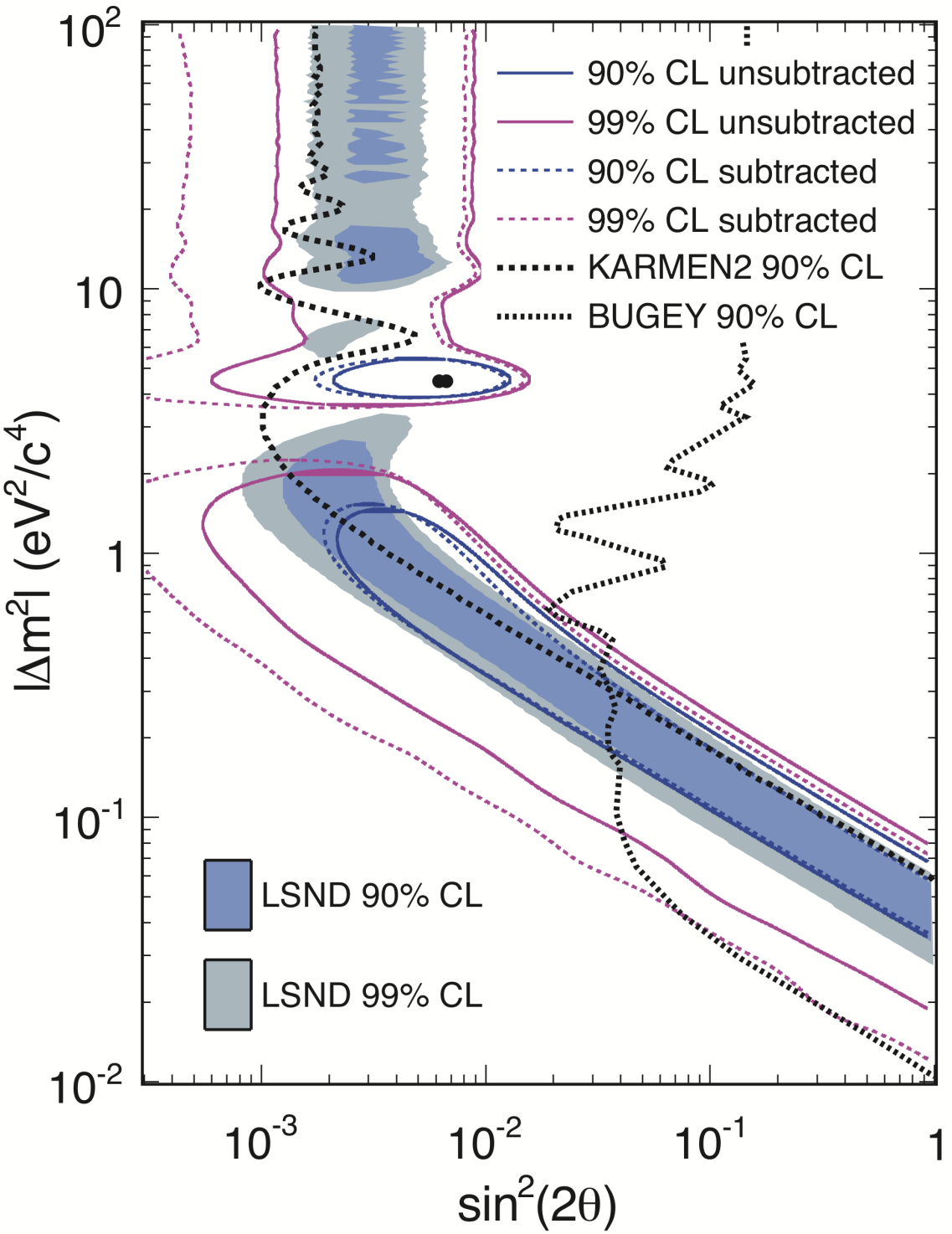
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed



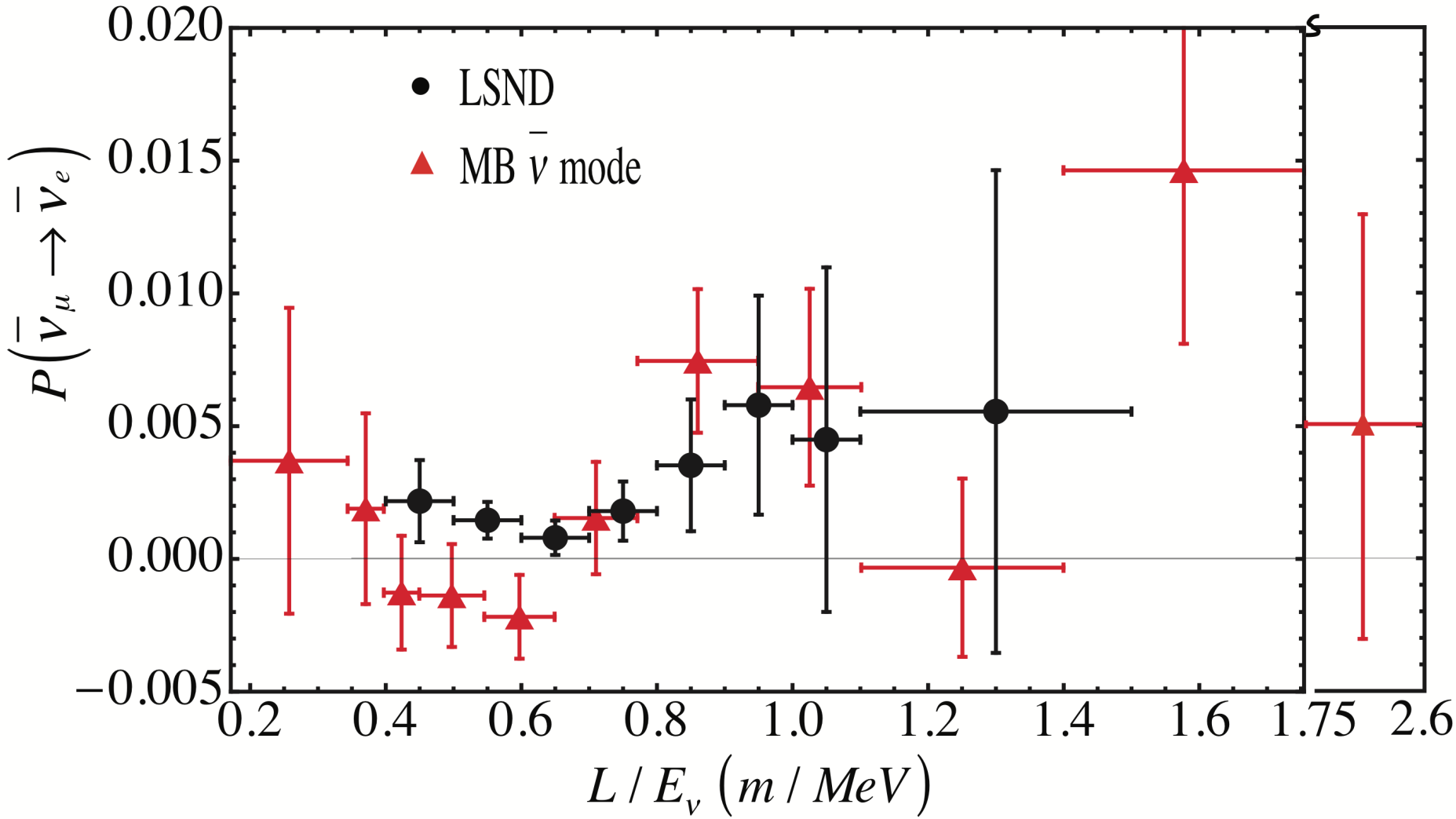
MiniBooNE Oscillation Fit

E>200 MeV

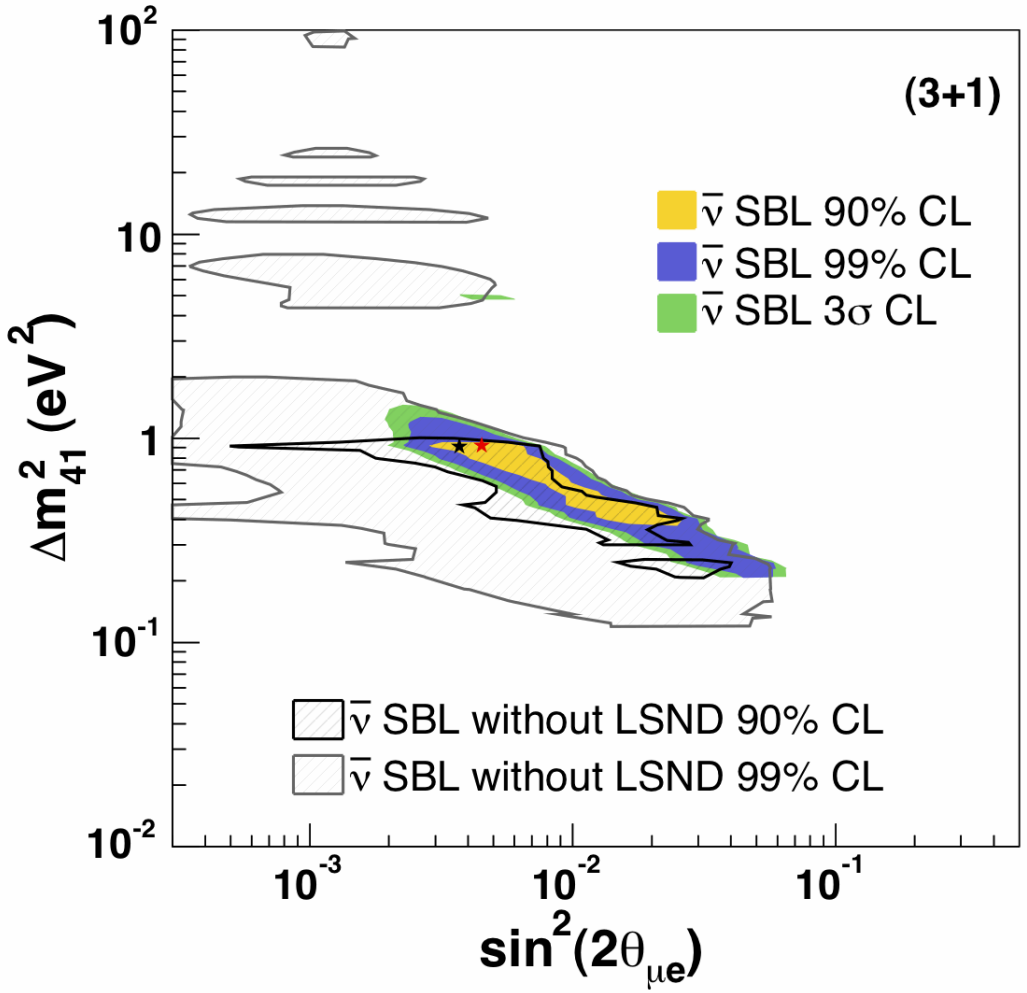
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed



LSND & MiniBooNE Data



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



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

Best 3+1 Fit:
$\Delta m^2_{41} = 0.92$ eV^2
$\sin^2 2\theta_{\mu e} = 0.0045$
$\chi^2 = 85.0/103$ DOF
Prob. = 90%

Predicts $\bar{\nu}_\mu$ & $\bar{\nu}_e$ disappearance of $\sin^2 2\theta_{\mu\mu} \sim 37\%$ and $\sin^2 2\theta_{ee} \sim 4.3\%$

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

In general, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < ¼\, P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x)\, P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$

Reactor Experiments: $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) < 5\%$

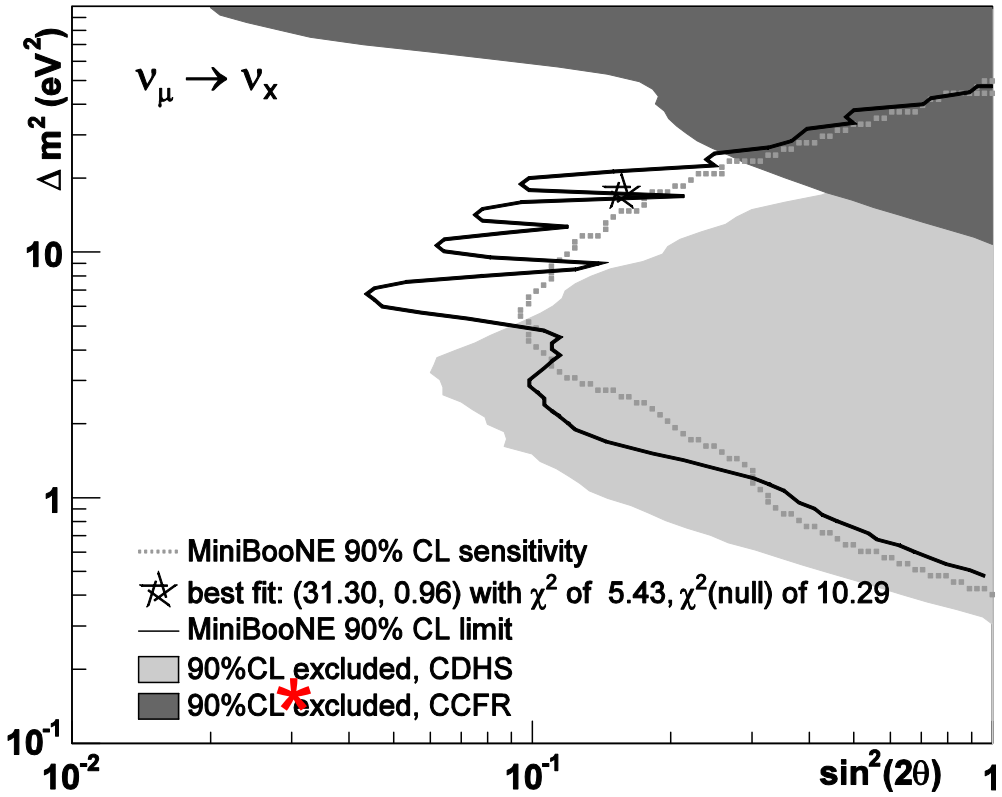
LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

