# *First $\nu$ Oscillations Results from MiniBooNE*

September 21, 2007
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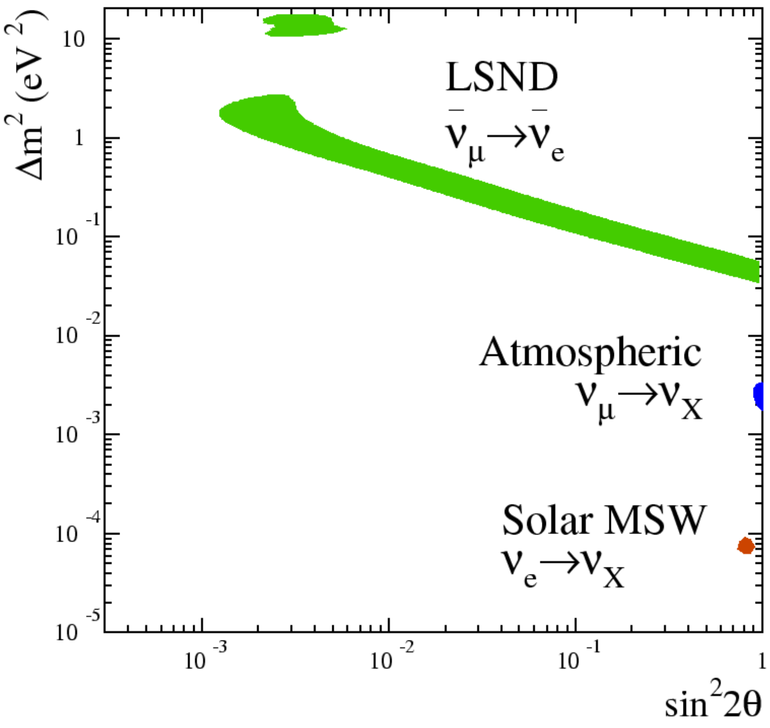
- Introduction
- Data Analysis
- Initial Results
- Future Experiments
- Conclusion

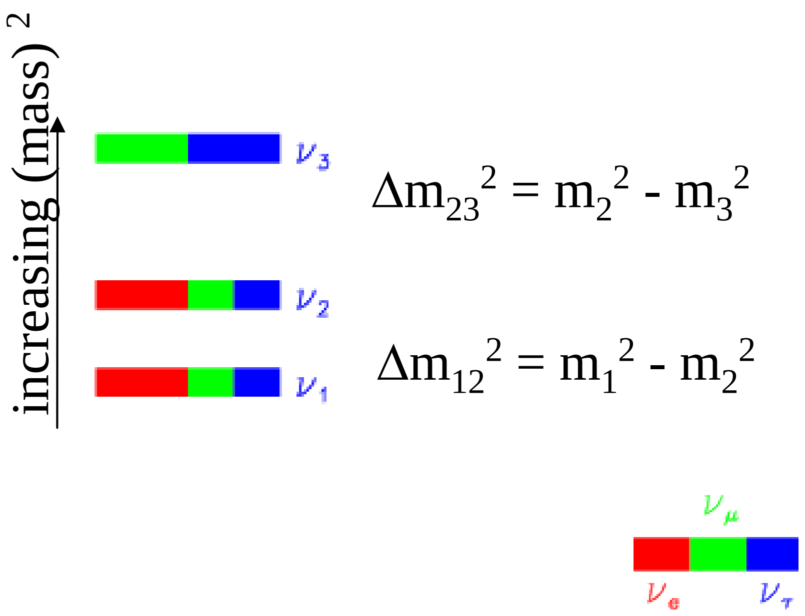
# *Evidence for Neutrino Oscillations*

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$




A 3 neutrino picture requires

$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$




The three oscillation signals cannot be reconciled without introducing Physics Beyond the Standard Model

# The MiniBooNE Collaboration

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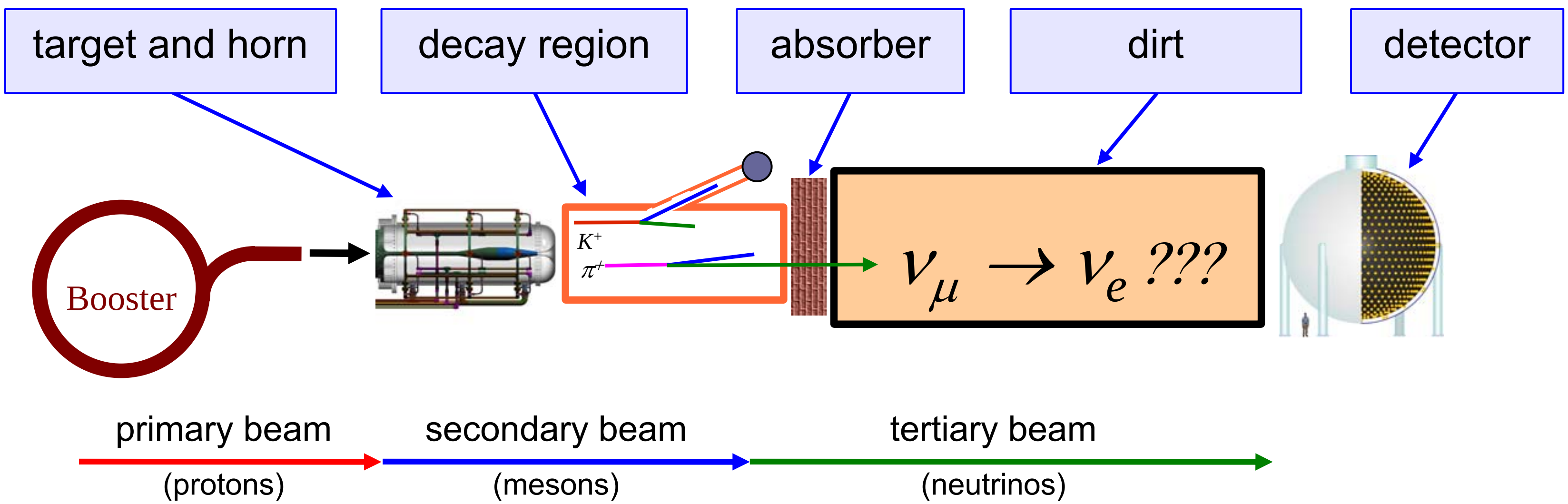
**Louisiana State University**
**University of Michigan**
**Princeton University**
**Saint Mary’s University of Minnesota**
**Virginia Polytechnic Institute**
**Western Illinois University**
**Yale University**

## *MiniBooNE's Design Strategy...*

Keep L/E same
while changing systematics, energy & event signature

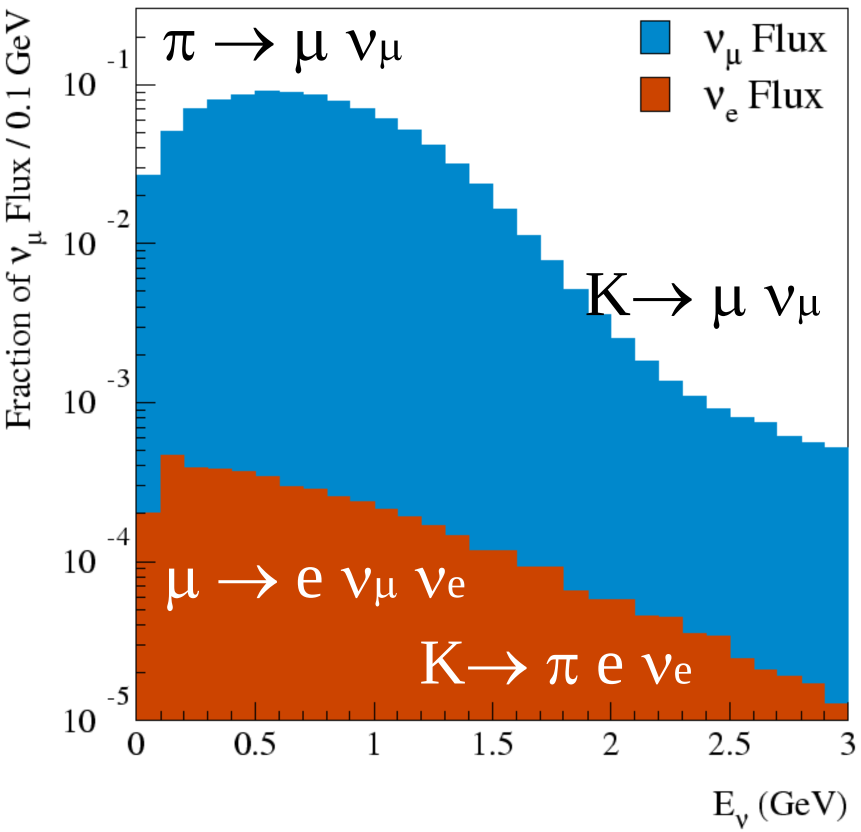
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$




Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

# *Neutrino Flux from GEANT4 Simulation*



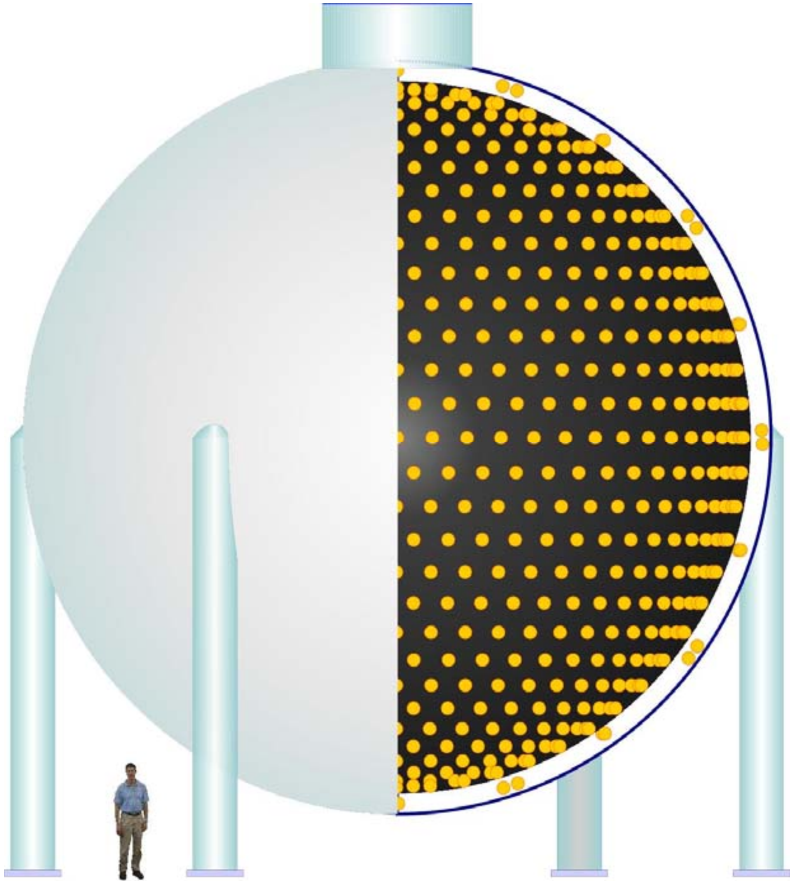

"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

| | |
|---|---|
| $\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\ \nu_e$ | (52%) |
| $K^+ \rightarrow \pi^0\ e^+\ \nu_e$ | (29%) |
| $K^0 \rightarrow \pi\ e\ \nu_e$ | (14%) |
| Other | ( 5%) |

$\nu_e/\nu_\mu = 0.5\%$

Antineutrino content: 6%

# *The MiniBooNE Detector*



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

  (10 meter "fiducial" volume)

  - Filled with 800 t

    of pure mineral oil ($CH_2$)

    (Fiducial volume: 450 t)

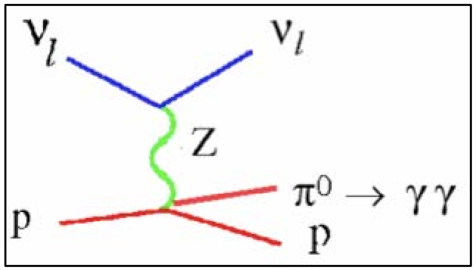
  - 1280 inner phototubes,

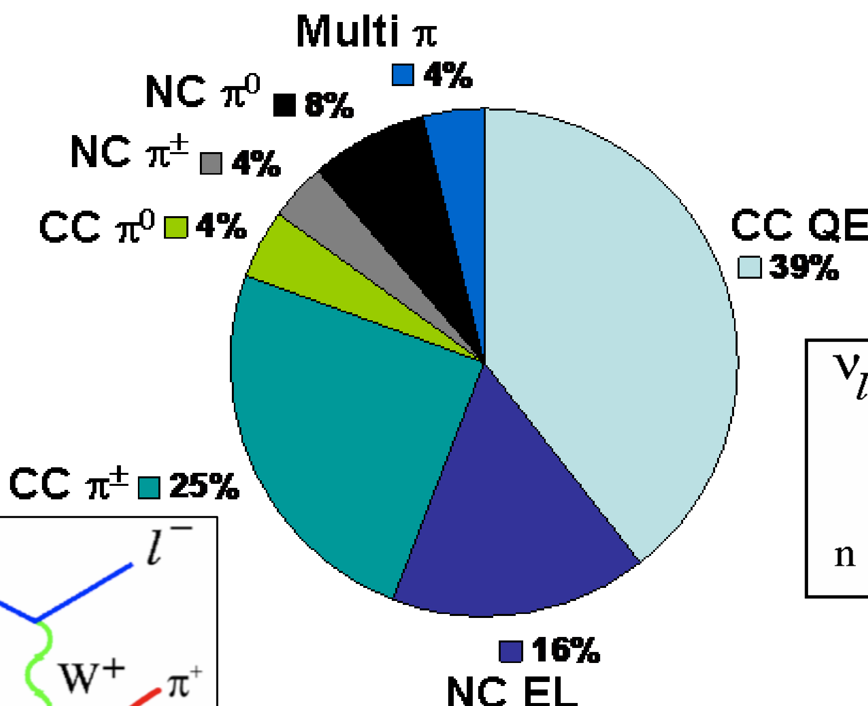
    240 veto phototubes

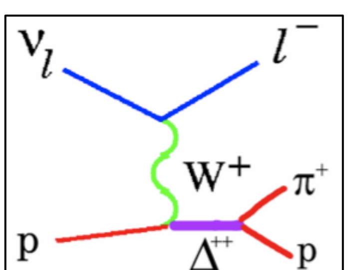
  - Simulated with a GEANT3 Monte Carlo

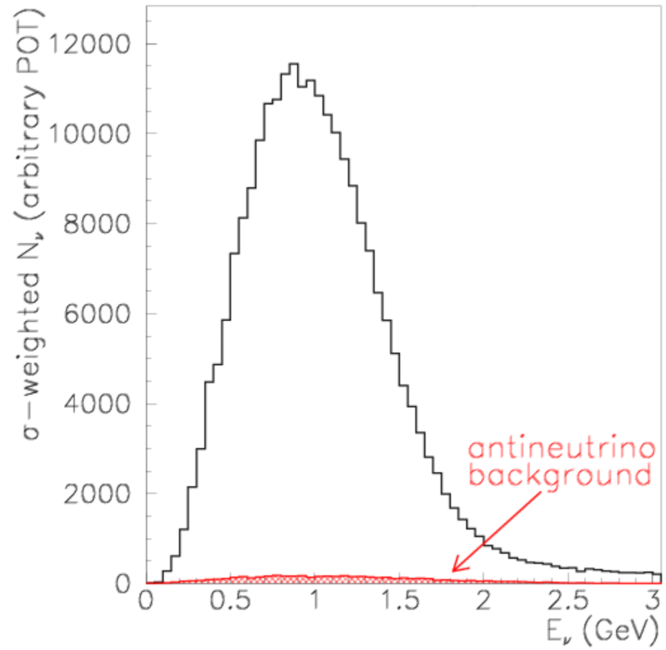
# *Predicted event rates before cuts (NUANCE Monte Carlo)*

