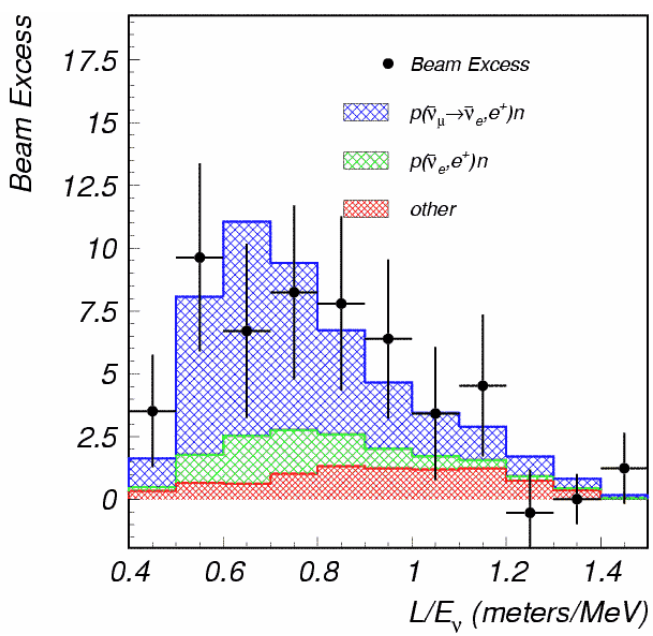
First Results from MiniBooNE

July 2, 2007
William Louis

- Introduction
- The Neutrino Beam
- Events in the MiniBooNE Detector
- Data Analysis
- Initial Results
- Future
- Conclusion

MiniBooNE was approved in 1998,
with the goal of addressing the LSND anomaly:

LSND observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam,
87.9 ± 22.4 ± 6.0 (3.8σ)



Points -- LSND data
Signal (blue)
Backgrounds (red, green)

LSND Collab, PRD 64, 112007

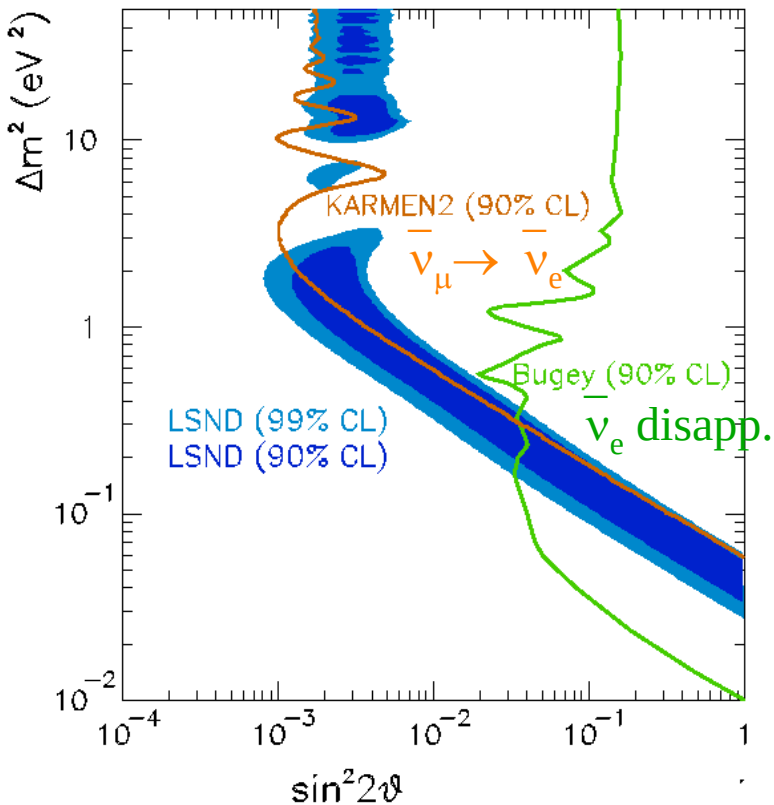
Interpreting LSND within a $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance model:

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

mixing angle

squared mass difference

travel distance / energy of the neutrinos



This model allows comparison to other experiments:

Karmen2

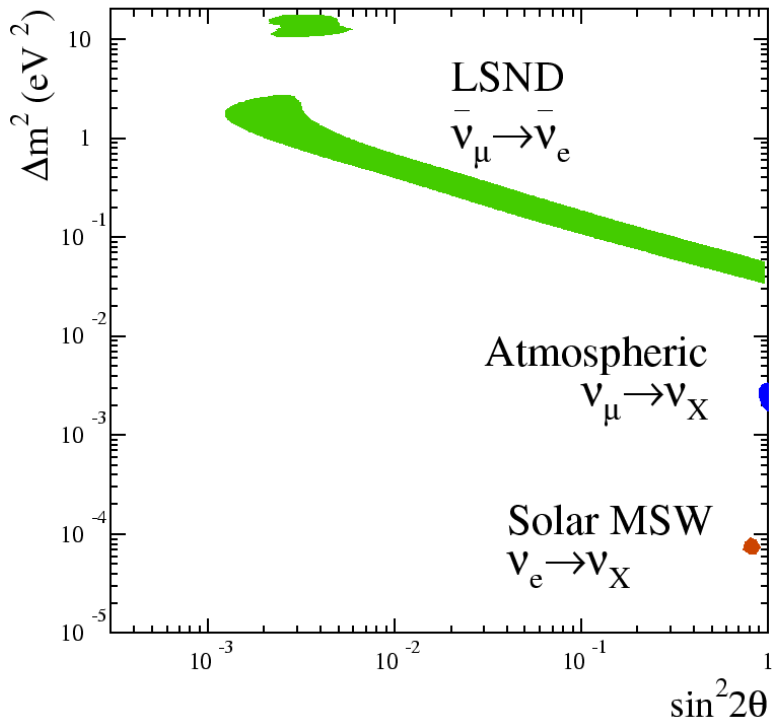
Bugey

Joint analysis with Karmen2:
64% compatible

Church, et al., PRD 66, 013001

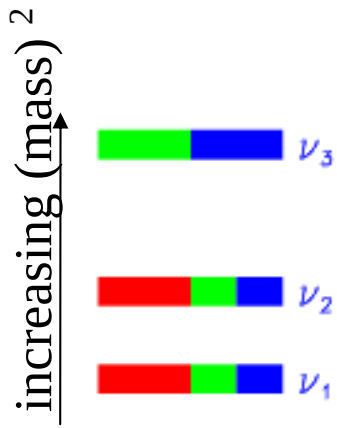
Evidence for Neutrino Oscillations

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



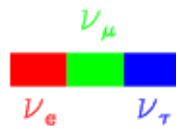
A 3 neutrino picture requires

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



$$\Delta m_{23}^2 = m_2^2 - m_3^2$$

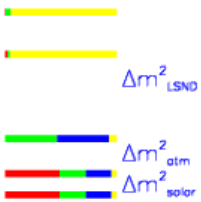
$$\Delta m_{12}^2 = m_1^2 - m_2^2$$



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

Beyond the Standard Model Explanations of All Neutrino Oscillation Data

3+2 Sterile Neutrinos — Sorel, Conrad, & Shaevitz (PRD70(2004)073004)



MaVaNs & 3+1 Sterile Neutrino — Hung (hep-ph/0010126)
Kaplan, Nelson, & Weiner (PRL93(2004)091801)

CPT Violation & 3+1 Sterile Neutrino — Barger, Marfatia, & Whisnant (PLB576(2003)303)

Quantum Decoherence — Barenboim & Mavromatos (PRD70(2004)093015)

Lorentz Violation — Kostelecky & Mewes (PRD70(2004)076002)
Katori, Kostelecky, Tayloe (hep-ph/0606154)

Extra Dimensions — Pas, Pakvasa, & Weiler (PRD72(2005)095017)

Sterile Neutrino Decay — Palomares-Ruiz, Pascoli, & Schwetz (JHEP509(2005)48)