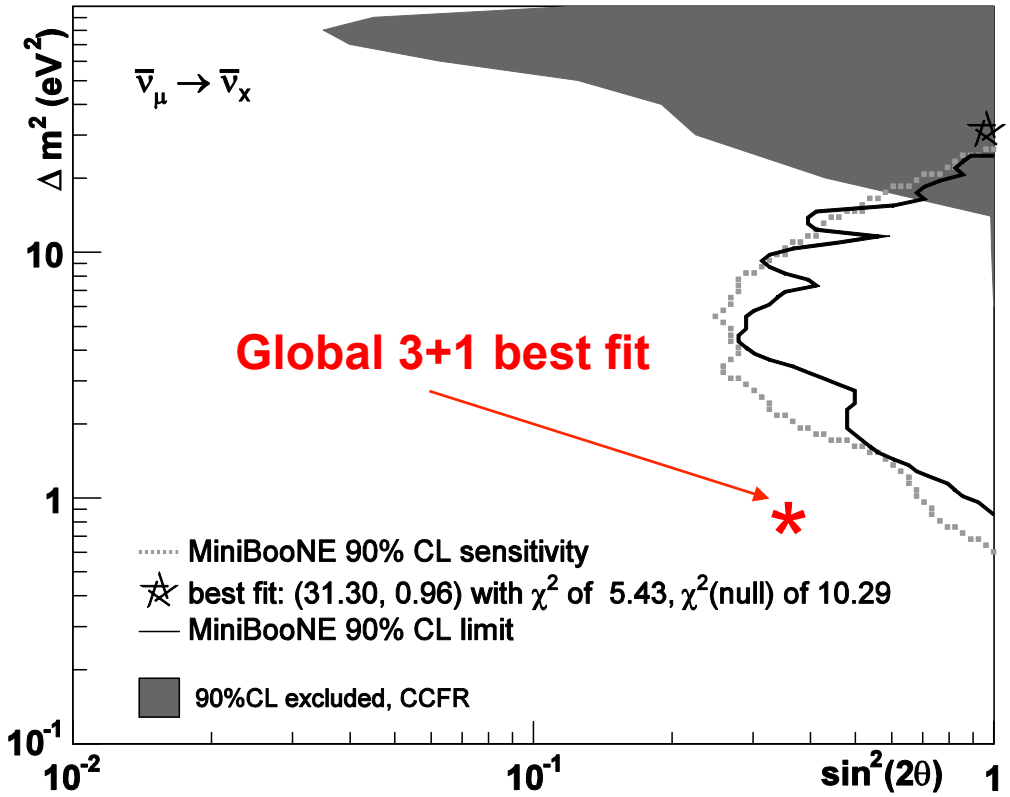
Therefore: **$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 20\%$**

(Assuming the light neutrinos are mostly active and the heavy neutrinos are mostly sterile.)

MiniBooNE Neutrino & Antineutrino Disappearance Limits

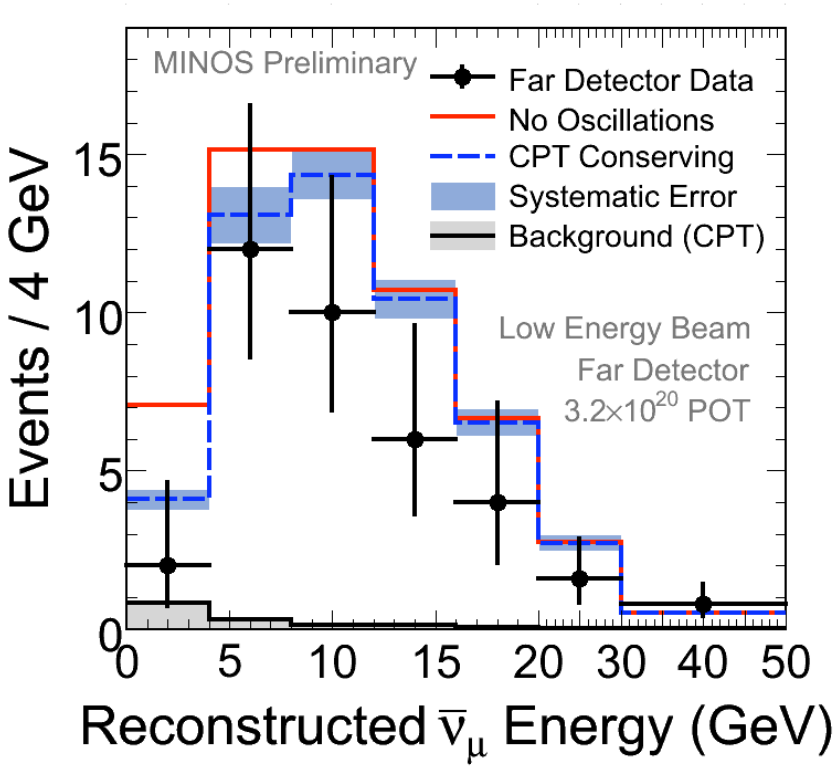
A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

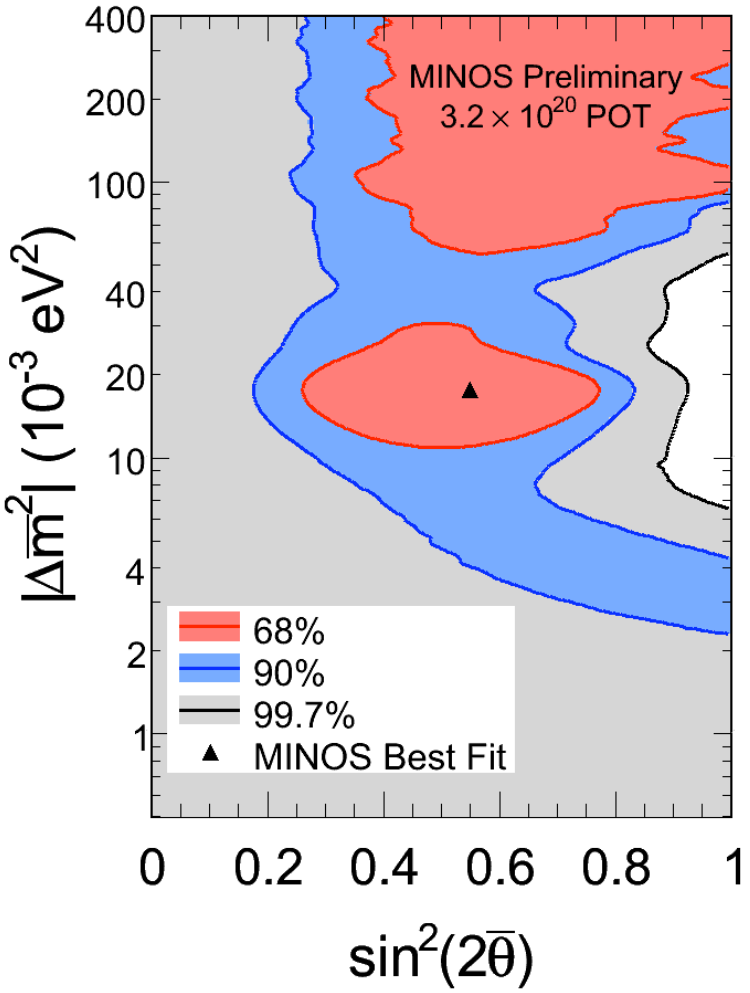




Improved results soon from MiniBooNE/SciBooNE Joint Analysis!

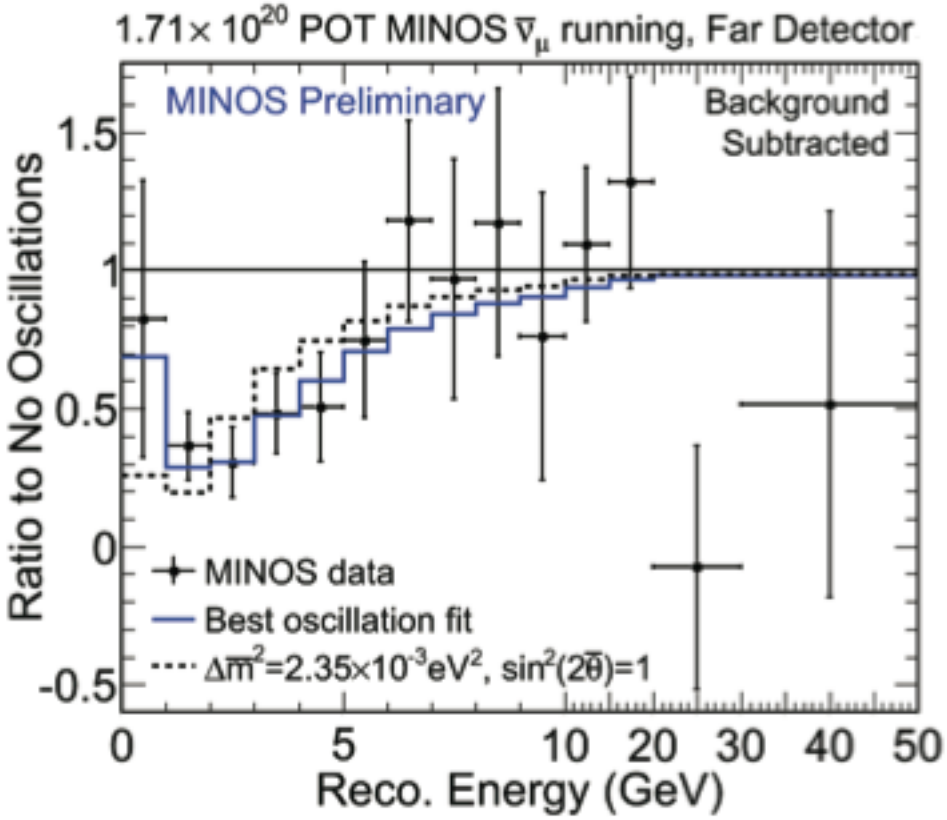
Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in ν Mode

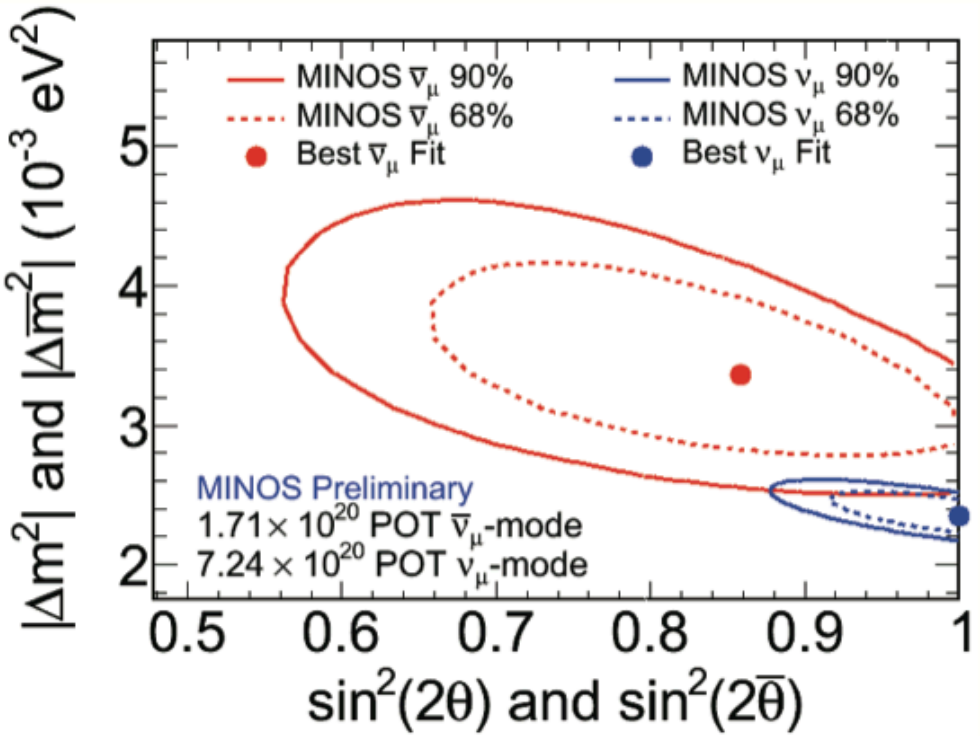




Expect $\bar{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.

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

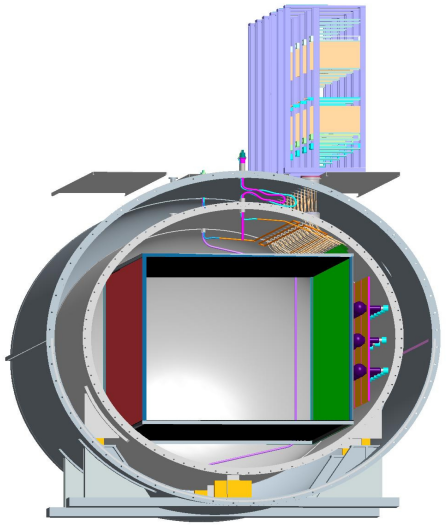




Expect $\bar{\nu}_\mu$ disappearance above 10 GeV for LSND neutrino oscillations.