D. Casper, NPS, 112 (2002) 161

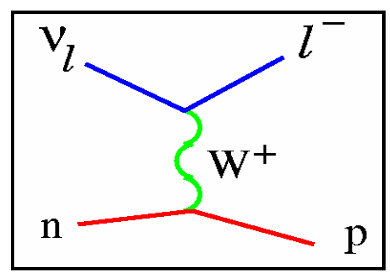


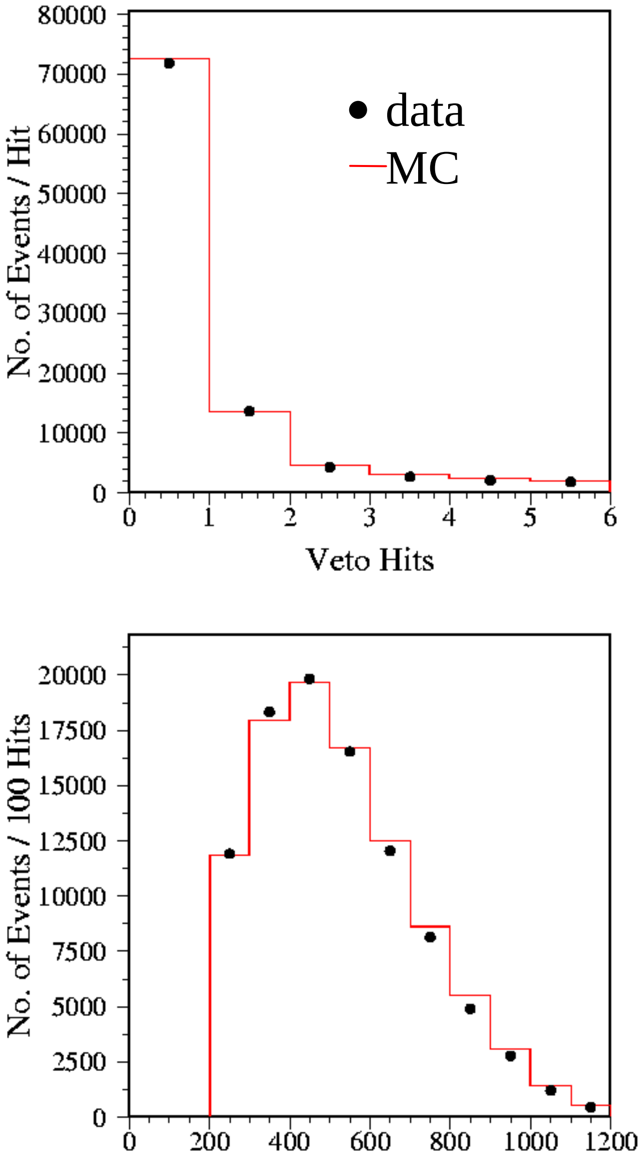




Event neutrino energy (GeV)



# *Analysis Pre-Cuts*

Event in time with beam
1 & only 1 event
Veto hits<6
Tank hits > 200
R<500 cm



# *Summary of PID cuts*

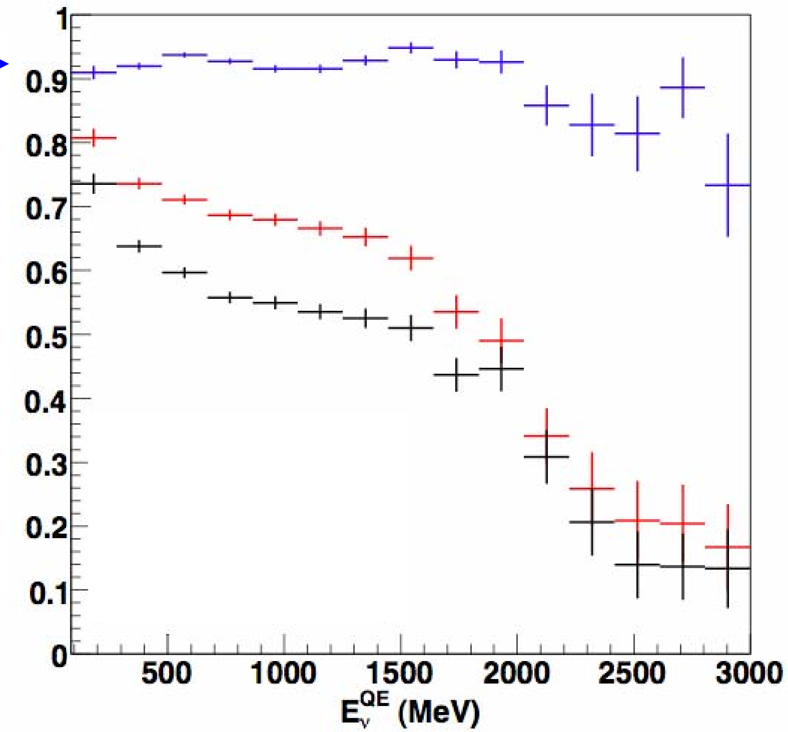
“Precuts” +

$\text{Log}(L_e/L_\mu)$

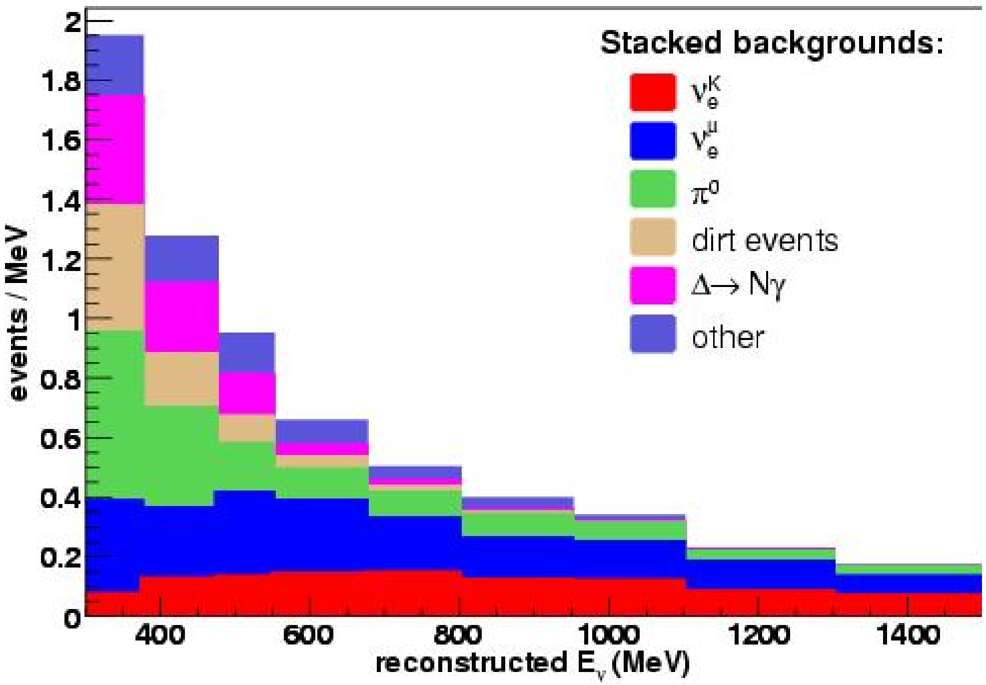
$+ \text{Log}(L_e/L_\pi)$

+ invariant mass

Efficiency:

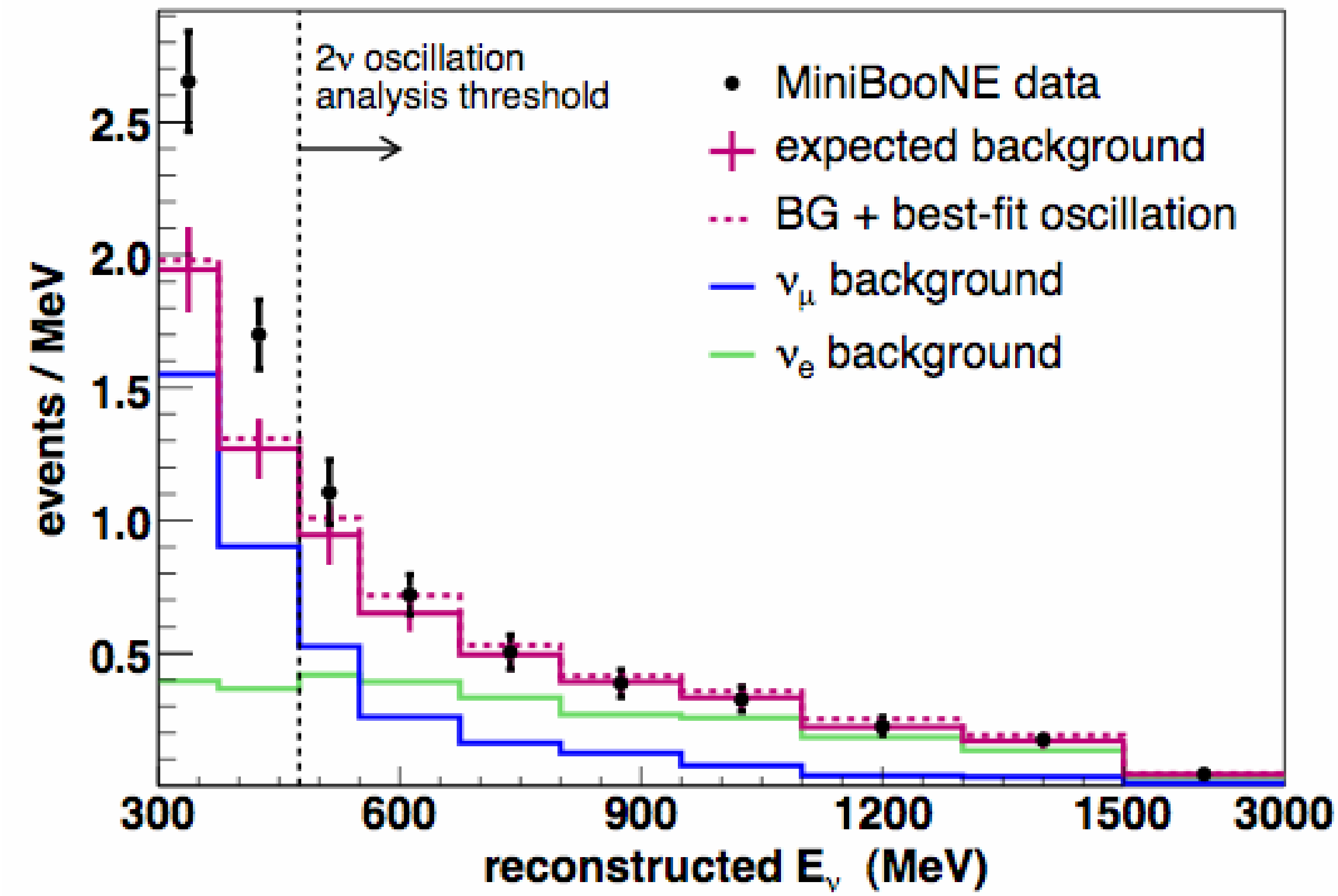



Backgrounds after cuts



| Source of Uncertainty On $\nu_e$ background | Error in % | Checked or Constrained by MB data | Further reduced by tying $\nu_e$ to $\nu_\mu$ |
|---|---|---|---|
| Flux from $\pi^+/\mu^+$ decay | 6.2 | √ | √ |
| Flux from $K^+$ decay | 3.3 | √ | √ |
| Flux from $K^0$ decay | 1.5 | √ | √ |
| Target and beam models | 2.8 | √ | |
| $\nu$-cross section | 12.3 | √ | √ |
| NC $\pi^0$ yield | 1.8 | √ | |
| External interactions ("Dirt") | 0.8 | √ | |
| Optical model | 6.1 | √ | √ |
| DAQ electronics model | 7.5 | √ | |

# *The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:*

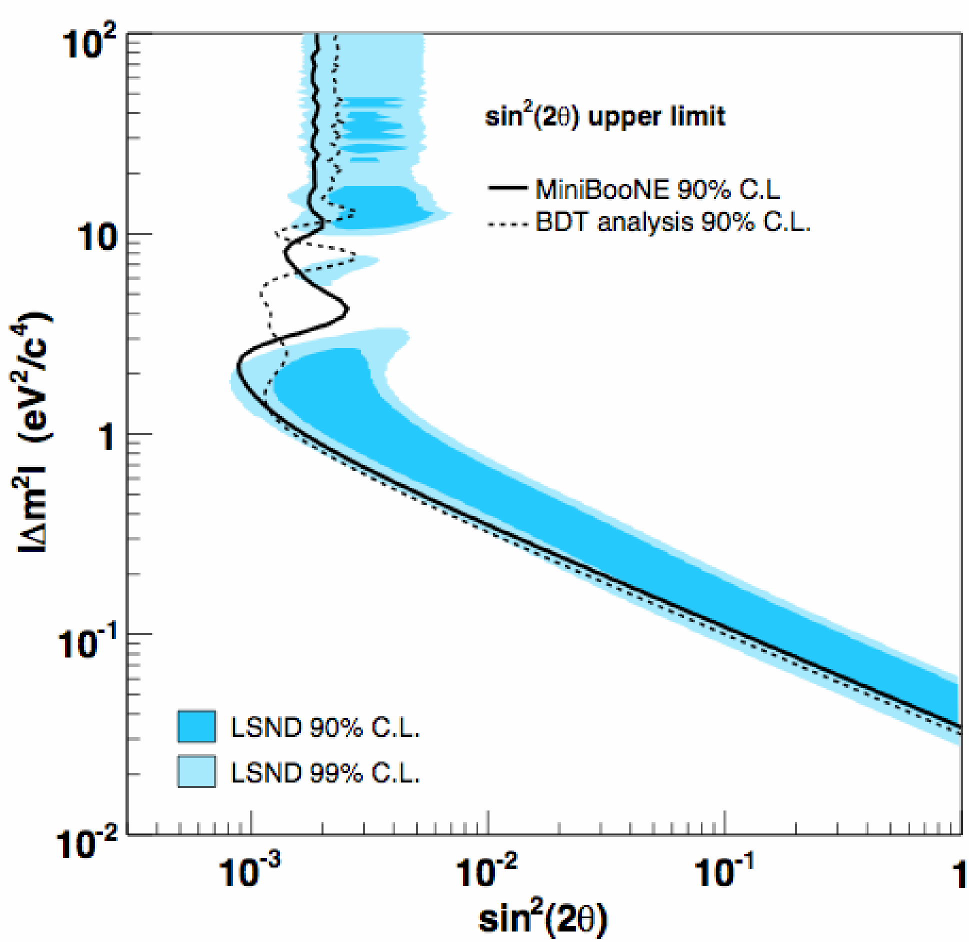



$300<E_\nu^{QE}<1250$ MeV : data: 749 events, MC: 631 ±25 ±45 events, 2.3 σ

$475<E_\nu^{QE}<1250$ MeV : data: 380 events, MC: 358 ±19 ±35 events, 0.55 σ

$300<E_\nu^{QE}<475$ MeV : data: 369 events, MC: 273 ±17 ±20 events, 3.7 σ

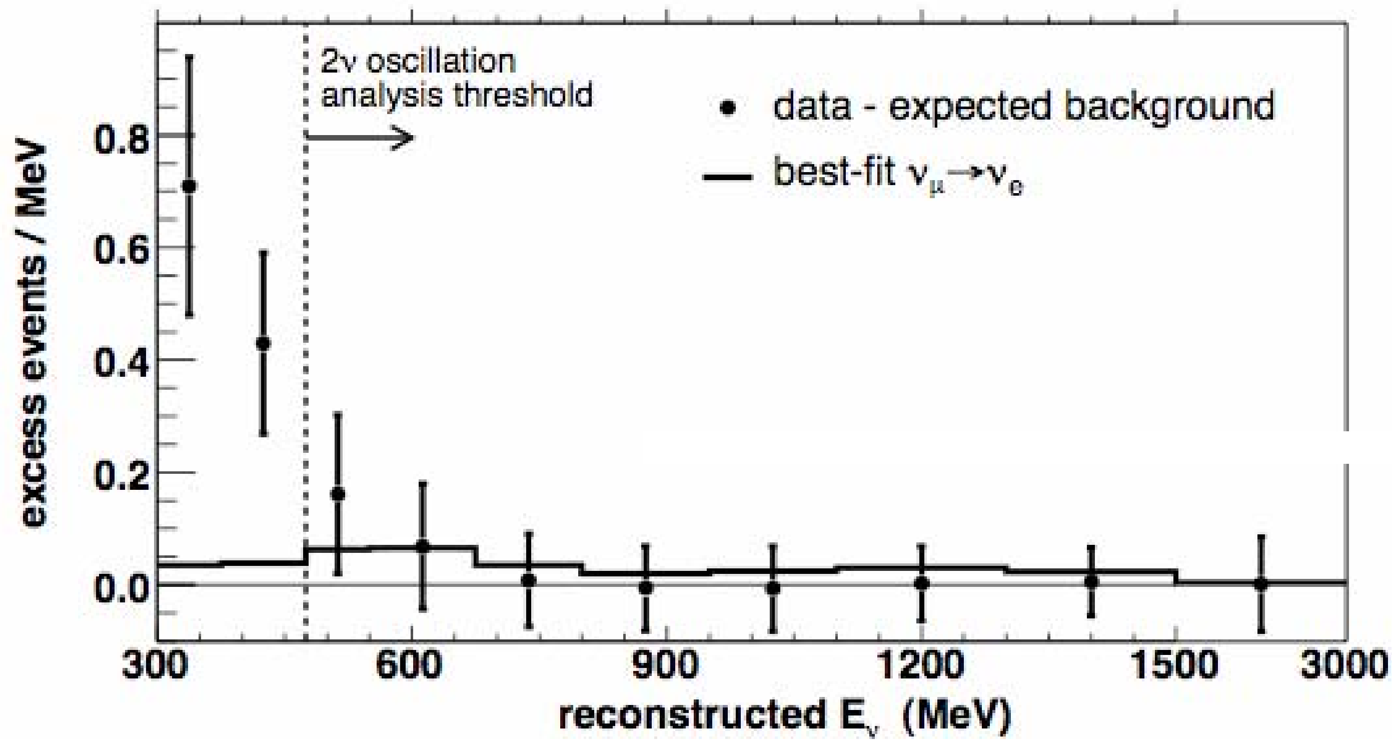
***The result of***
***the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis***
***is a <u>limit</u> on oscillations:***




Simple 2-neutrino oscillations excluded at 98% C.L.