The MiniBooNE Collaboration

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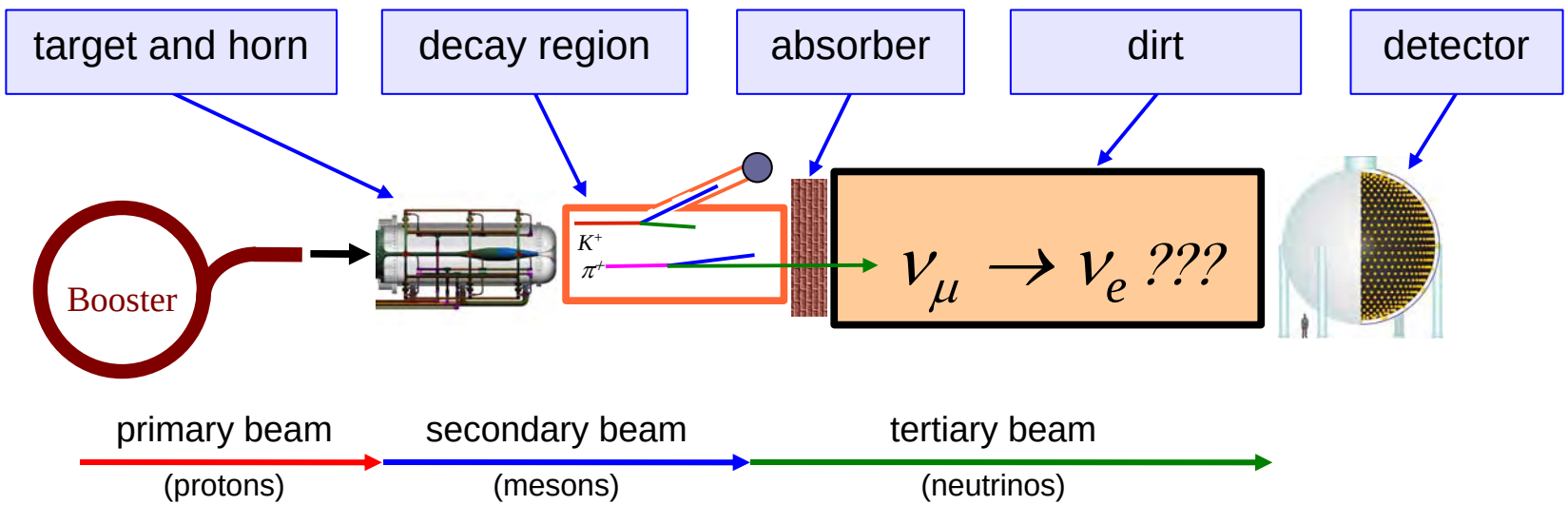
Fermi National Accelerator Laboratory
Indiana University
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

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)

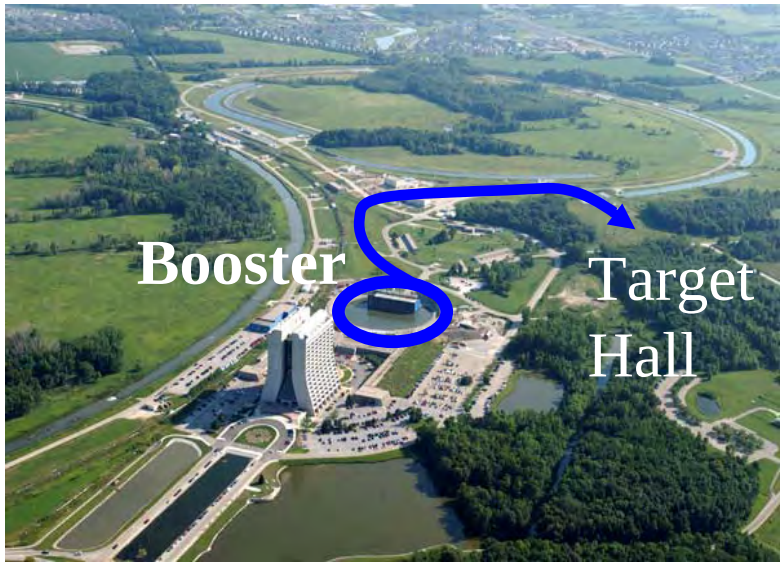
MiniBooNE's initial results on testing the LSND anomaly:

- A generic search for a ν_e excess in our ν_μ beam,
- An analysis of the data within a $\nu_\mu \rightarrow \nu_e$ appearance context