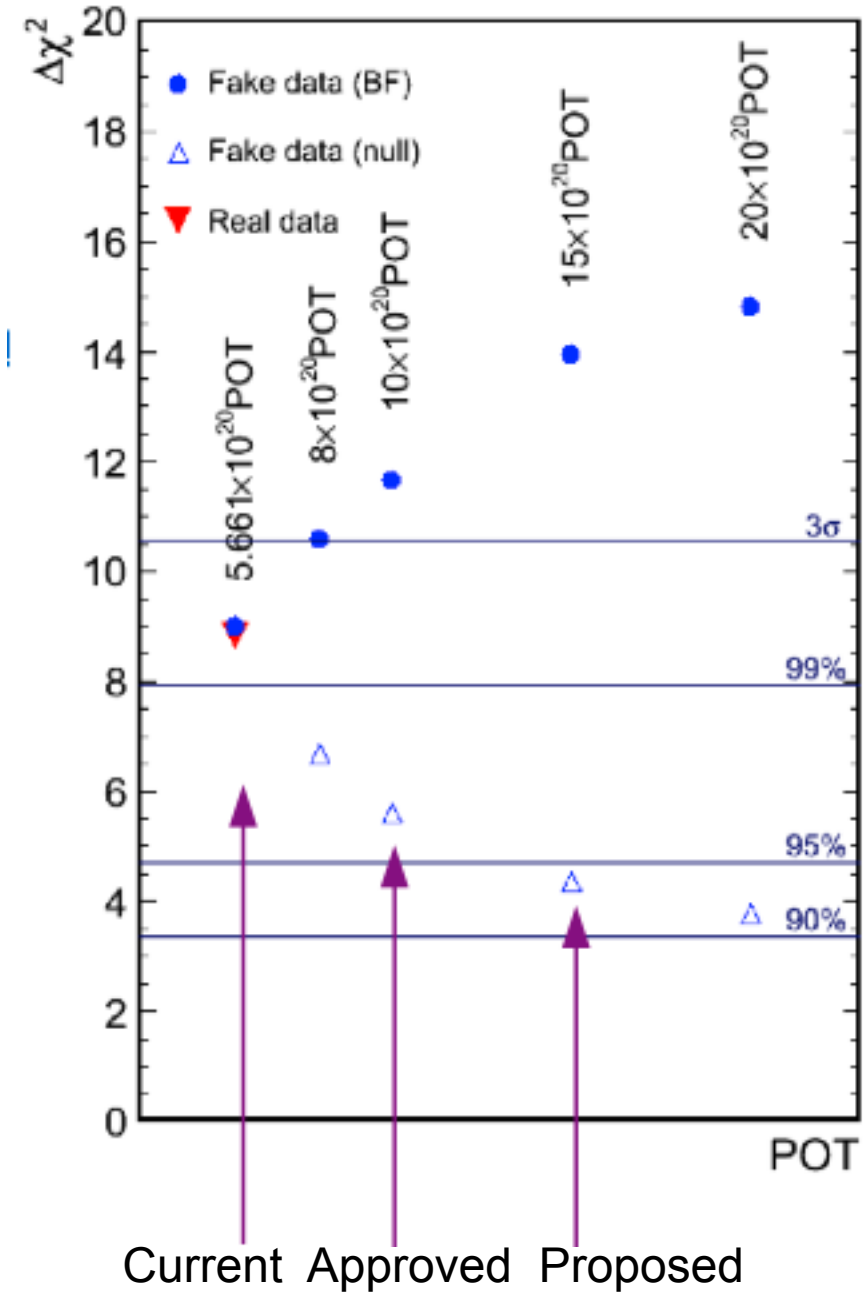
Future Experiments

- More MiniBooNE $\overline{\nu}$ Data (15E20 POT)
- MicroBooNE
  - CD1 approved
  - Address low energy excess



- Few ideas under consideration: (talk by Mills)
  - Move or build a MiniBooNE like 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/)

More MiniBooNE Antineutrino Running



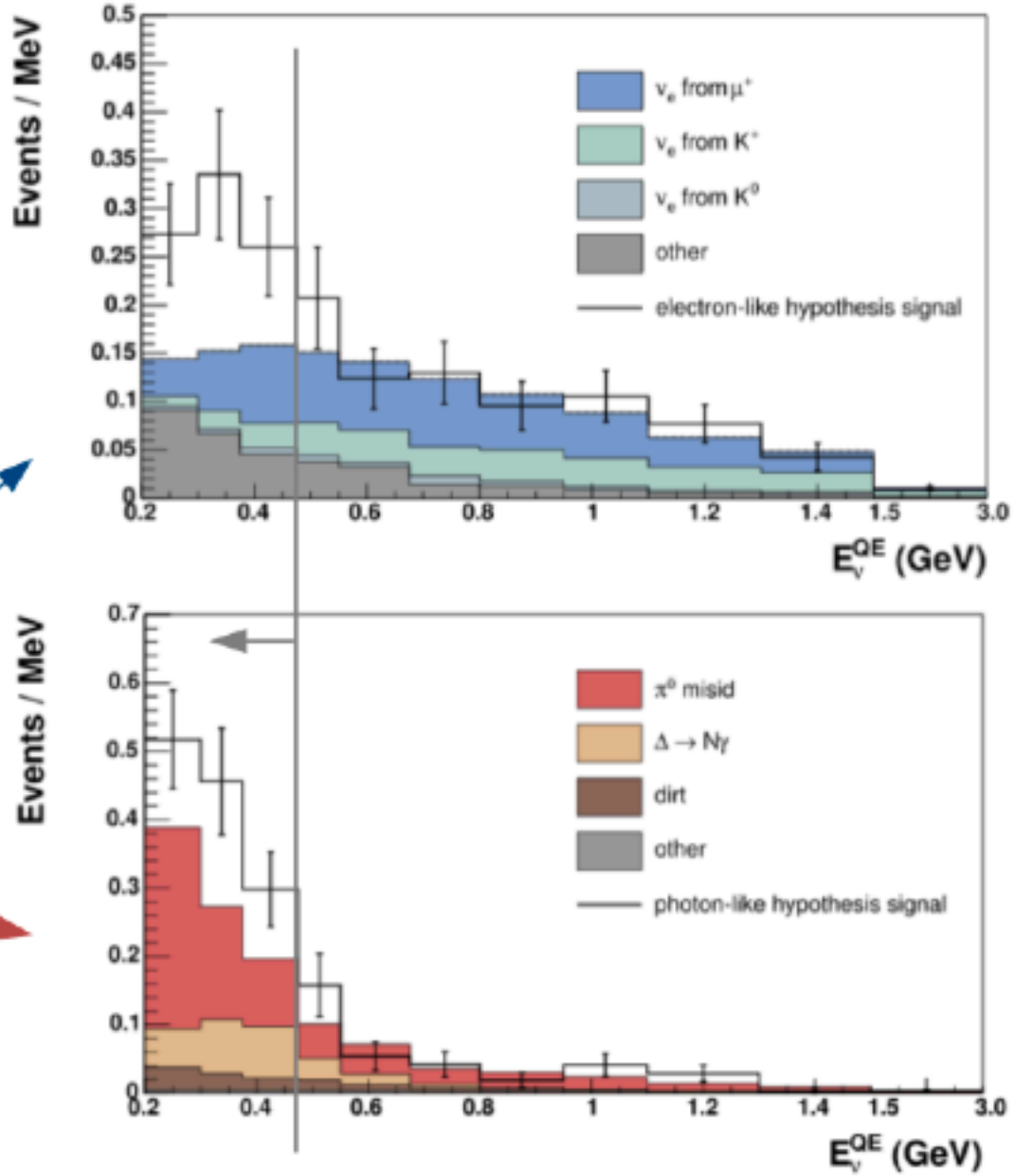
MicroBooNE

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



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.

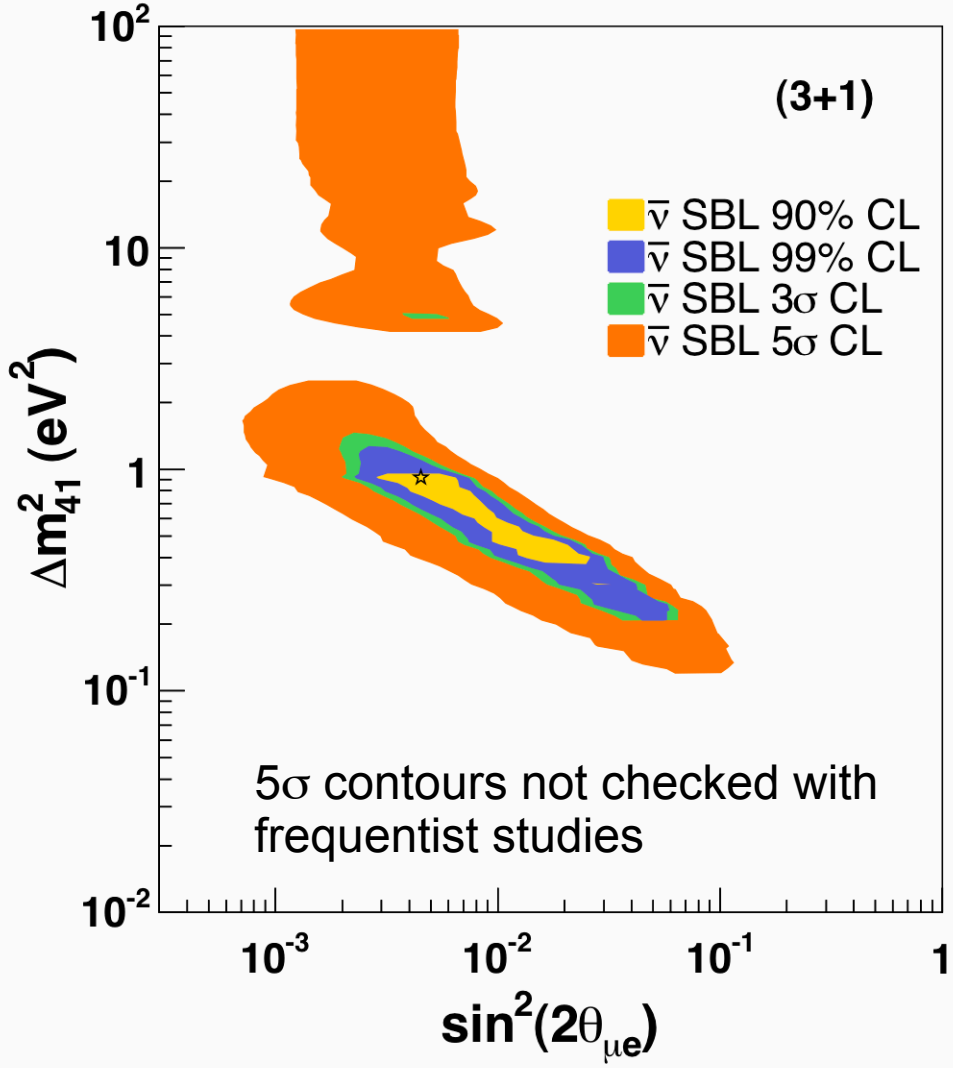
• The MiniBooNE $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillation allowed region appears to be different from the ν_μ -> ν_e oscillation allowed region. (CP Violation?)

• The world antineutrino data fit well to a 3+1 oscillation model with $\Delta m^2 \sim 1$ eV^2. All 3+N models predict large $\bar{\nu}_\mu$ disappearance.

• Future Experiments (BooNE at FNAL, ICARUS at CERN, or OscSNS at ORNL) could measure neutrino oscillations with high significance (>5σ) and prove that sterile neutrinos exist!

Backup

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

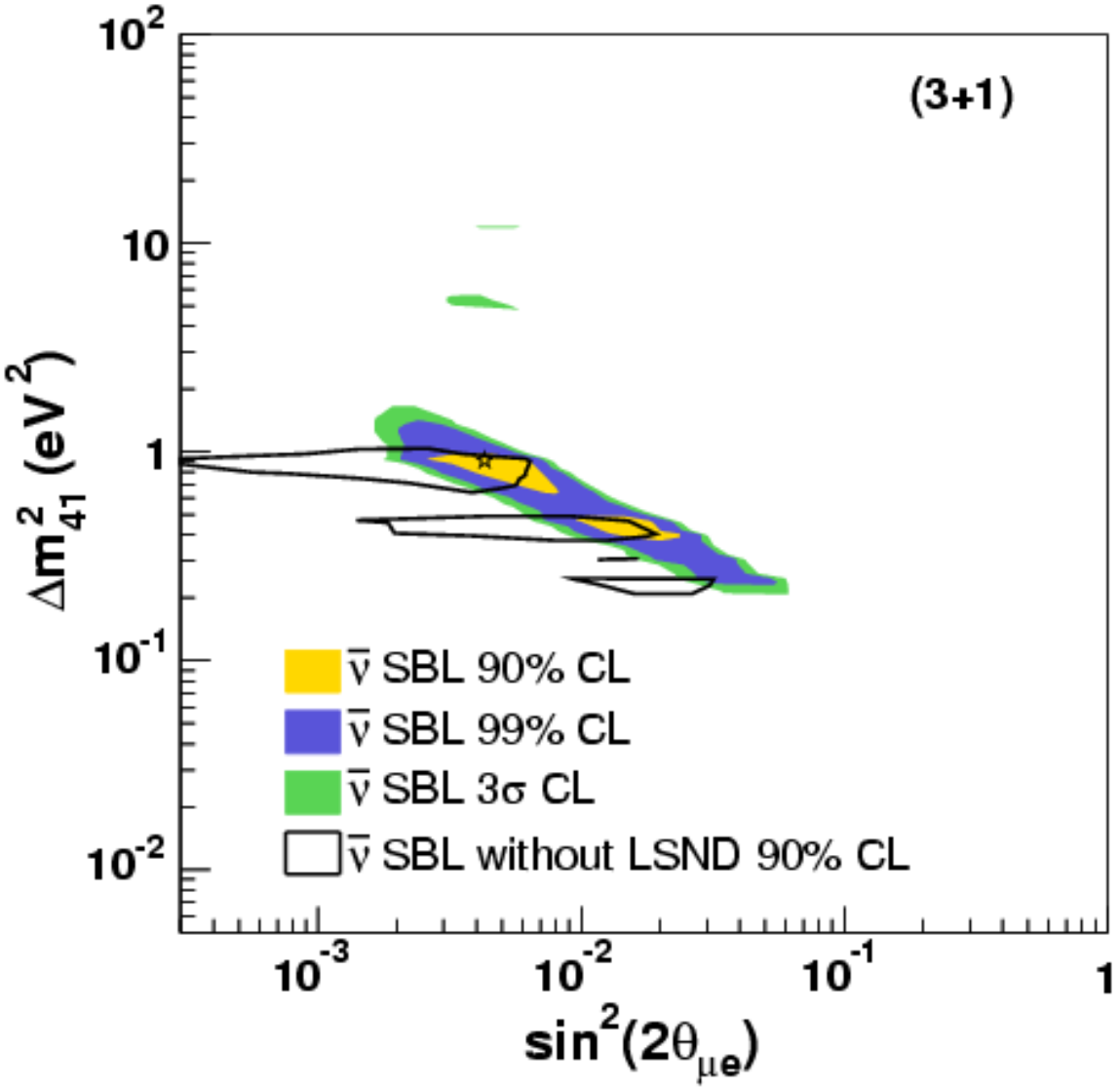


Updated from G. Karagiorgi et al., PRD80, 073001 (2009)

Best 3+1 Fit:
$\Delta m^2_{41} = 0.92$ eV^2
$\sin^2 2\theta_{\mu e} = 0.0045$
$\chi^2 = 85.0/103$ DOF
Prob. = 90%