Energy fit: $475 < E_\nu^{QE} < 3000$ MeV

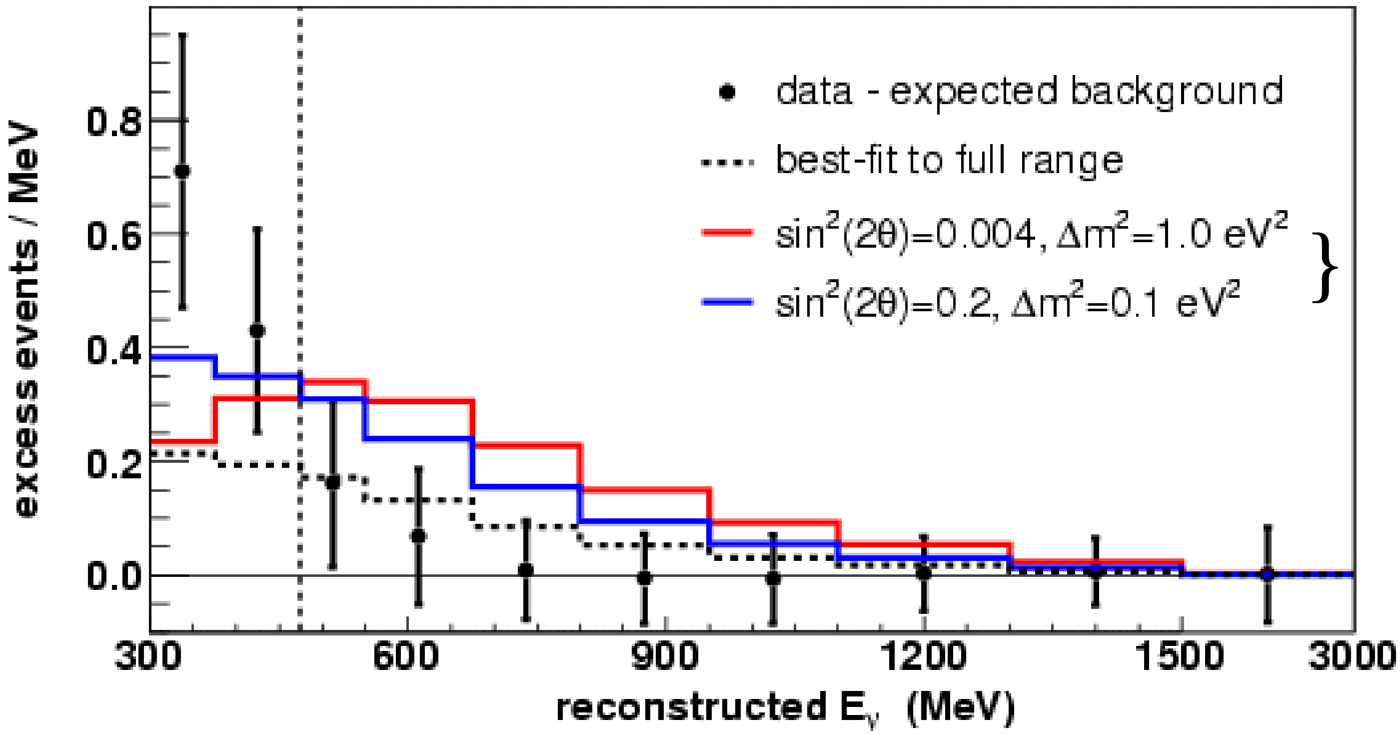
***Background Subtracted***




96 ± 17 ± 20 events above background, for $300 < E_\nu^{QE} < 475$MeV
Deviation: 3.7σ

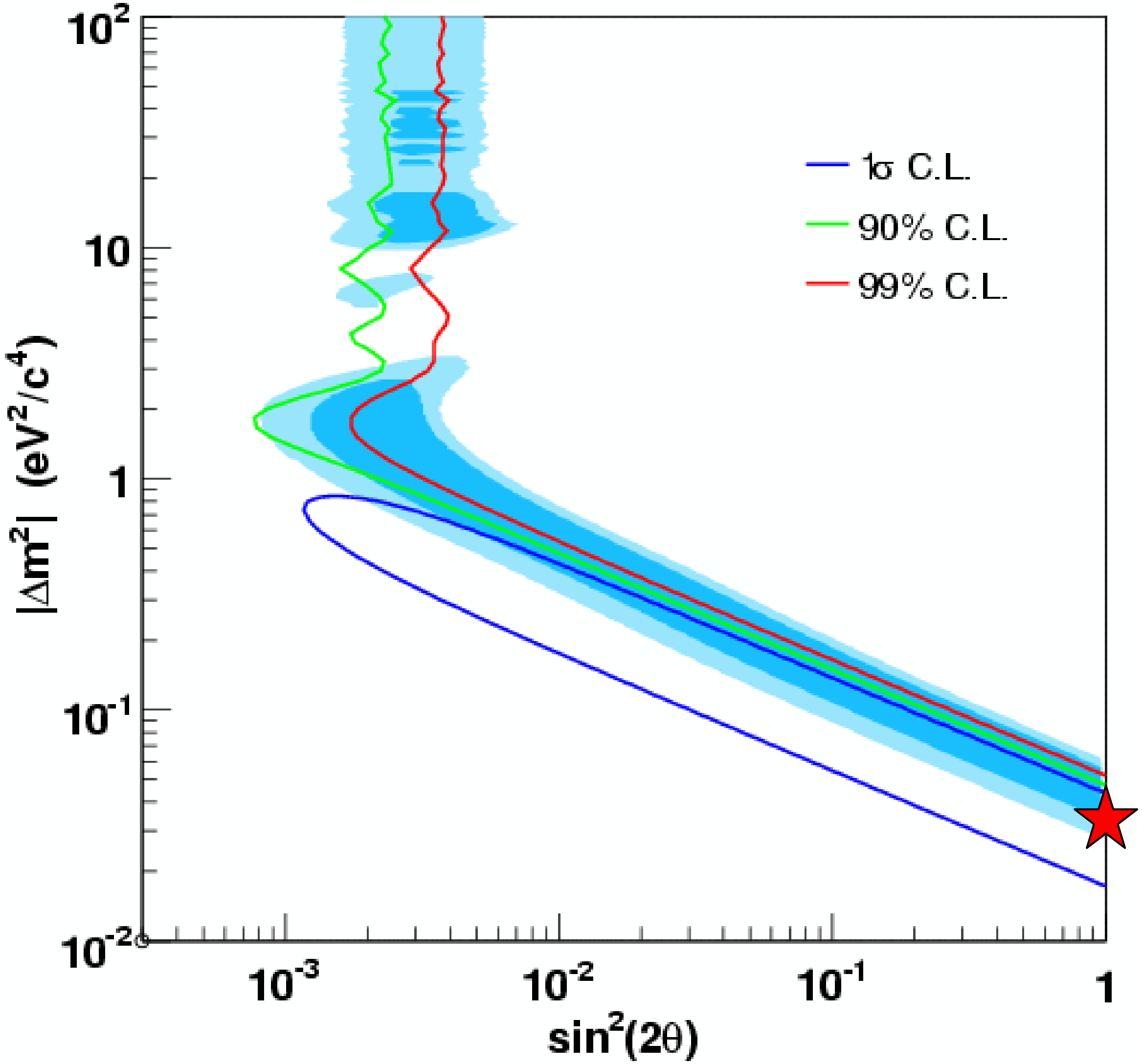
## ***Fit to the > 300 MeV range:***

Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03\ \mathrm{eV}^2)$
$\chi^2$ Probability: 18%