This was a blind analysis.
The box was opened on March 26, 2007

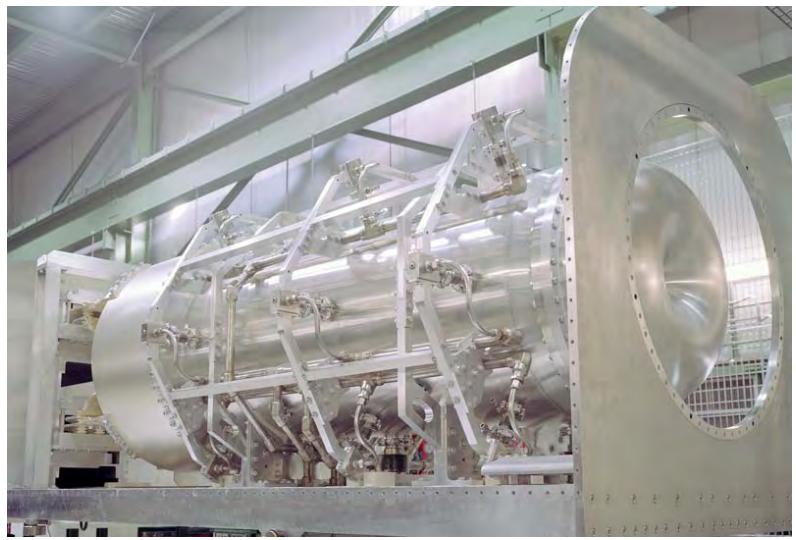
Two independent analyses were performed.
The primary analysis was chosen based on $\nu_\mu \rightarrow \nu_e$ sensitivity, prior to unblinding.

The MiniBooNE Neutrino Beam



MiniBooNE extracts beam from the 8 GeV Booster

Delivered to a 1.7 λ Be target



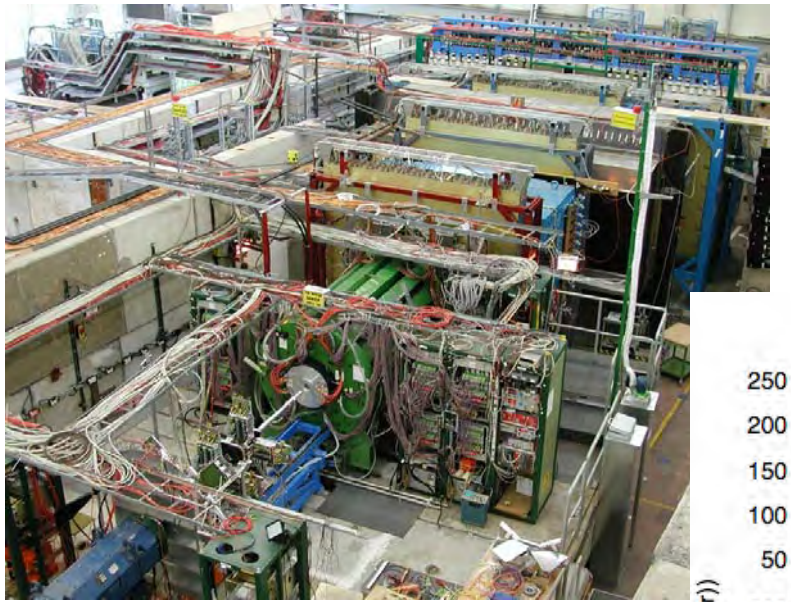
4×10^{12} protons per 1.6 μs pulse delivered at up to 5 Hz.

6.3×10^{20} POT delivered.