Predicts $\bar{\nu}_\mu$ & $\bar{\nu}_e$ disappearance of $\sin^2 2\theta_{\mu\mu} \sim 37\%$ and $\sin^2 2\theta_{ee} \sim 4.3\%$

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

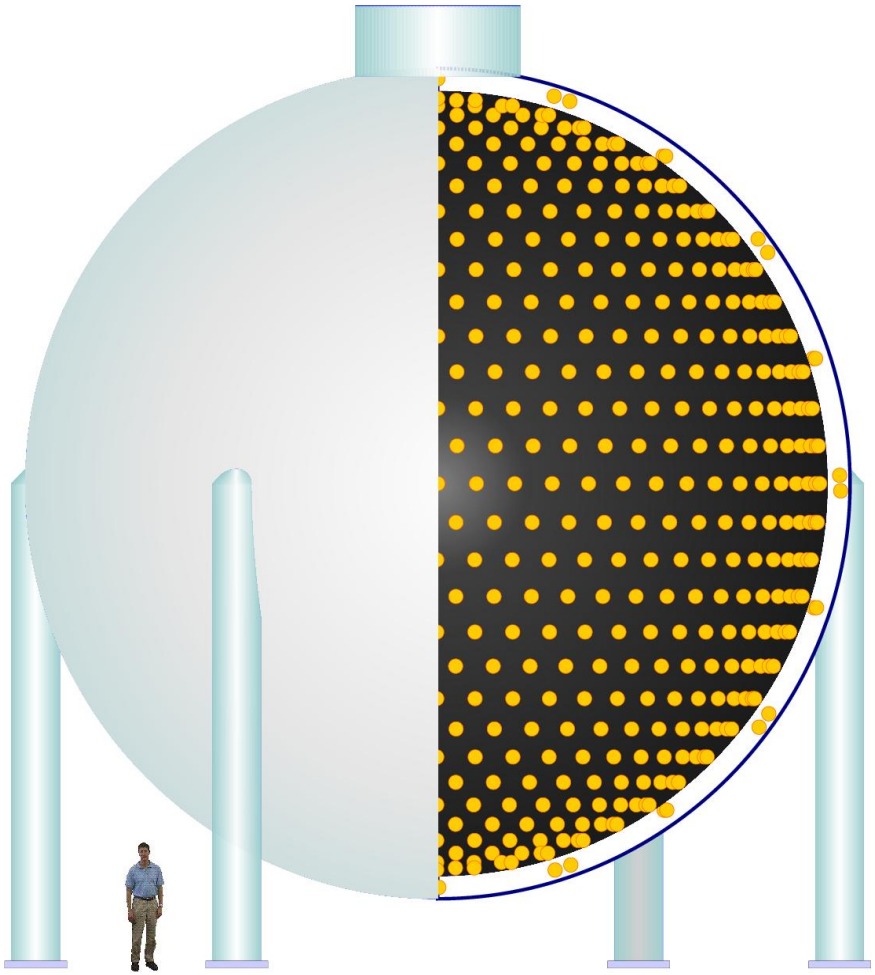


G. Karagiorgi et al., PRD80, 073001 (2009)

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

Predicts $\overline{\nu}_\mu$ & $\overline{\nu}_e$ disappearance of $\sin^2 2\theta_{\mu\mu}$ ~ 35% and $\sin^2 2\theta_{ee}$ ~ 4.3%

The MiniBooNE Detector



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

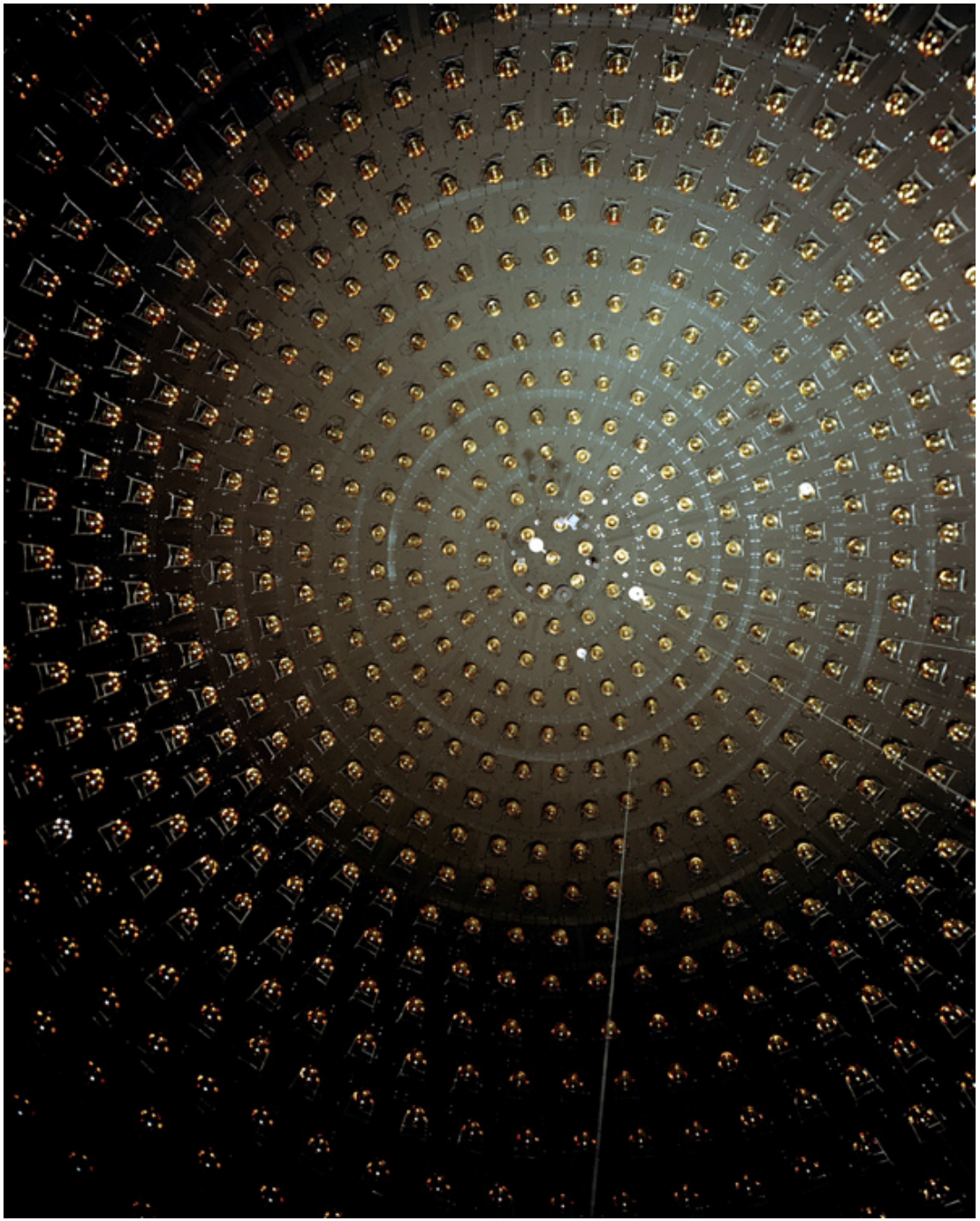
  (10 meter "fiducial" volume)

  - 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

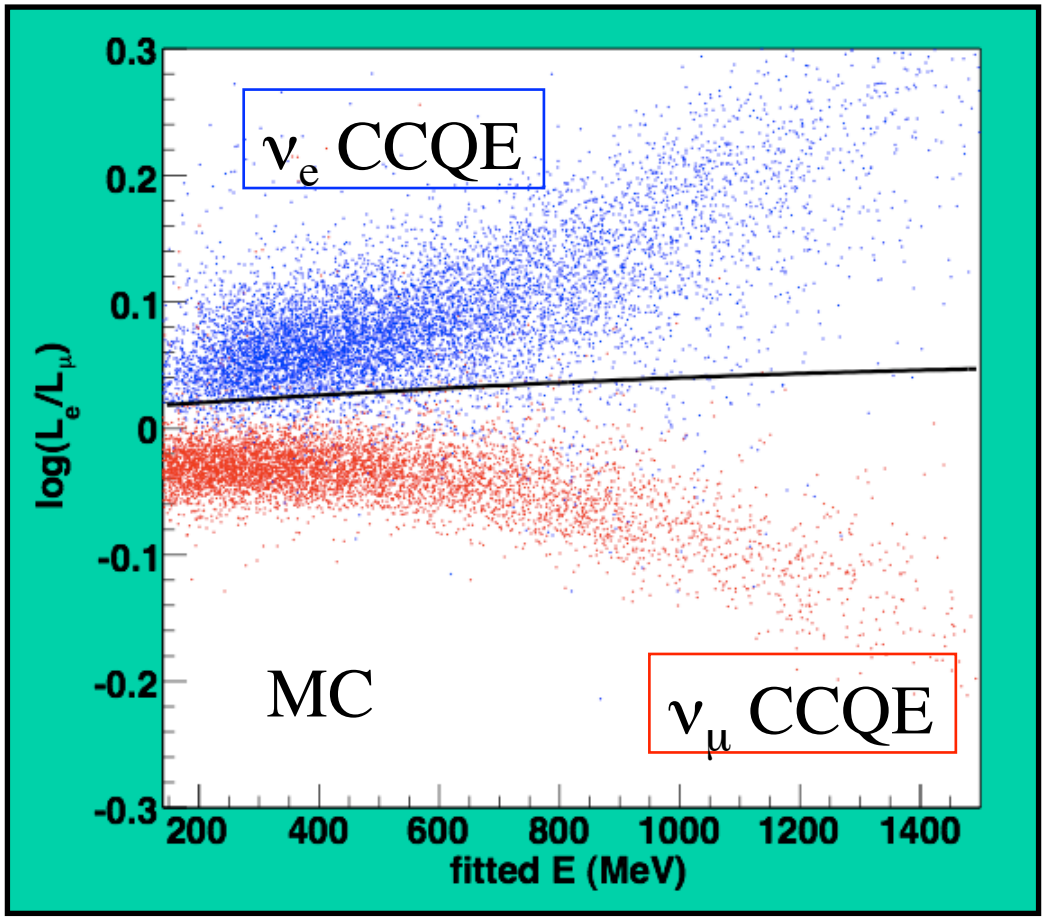
Two types of
Hamamatsu Tubes:
R1408, R5912

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)

$\log(L_e/L_\mu)>0$ favors electron-like hypothesis



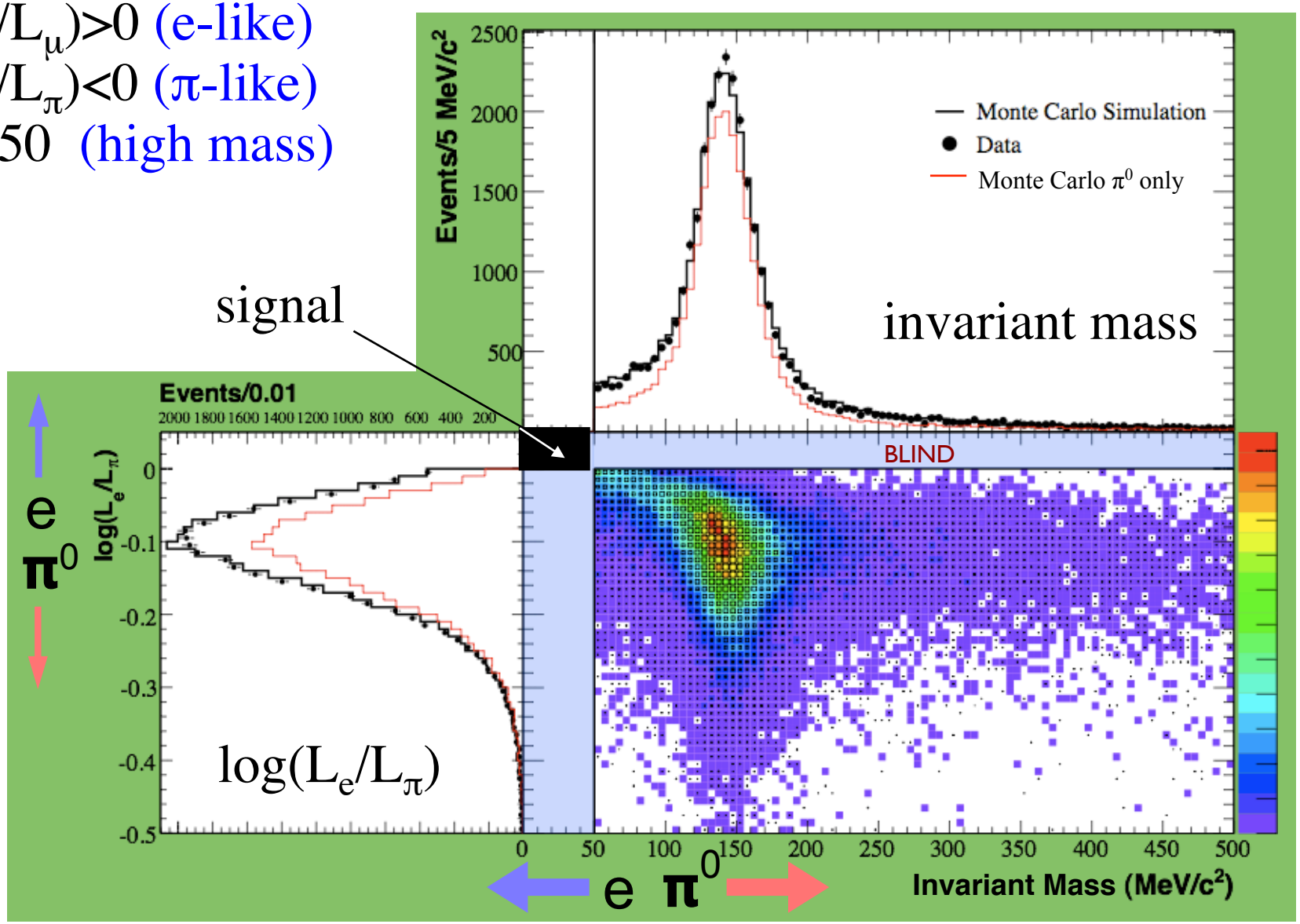
Note: photon conversions are electron-like.
This does not separate e/π^0.