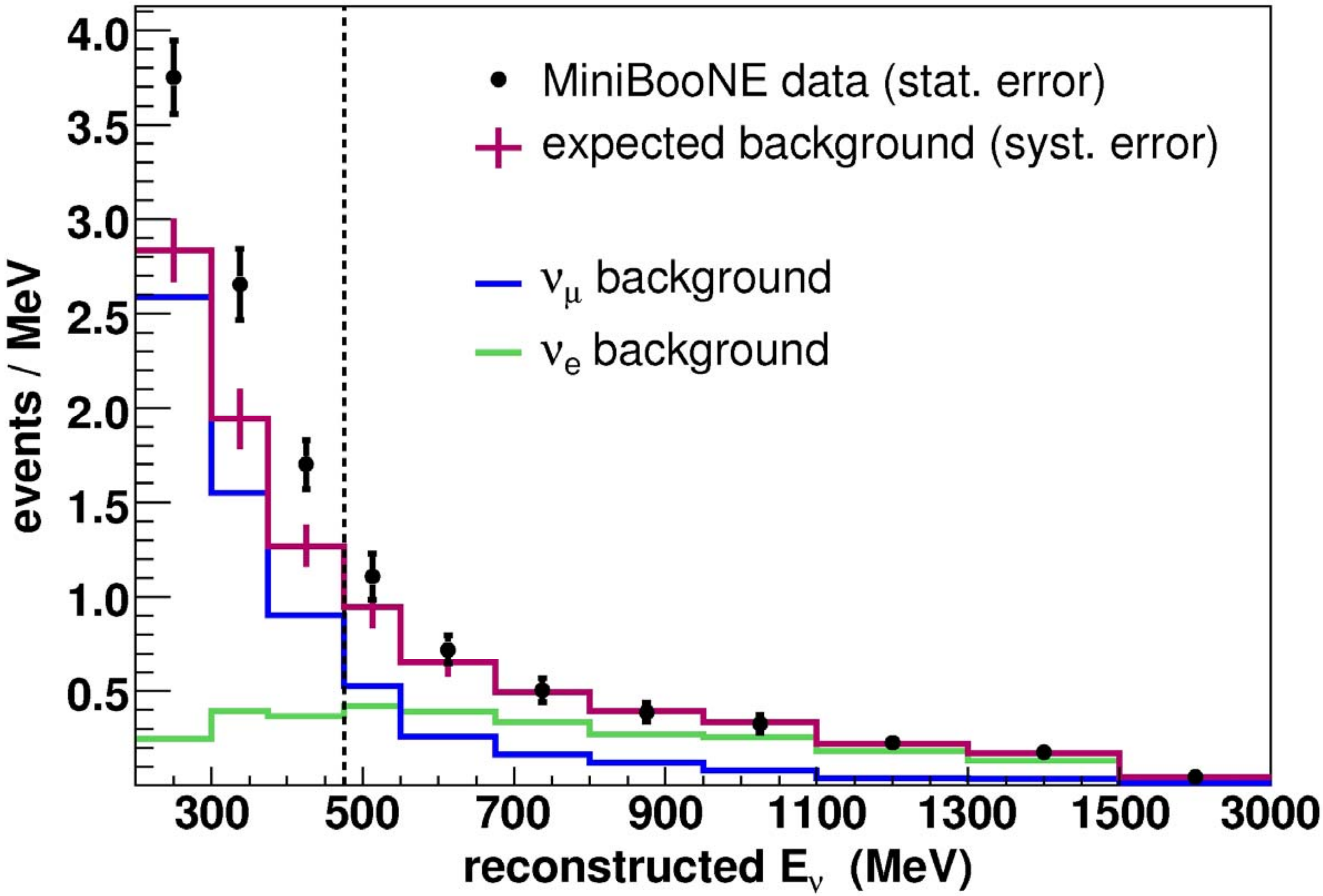


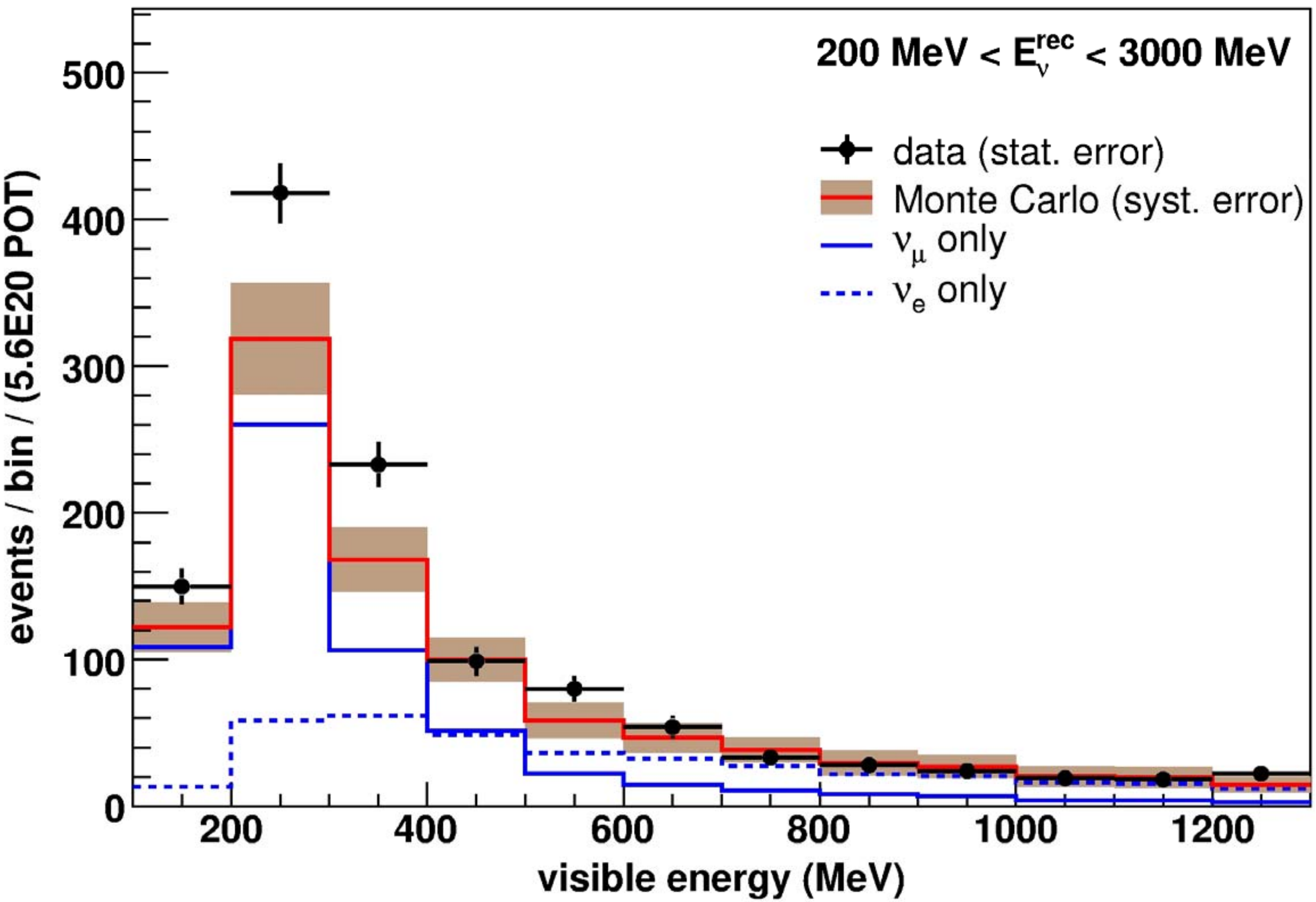
# *Allowed Region*

Energy Fit : $0.3 < E_\nu^{QE} < 3$ GeV

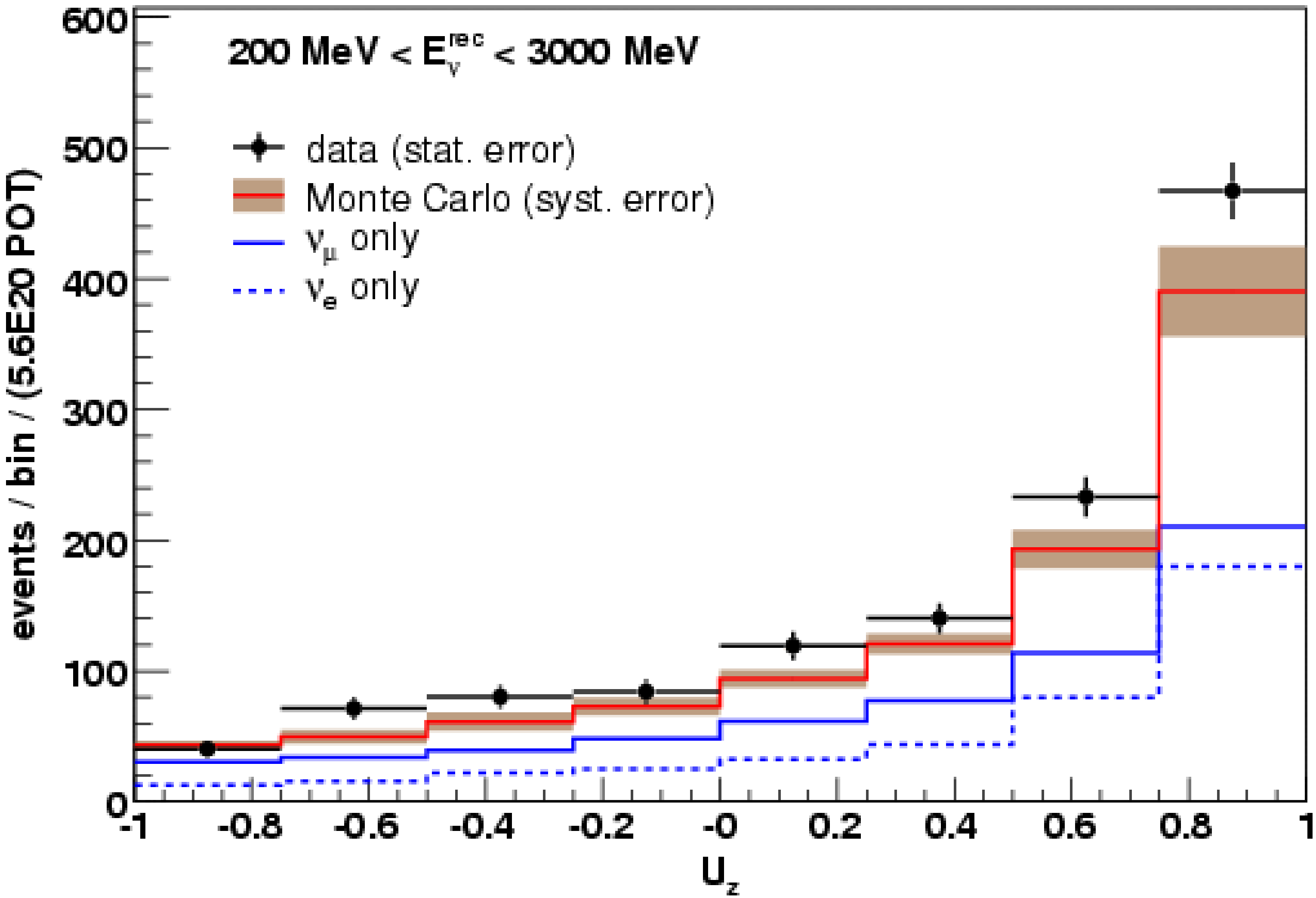


## *Excess Continues at Lower Energies!*





200 MeV < E$_\nu^{rec}$ < 3000 MeV
data (stat. error)
Monte Carlo (syst. error)
$\nu_\mu$ only
$\nu_e$ only
events / bin / (5.6E20 POT)
visible energy (MeV)
0
100
200
300
400
500
200
400
600
800
1000
1200



200 MeV < $E_\nu^{rec}$ < 3000 MeV
data (stat. error)
Monte Carlo (syst. error)
$\nu_\mu$ only
$\nu_e$ only
events / bin / (5.6E20 POT)
$U_z$

## ***Background?***

- Is low-energy excess due to background?
- e.g. some NC gamma production or other electromagnetic process?
- Presently studying photonuclear interactions, neutron radiative scattering, & pion absorption

## *Signal?*

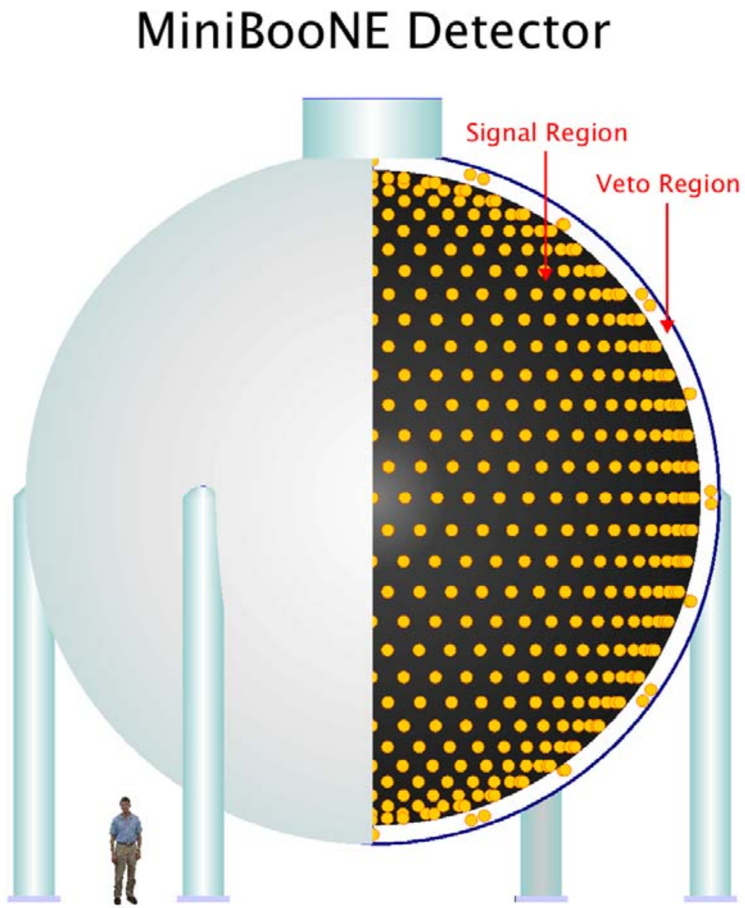
- Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density (arXiv:0708.1281: Jeffrey A. Harvey, Christopher T. Hill, Richard J. Hill)
- CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107
- Extra Dimensions 3+1 Model: Paes, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017
- Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009
- CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

# Future Experiments: BooNE & OscSNS

**Two possible follow-up experiments:**

**BooNE** would involve a second "MiniBooNE-like" detector (~$8M) at FNAL at a different distance; with 2 detectors, many of the systematics would cancel

**OscSNS** would involve building a "MiniBooNE-like" detector (~$12M) with higher PMT coverage at a distance of ~60 m from the SNS beam stop at ORNL



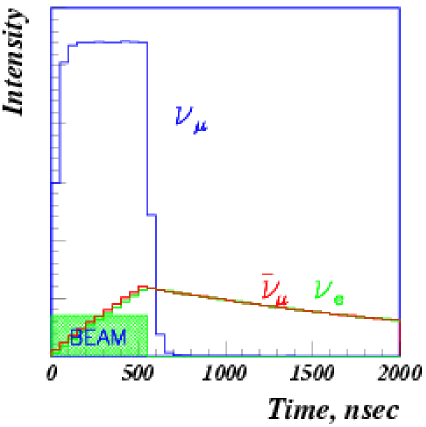

# BooNE at FNAL

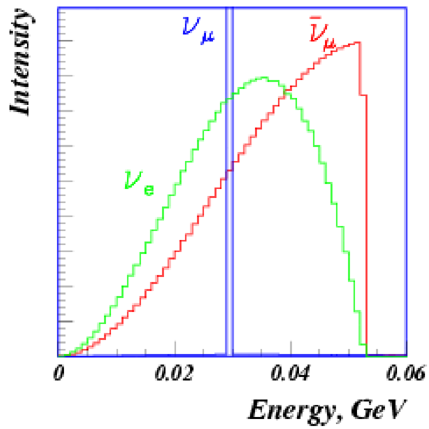
Two identical detectors at different distances

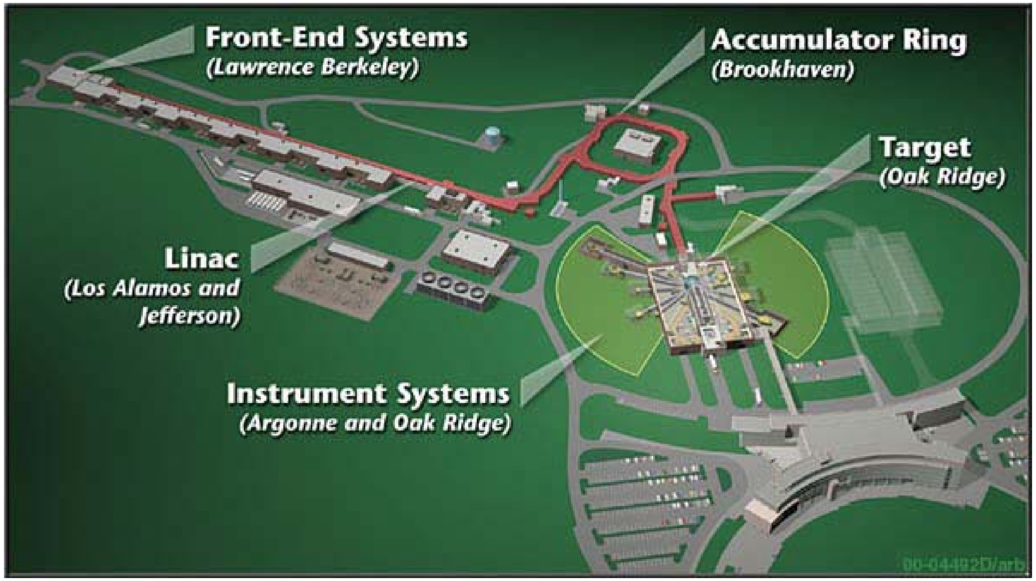
Search for sterile neutrinos via **NCPI0** scattering & **NCEL** scattering

Problem: imprecise $\nu$ energy determination smears oscillations!