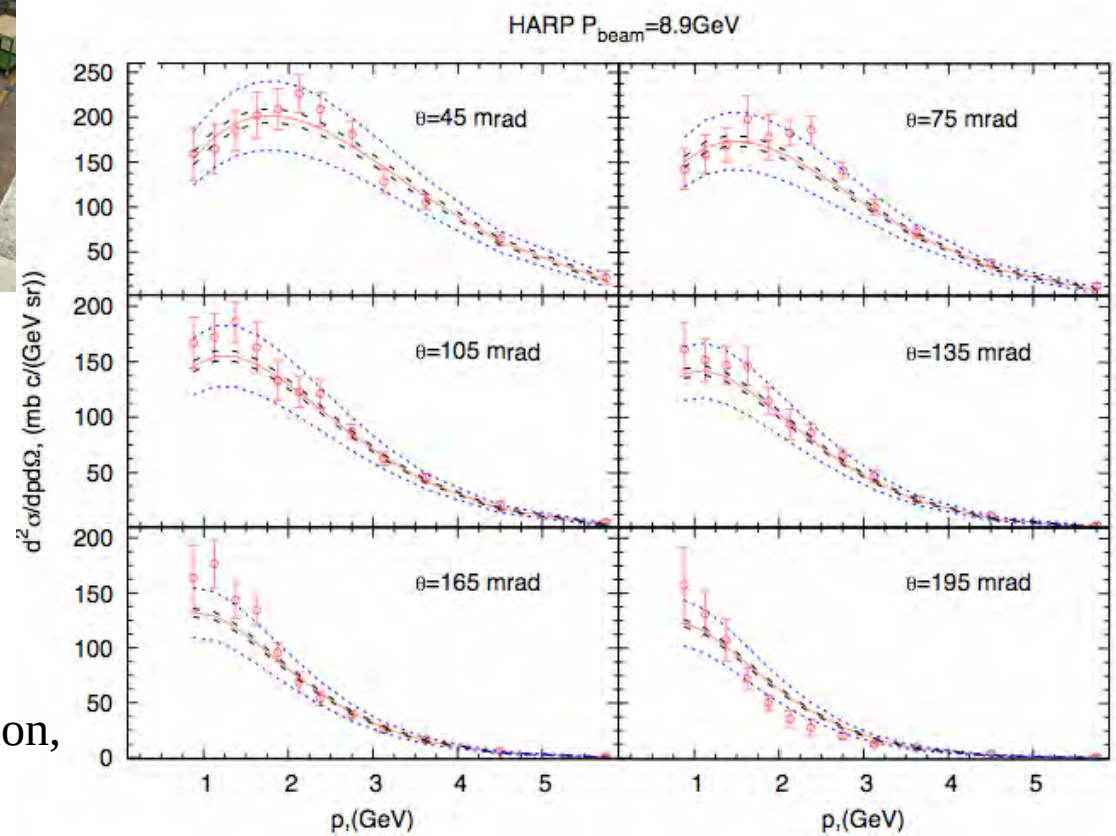
Results correspond to $(5.58 \pm 0.12) \times 10^{20}$ POT

within a magnetic horn (2.5 kV, 174 kA) that (increases the flux by ×6)