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)



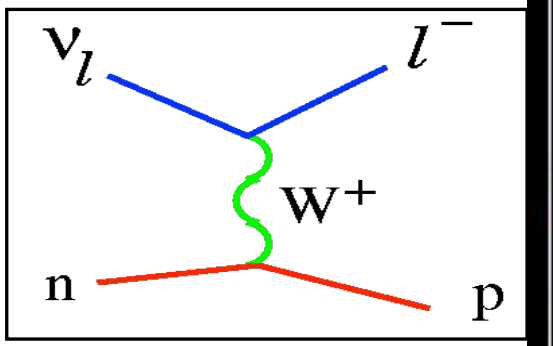
MiniBooNE Detects Cherenkov Light

Pattern of Cerenkov Light Gives Event Type

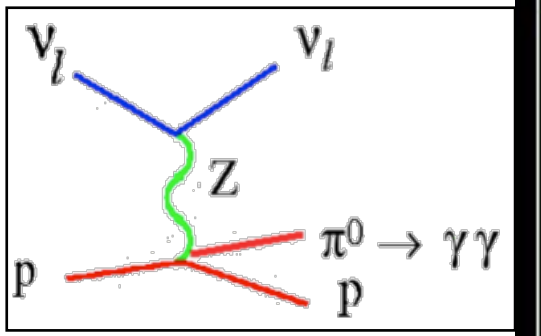
The most important types of neutrino events in the oscillation search:

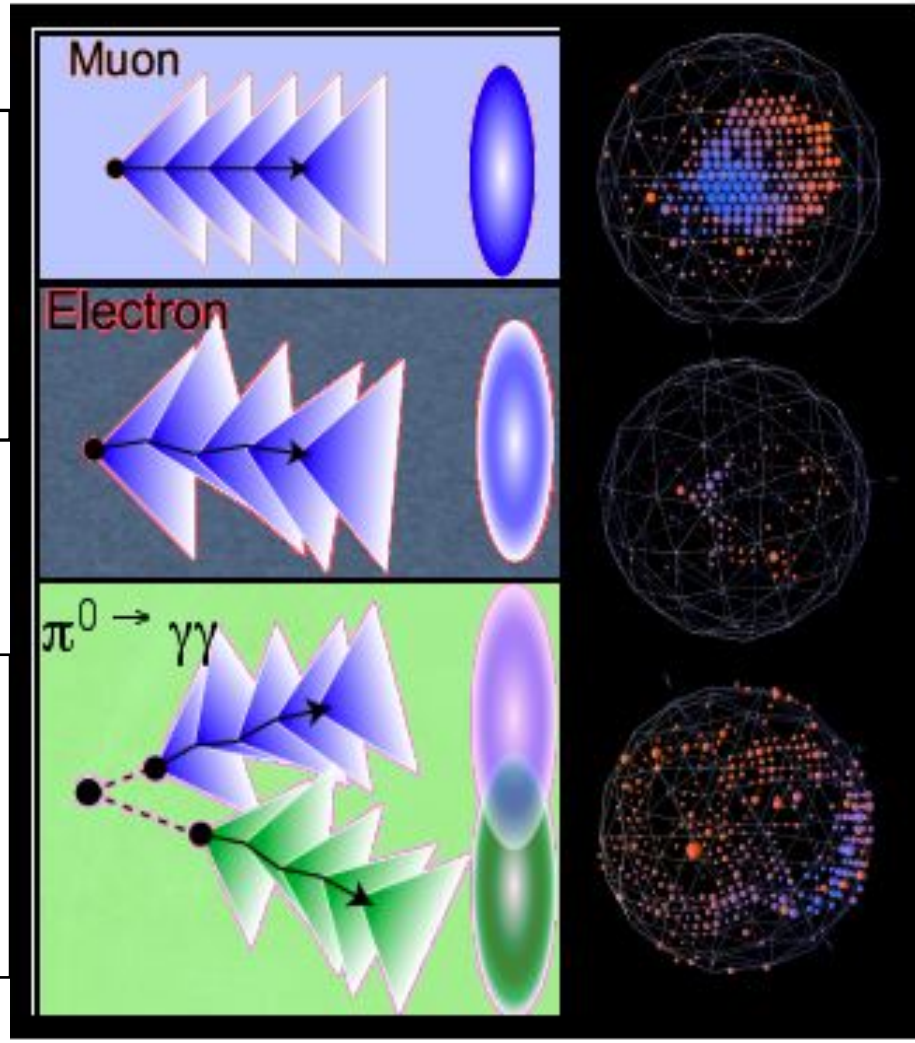
Background Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents
or exiting through veto.

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

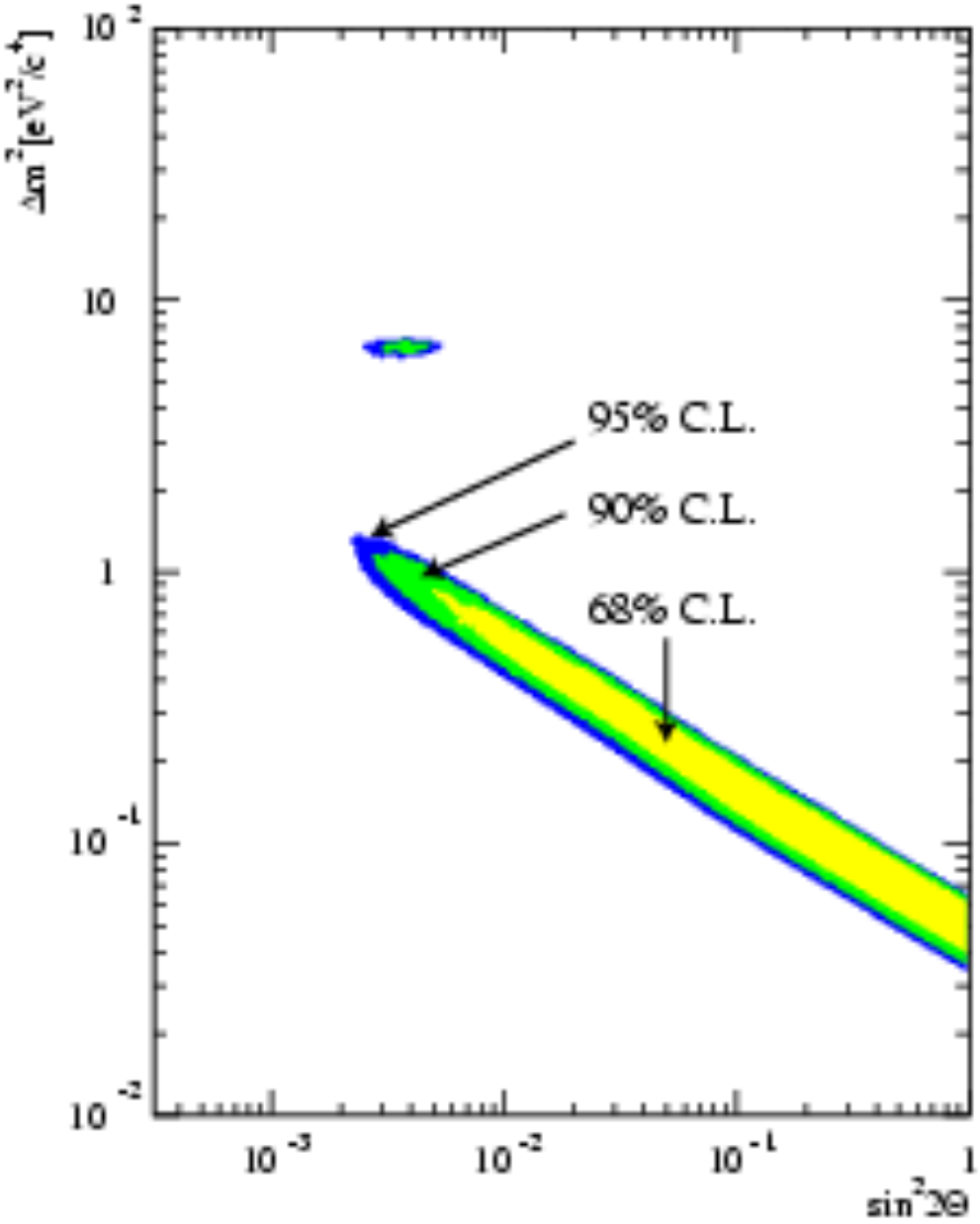


Background π^0s:
Can form a background if one
photon is weak or exits tank.
In NC case, 1 subevent.





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

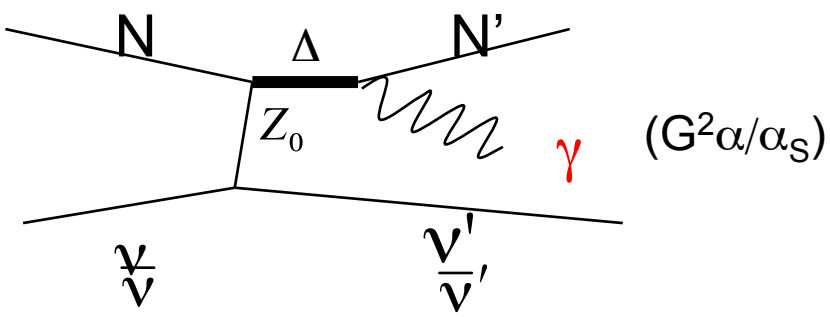
Zhemchugov Seminar: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at CERN on September 14, 2010

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.

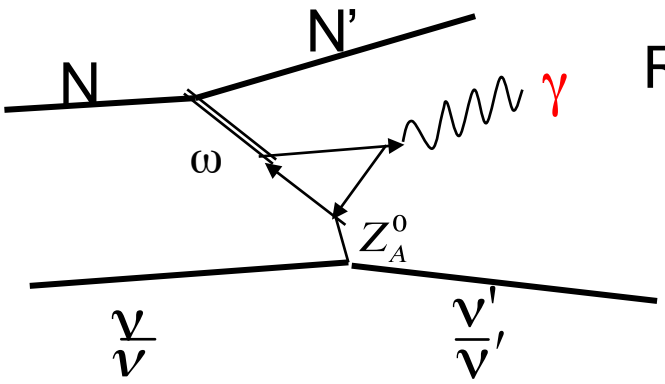
Note that LSND measures the correct rate of $\bar{\nu}_\mu$ p -> μ^+ n interactions, which confirms the π^- production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV!

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

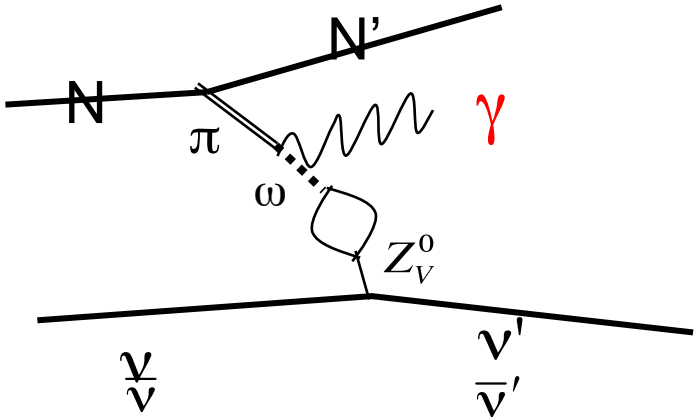
Dominant process accounted for in MC!



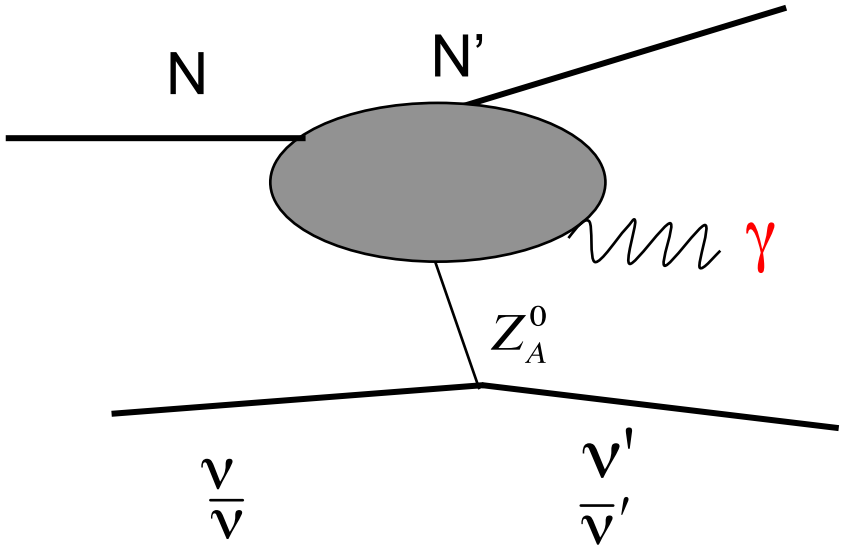
Radiative Delta Decay



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:

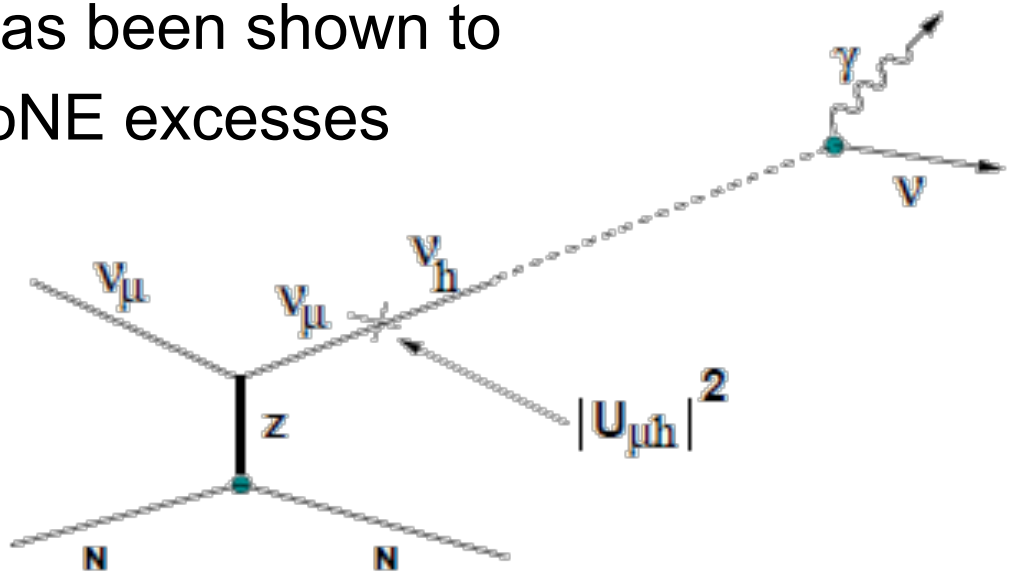
R. Hill, arXiv:0905.0291

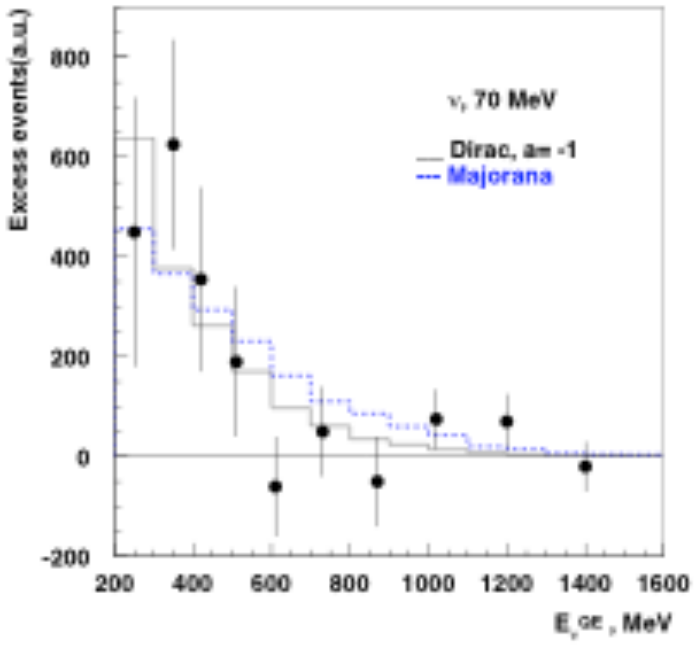
Jenkins & Goldman, arXiv:0906.0984

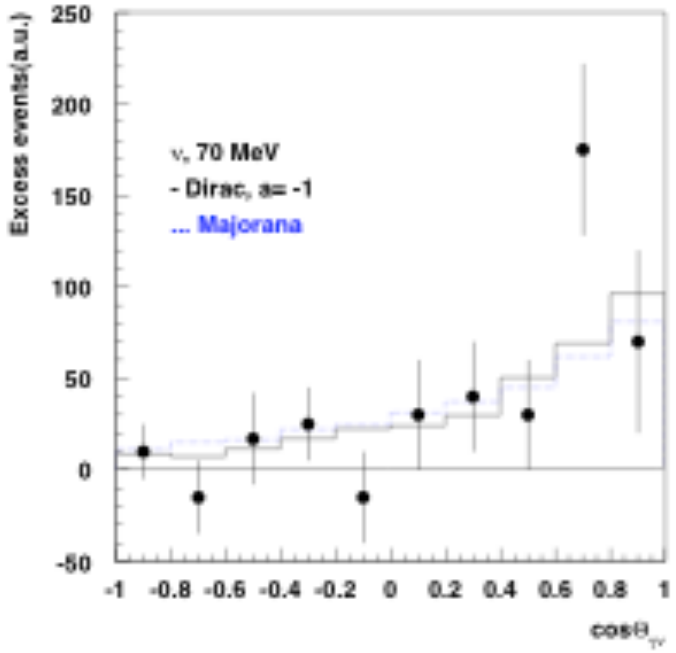
Sterile ν Decay?

- 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

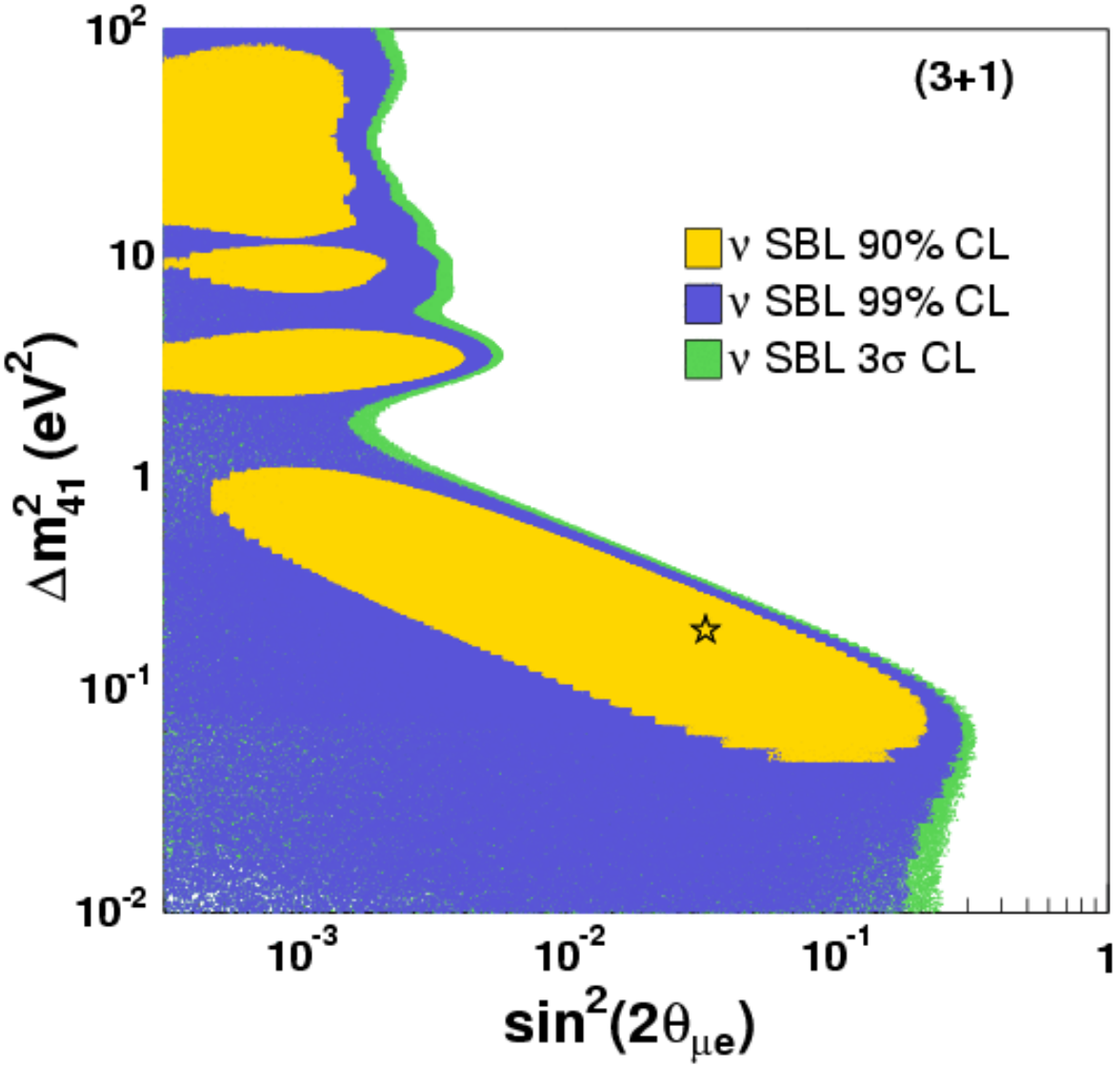






More Complicated ν Oscillations?

3+1 Global Fit to World Neutrino Data Only



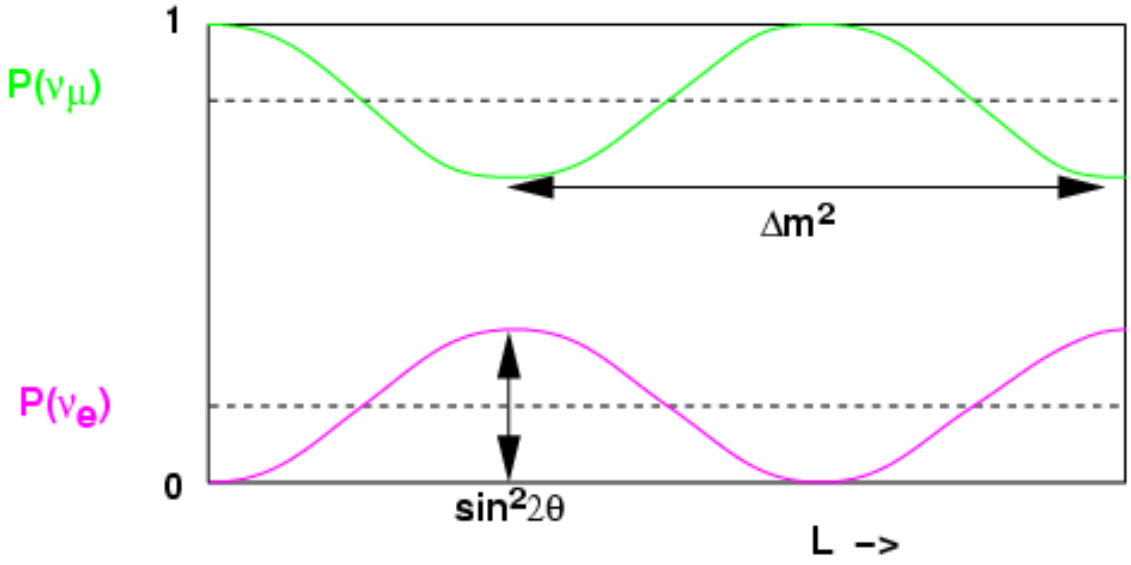
G. Karagiorgi et al., arXiv:0906.1997

Best 3+1 Fit:
Δm_{41}^2 = 0.19 eV²
$\sin^2 2\theta_{\mu e}$ = 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%

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

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

As N increases, the formalism gets rapidly more complicated!

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

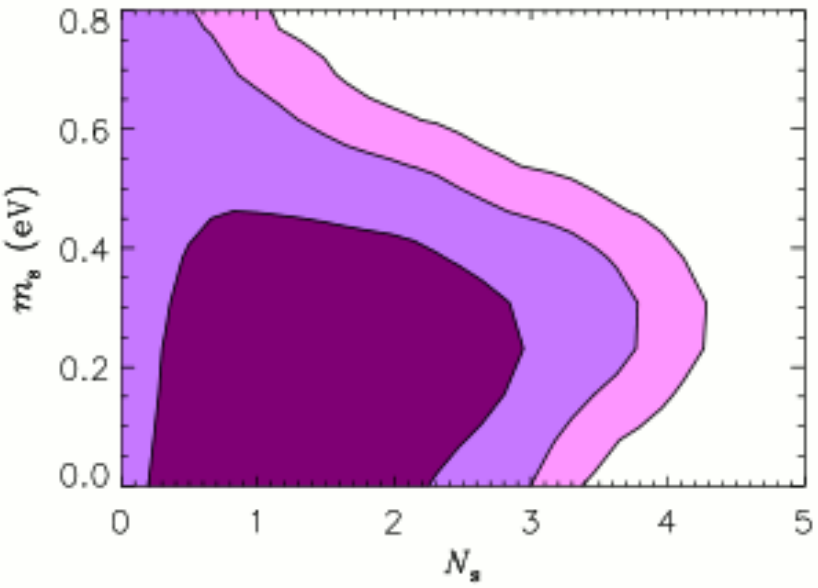
T & CP & CPT Violation in the Lepton Sector

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

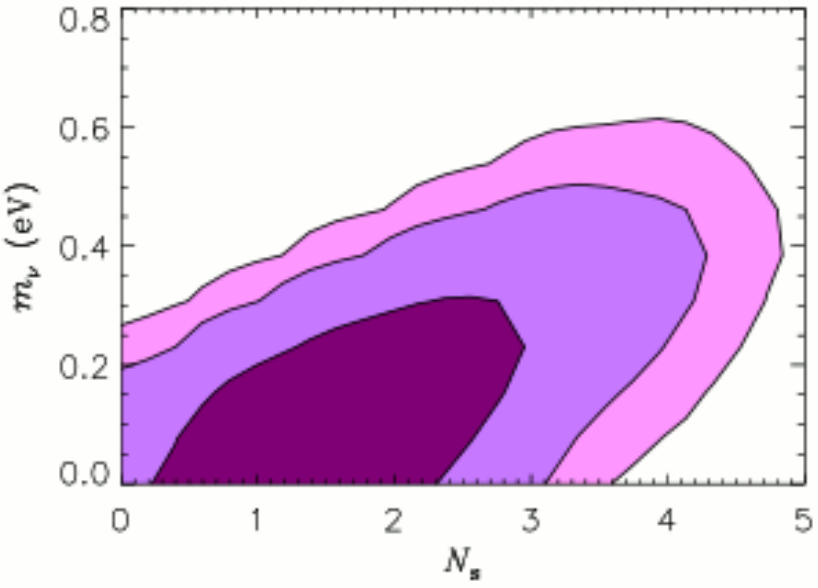
$\nu_\alpha \rightarrow \nu_\beta \neq \overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta$ CP Violation

$\nu_\alpha \rightarrow \nu_\beta \neq \overline{\nu}_\beta \rightarrow \overline{\nu}_\alpha$ CPT Violation