# OscSNS at ORNL




**SNS: ~1 GeV, ~1.4 MW**

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

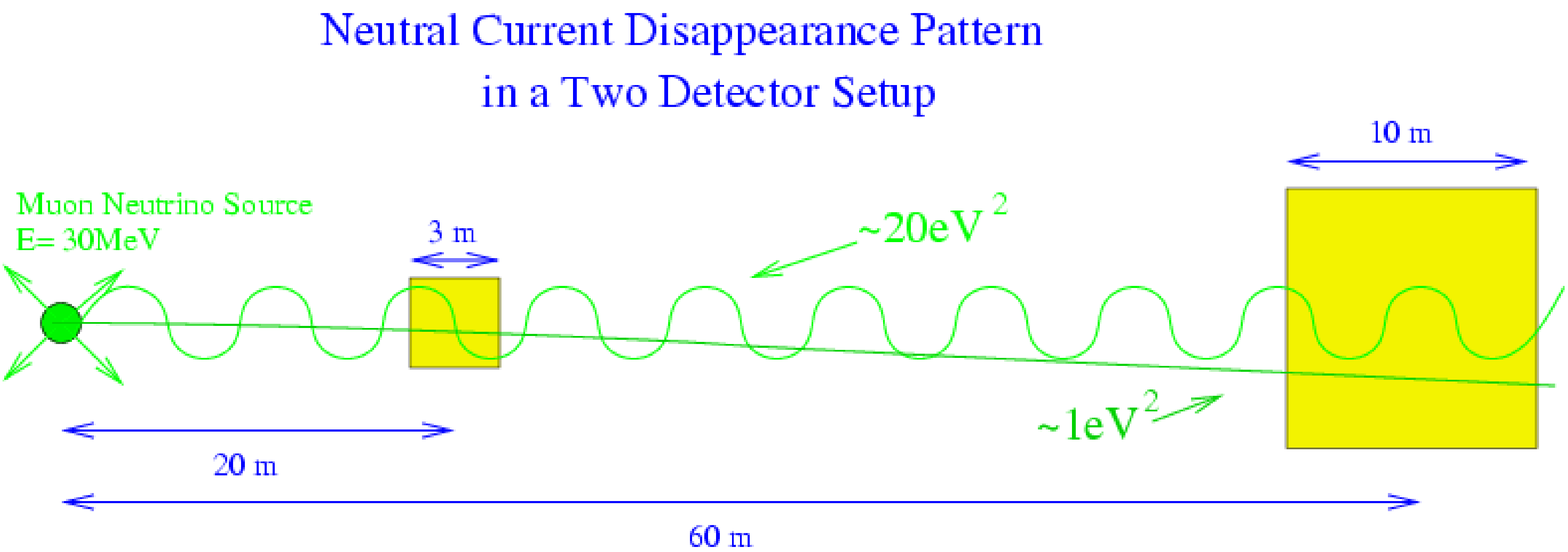
$\nu_\mu$ -> $\nu_s$ $\Delta(L/E) < 1\%$ ; **Monoenergetic** $\nu_\mu$ !; $\nu_\mu\, C$ -> $\nu_\mu\, C^*(15.11)$

OscSNS would be capable of making precision measurements of $\bar{\nu}_e$ appearance & $\nu_\mu$ disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)). Flux shapes are known perfectly and cross sections are known very well

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

## $\nu_\mu$ C -> $\nu_\mu$ C*(15.11)

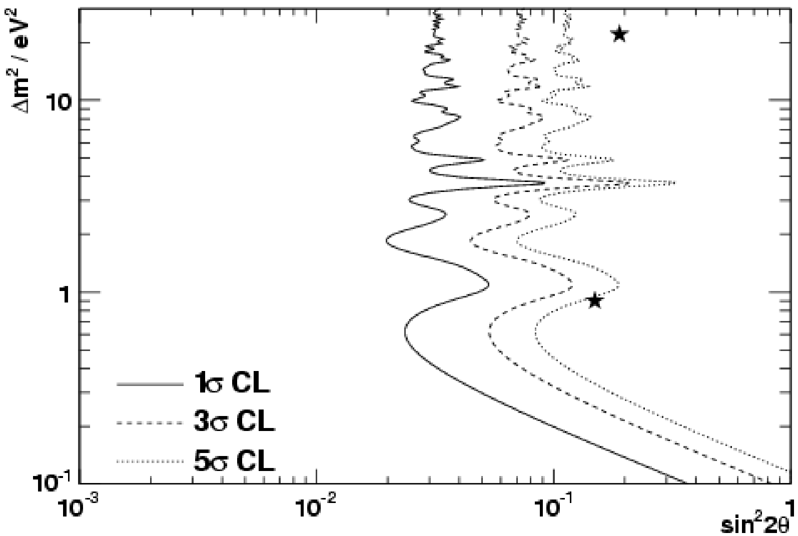
**Garvey et al., Phys. Rev. D72 (2005) 092001**

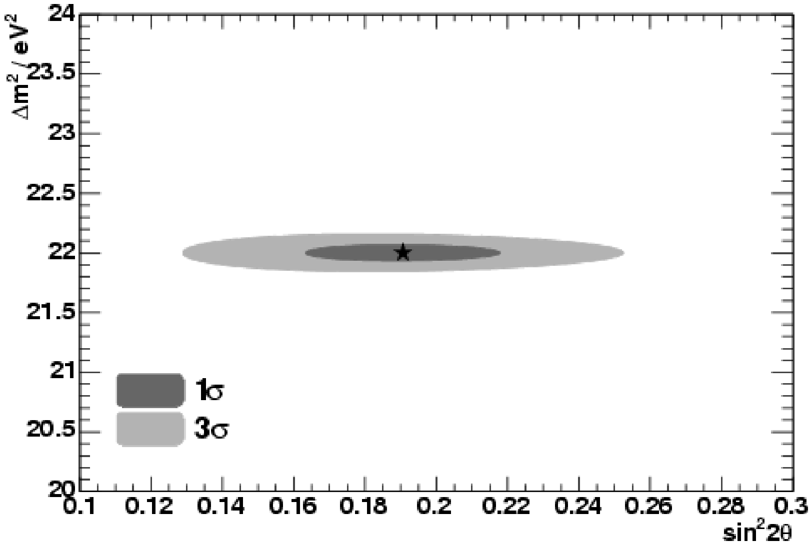


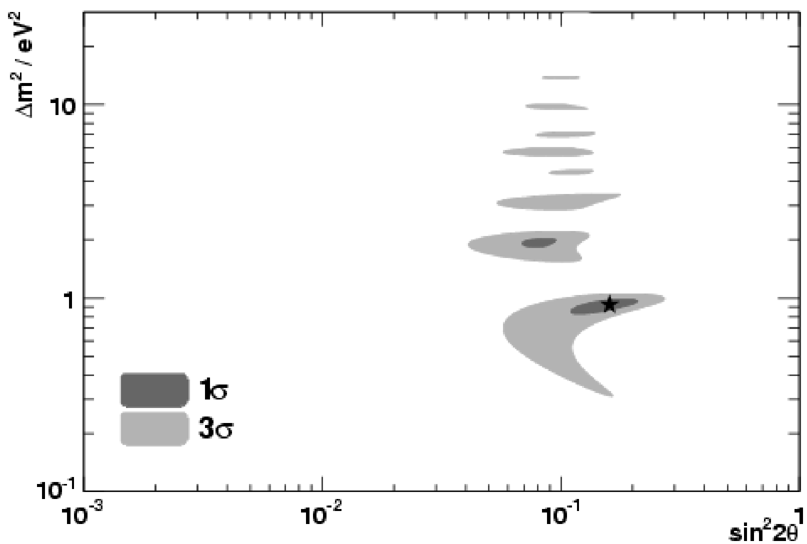
# Measurement of 3+2 Model with OscSNS

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

$\nu_\mu \to \nu_s$



# *Conclusions*

Within the energy range defined by the oscillation analysis, $475<E_\nu^{QE}<1250$ MeV, the event rate is consistent with background.

MiniBooNE rules out a simple $\nu_\mu \rightarrow \nu_e$ appearance-only model as an explanation of the LSND excess at 98% CL.

However, more events are observed than expected in the lower energy range from $200<E_\nu^{QE}<475$MeV.

This unexplained deviation is under investigation.

## ***Future***

- Understand the low-energy excess of events!
- Analyze antineutrino data, NuMI $\nu$ in MiniBooNE data, & SciBooNE data.
- If low-energy excess is consistent with a signal, new experiments at FNAL (BooNE) and/or SNS (OscSNS) will be proposed to explore physics Beyond the Standard Model.