Modeling Production of Secondary Pions



- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum



Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024

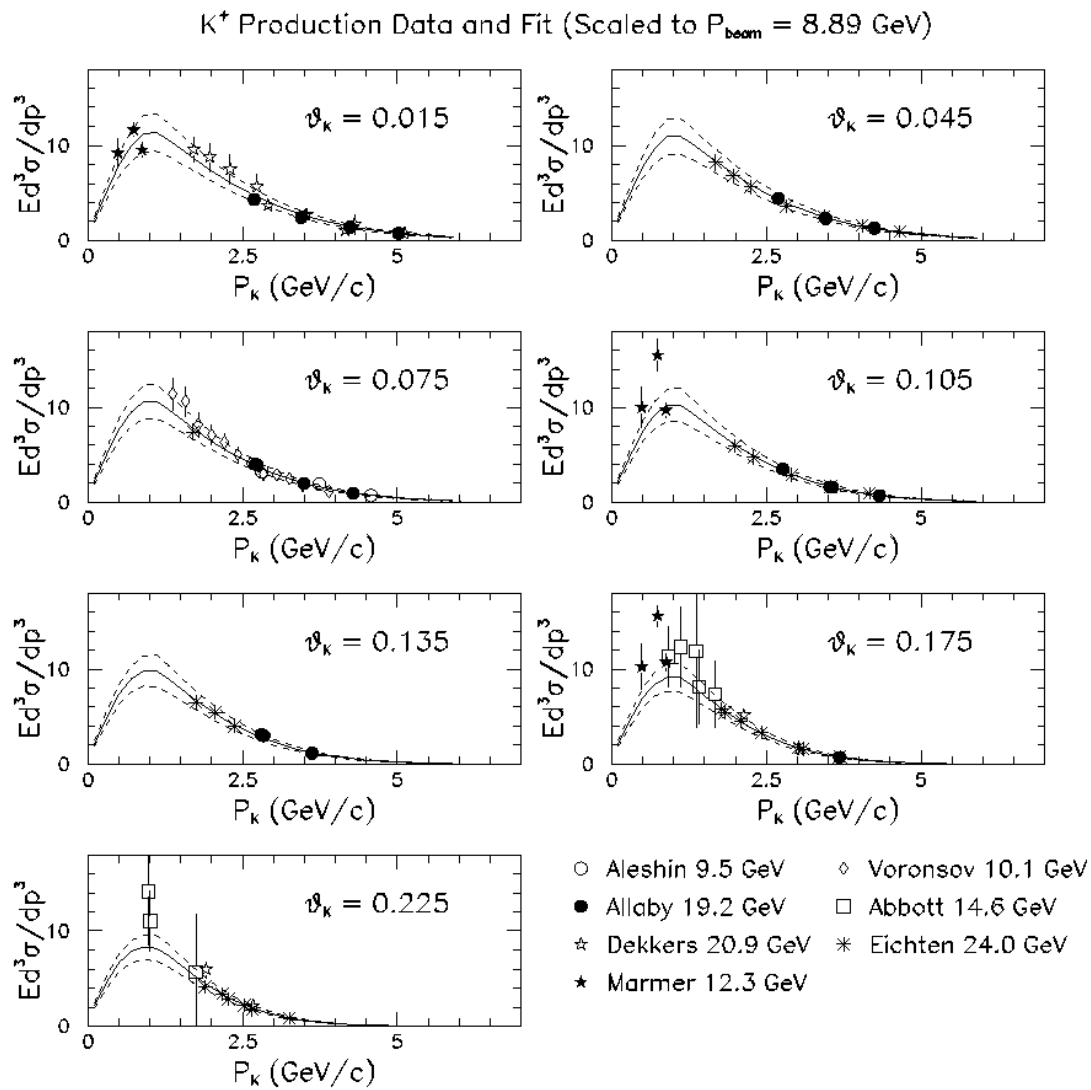
Modeling Production of Secondary Kaons

K^+ Data from 10 - 24 GeV. Uses a Feynman Scaling Parameterization.

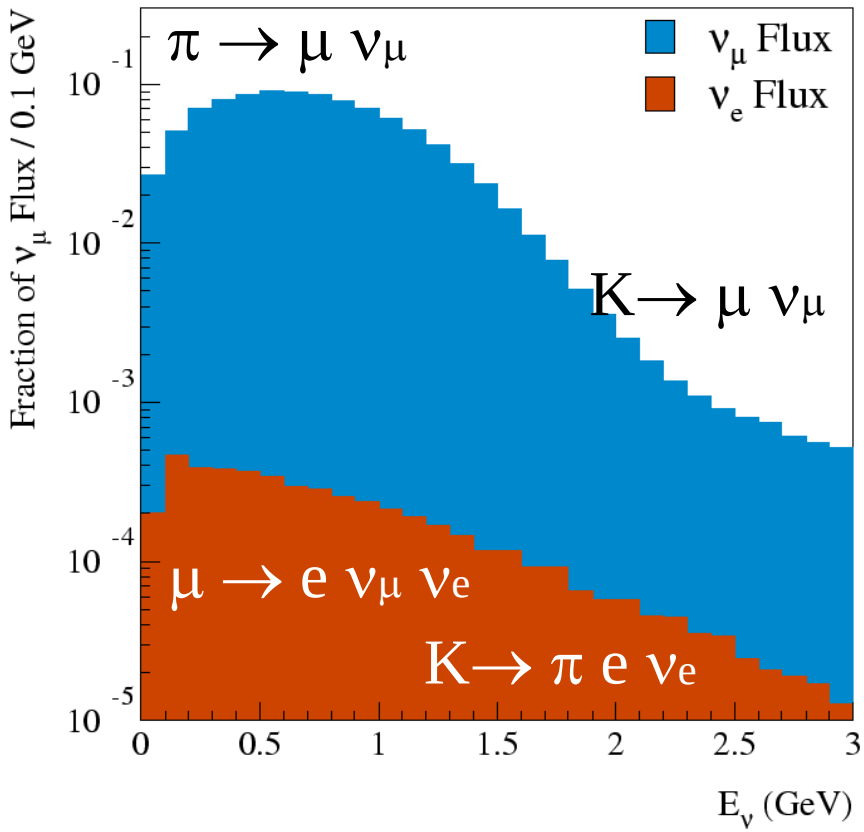
data -- points
dash --total error
(fit ⊕ parameterization)

K^0 data are also parameterized.