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

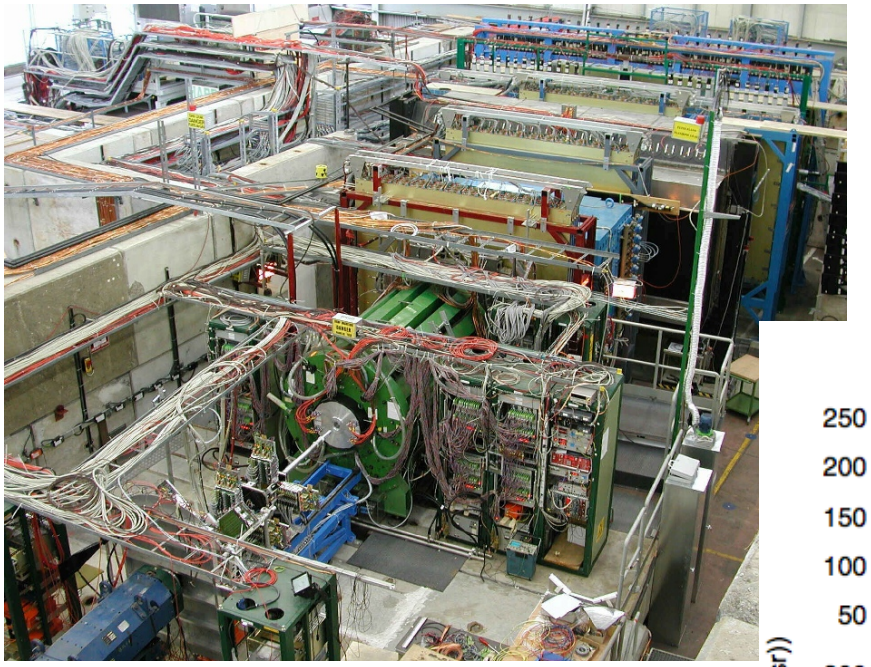


$3 + N_s$
$m_\nu = 0$



$3 + N_s$
$m_s = 0$

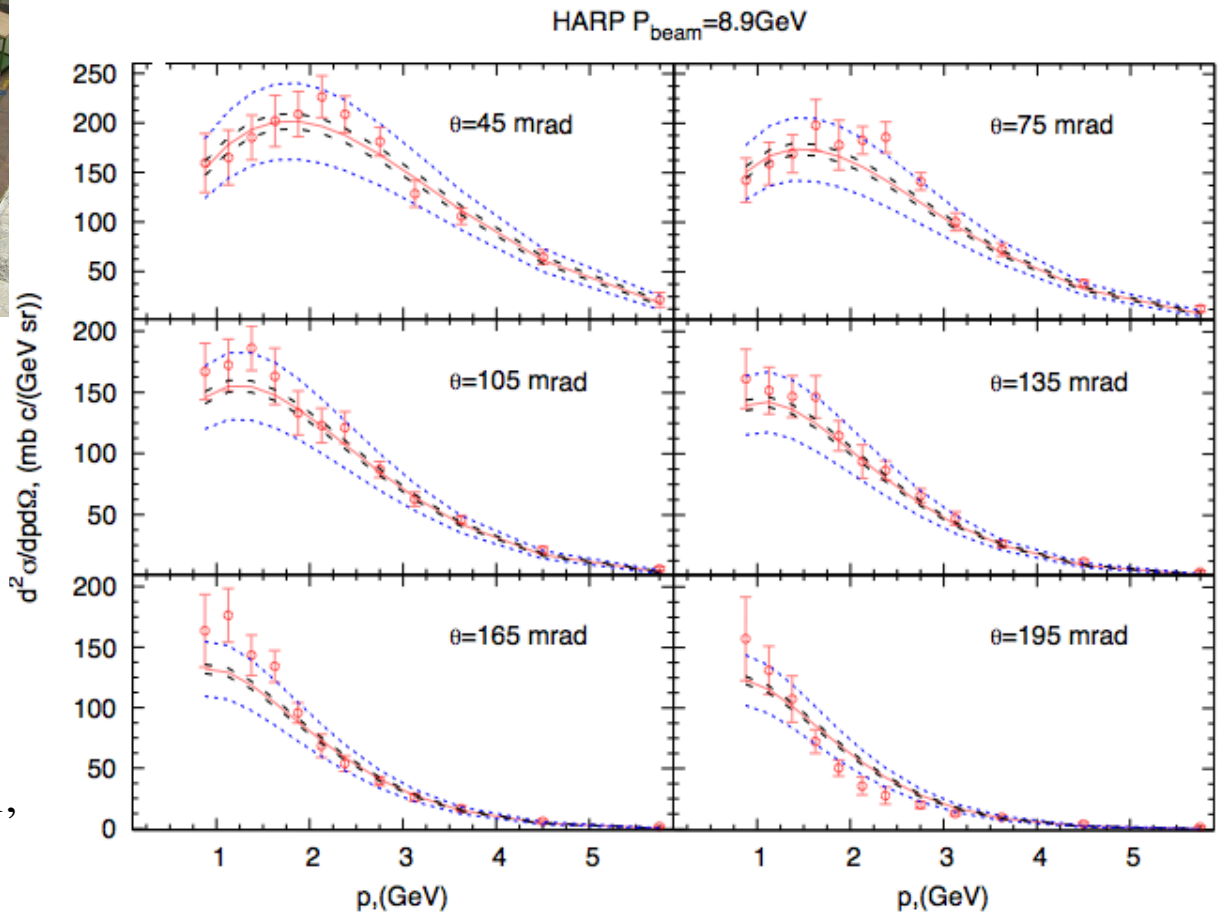
Modeling Production of Secondary Pions



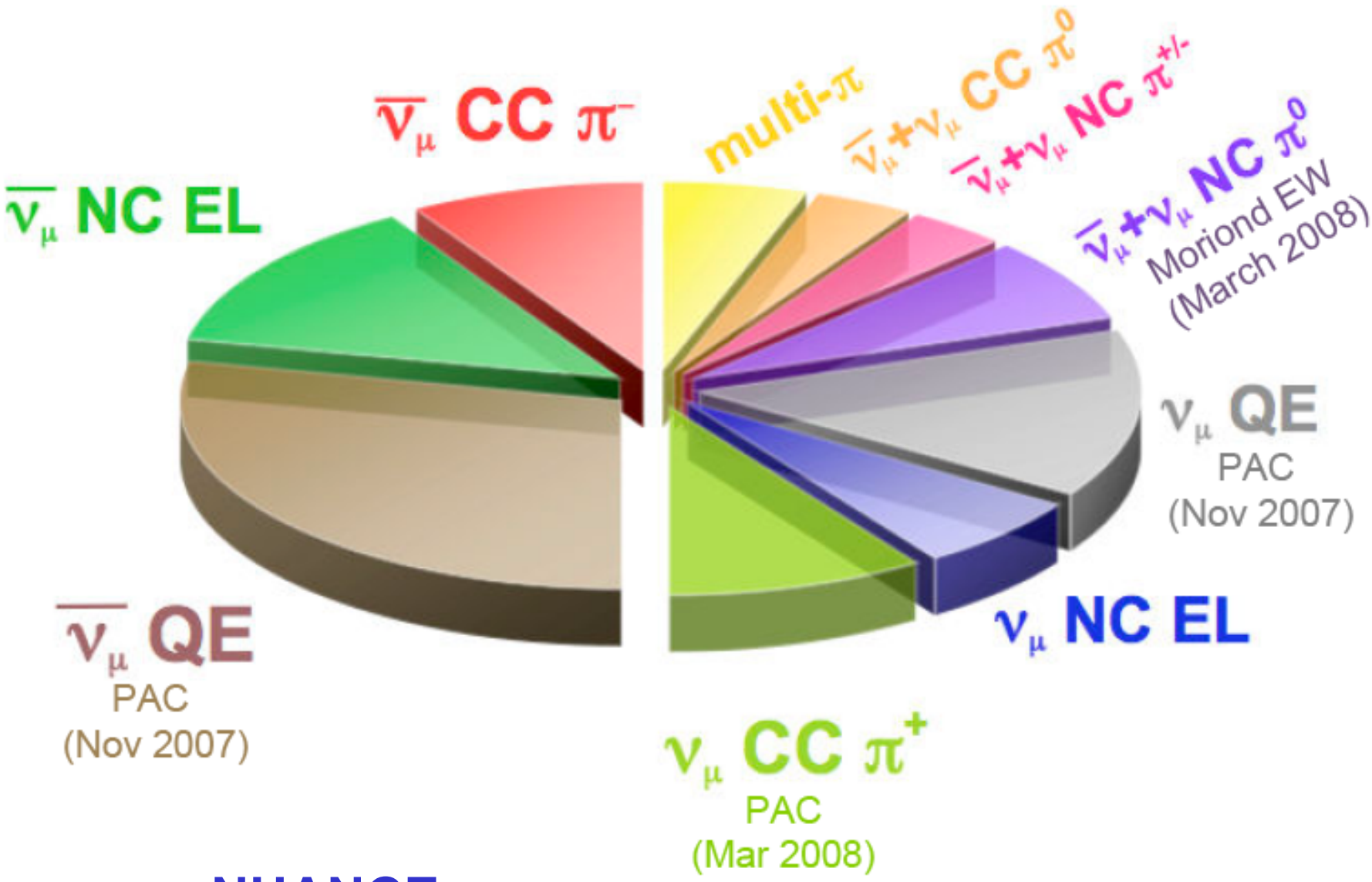
- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum
  - π^+ & π^-

Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024



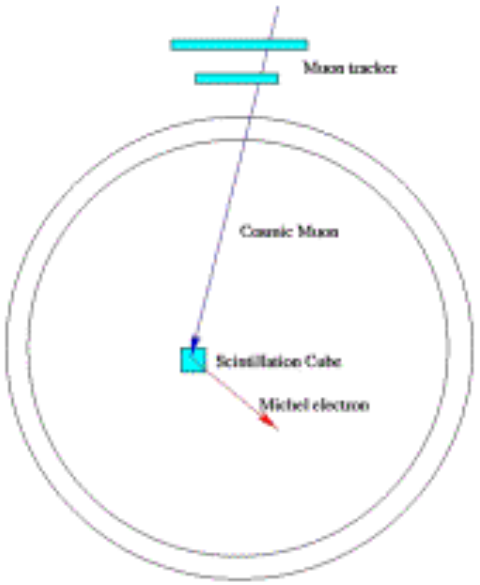
Antineutrino Cross Sections

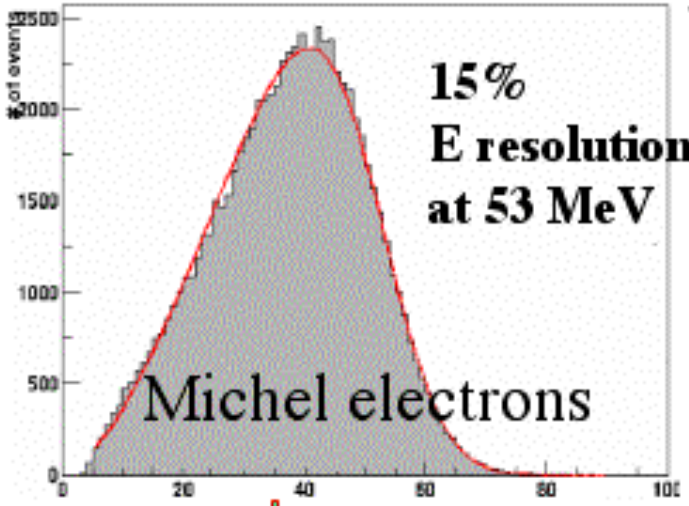


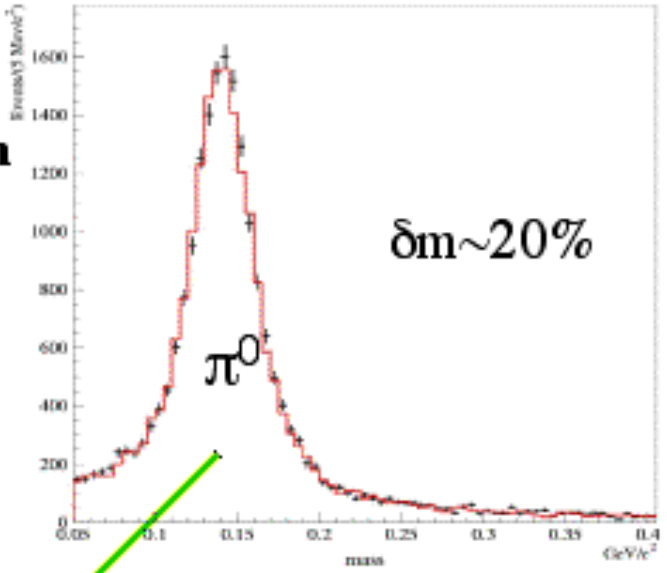
NUANCE

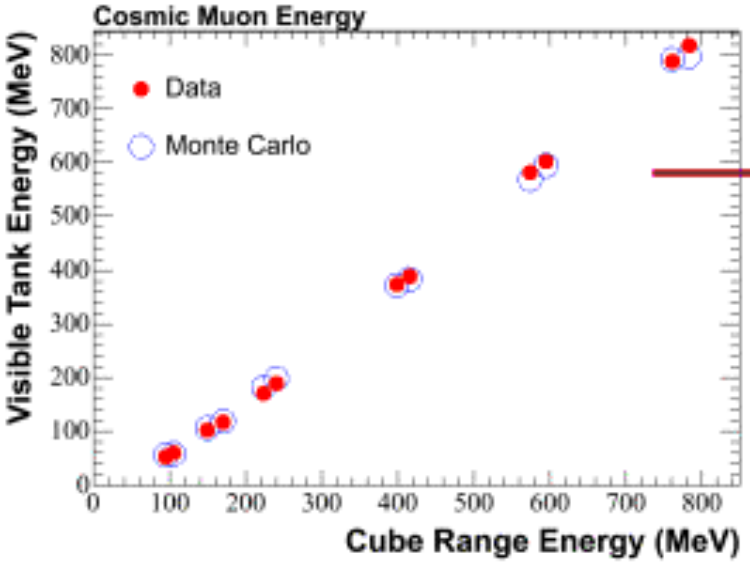
Calibration Sources

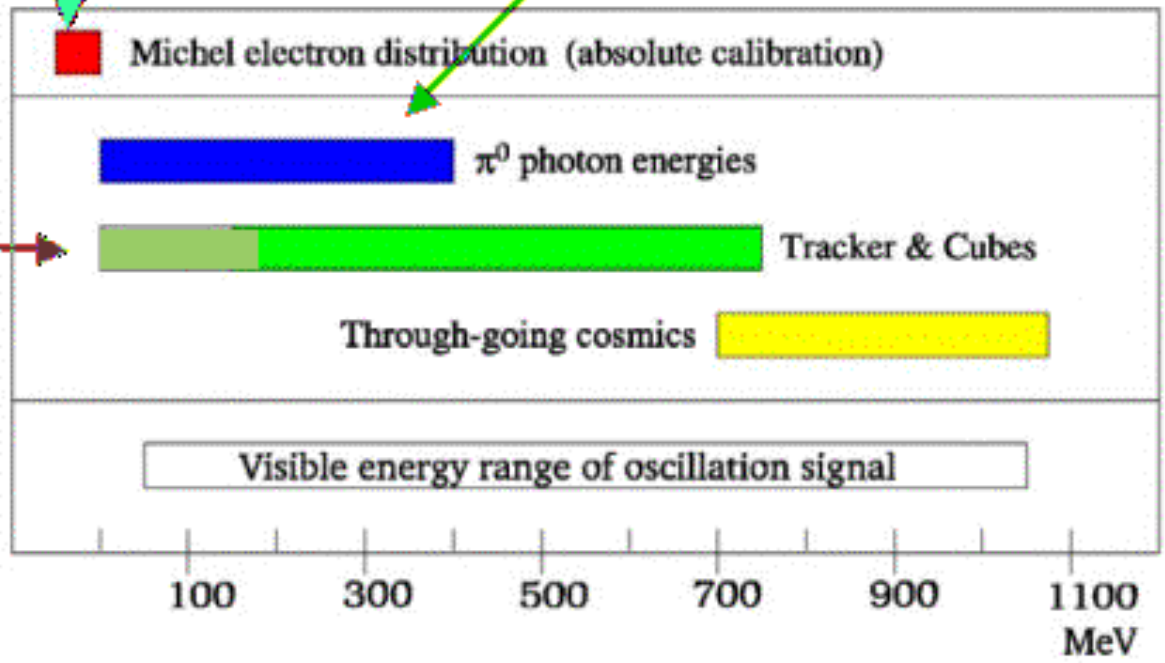
Tracker system











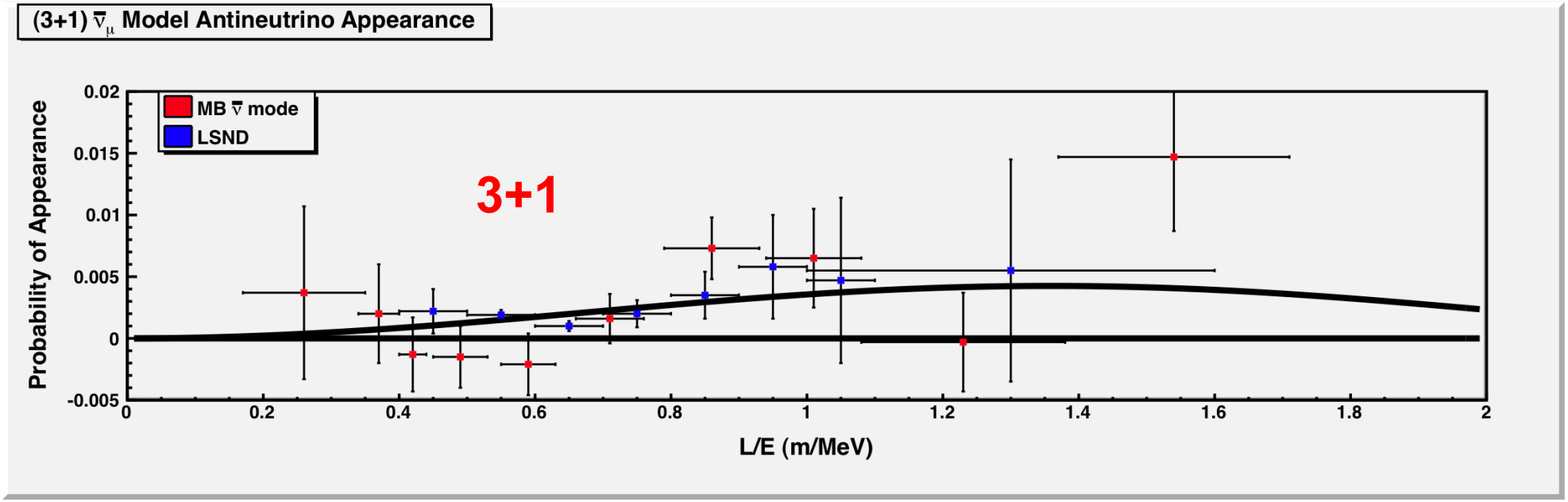
Number of Excess Events

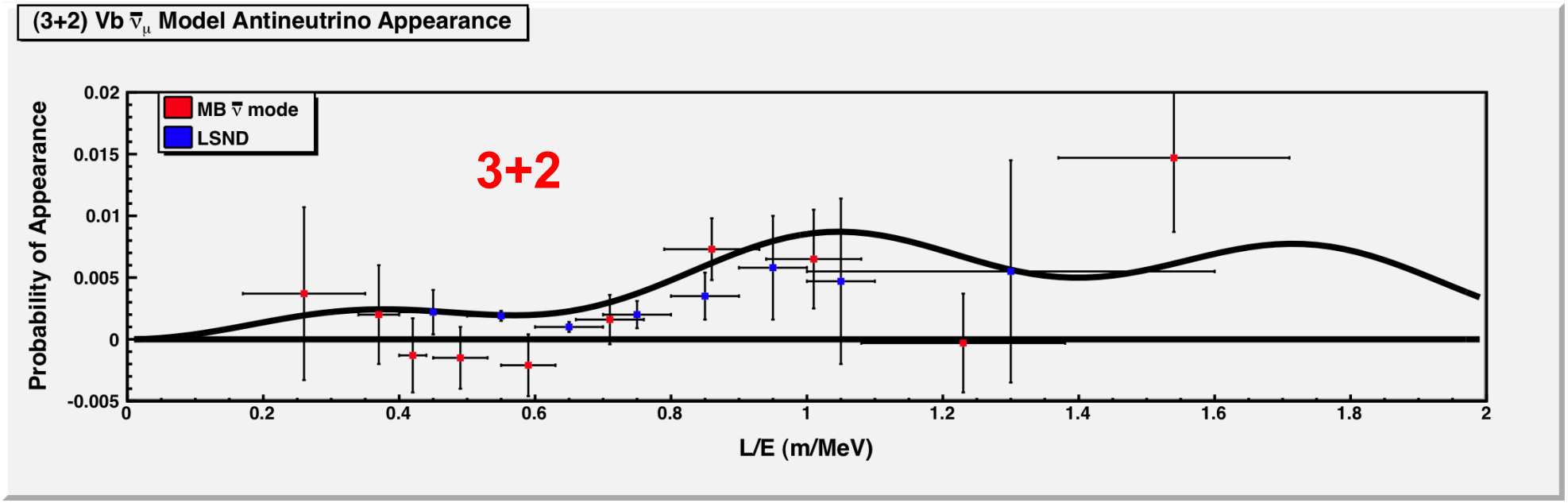
Energy (MeV)	**Data**	**Background**	**Excess**	**#σ_{tot}**	**(#σ_{stat})**
200-300	232	186.8+-26.0	45.2+-13.7+-22.1	1.7	(3.3)
300-475	312	228.3+-24.5	83.7+-15.1+-19.3	3.4	(5.5)
200-475	544	415.2+-43.4	128.8+-20.4+-38.3	3.0	(6.3)
475-1250	408	385.9+-35.7	22.1+-19.6+-29.8	0.6	(1.1)
200-1250	952	801.0+-58.1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

Number of Excess Events

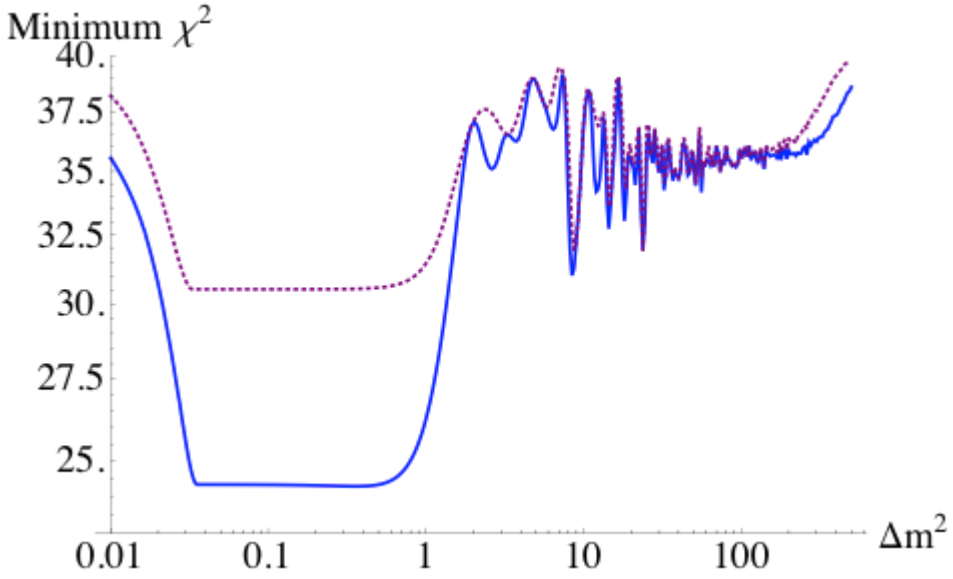
Energy (MeV)	Data	Background	Excess	$\#\sigma_{tot}$	($\#\sigma_{stat}$)
200-475	119	100.5+-14.3	18.5+-10.0+-10.2	1.3	(1.9)
475-675	64	38.3+-7.2	25.7+-6.2+-3.7	3.6	(4.1)
475-1250	120	99.1+-14.0	20.9+-10.0+-9.8	1.5	(2.1)
475-3000	158	133.3+-18.0	24.7+-11.5+-13.8	1.4	(2.1)
200-3000	277	233.8+-22.5	43.2+-15.3+-16.5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

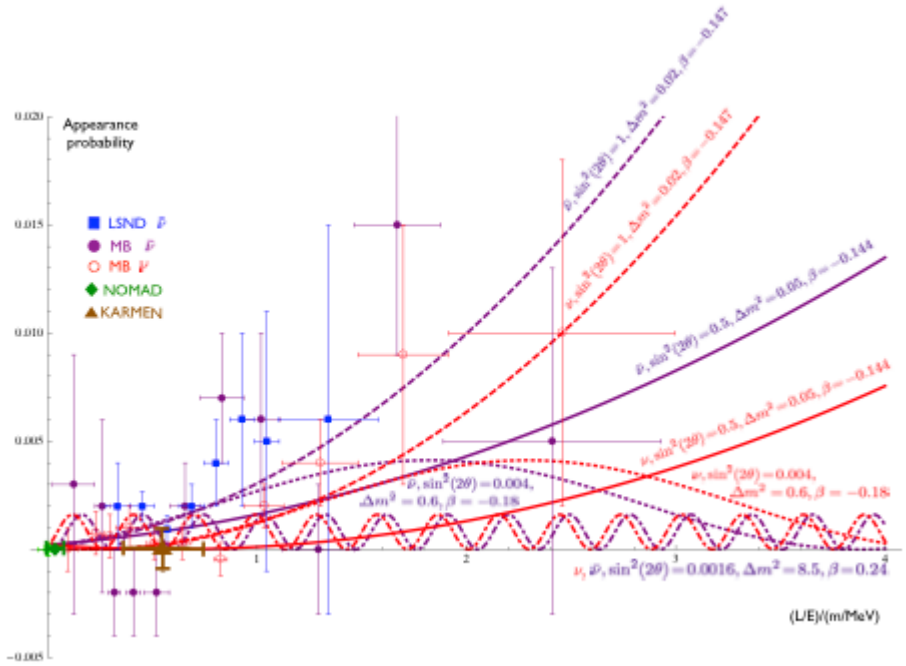
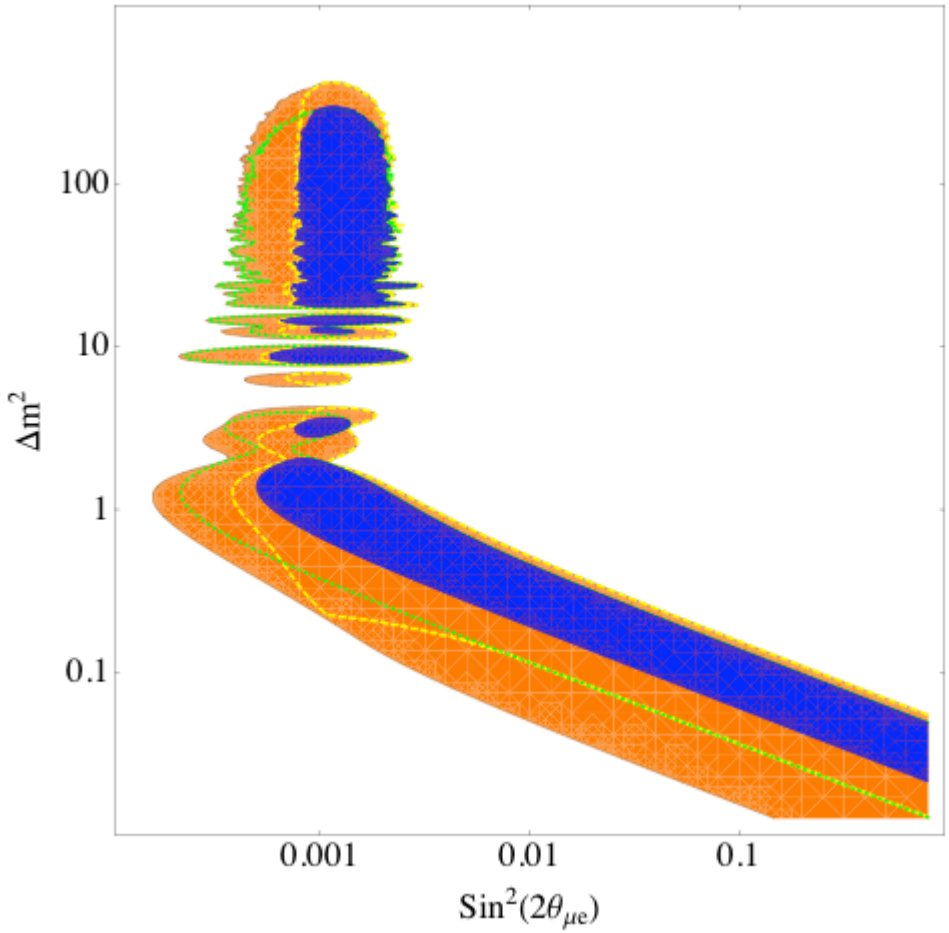
LSND/MiniBooNE Data Compared to 3+N Global Fits





3+2 Global Fit to the World ν & $\bar{\nu}$ Data





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