In situ measurement of K^+ from LMC agrees within errors with parameterization



Neutrino Flux from GEANT4 Simulation



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

$\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\ \nu_e$ (52%)

$K^+ \rightarrow \pi^0\ e^+\ \nu_e$ (29%)

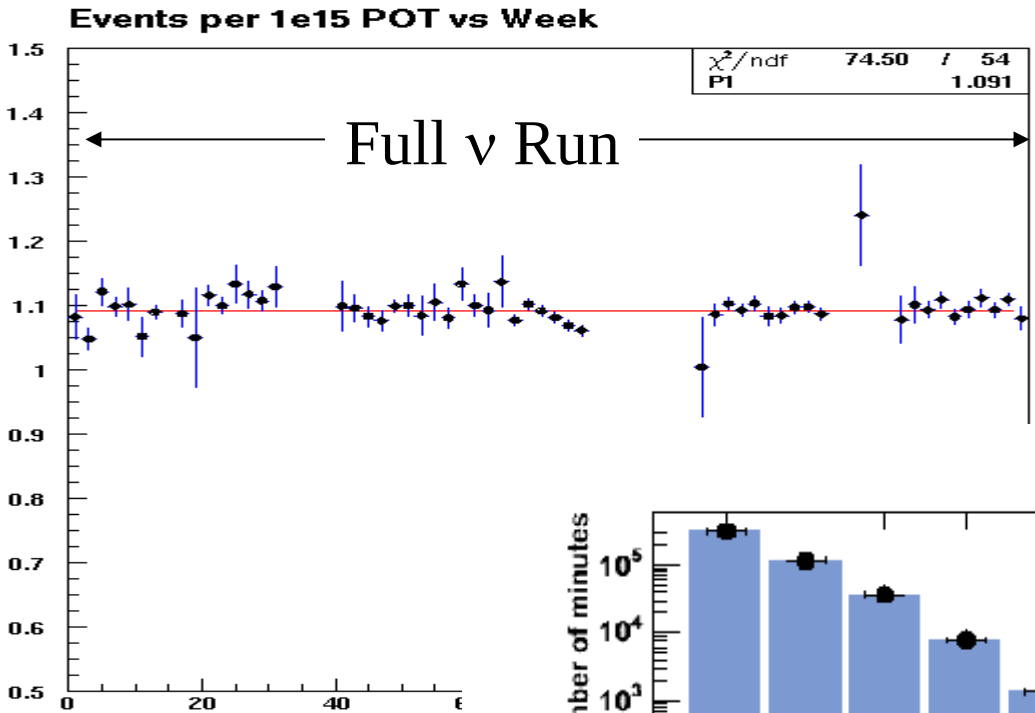
$K^0 \rightarrow \pi\ e\ \nu_e$ (14%)

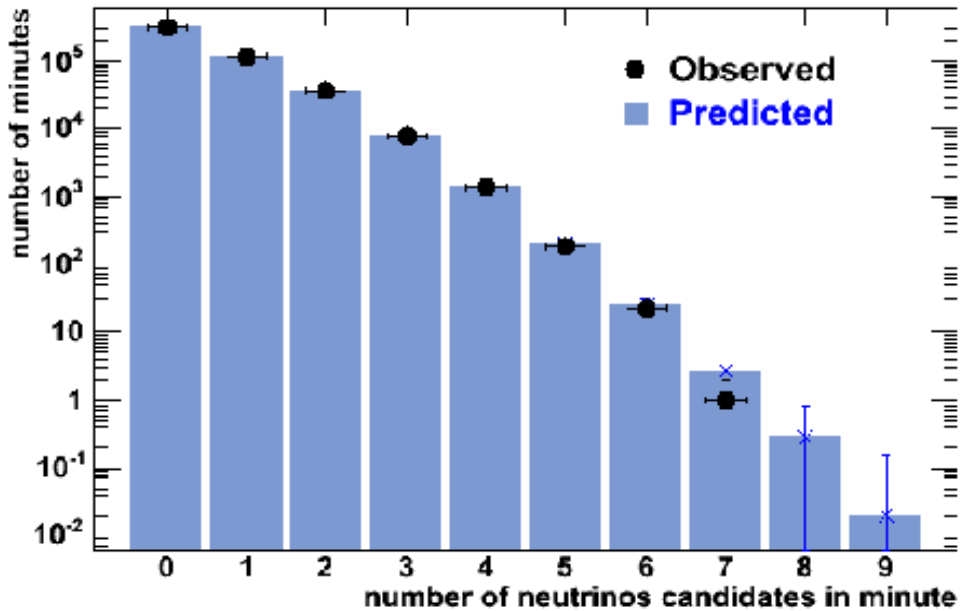
Other (5%)

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

Antineutrino content: 6%

Stability of running:

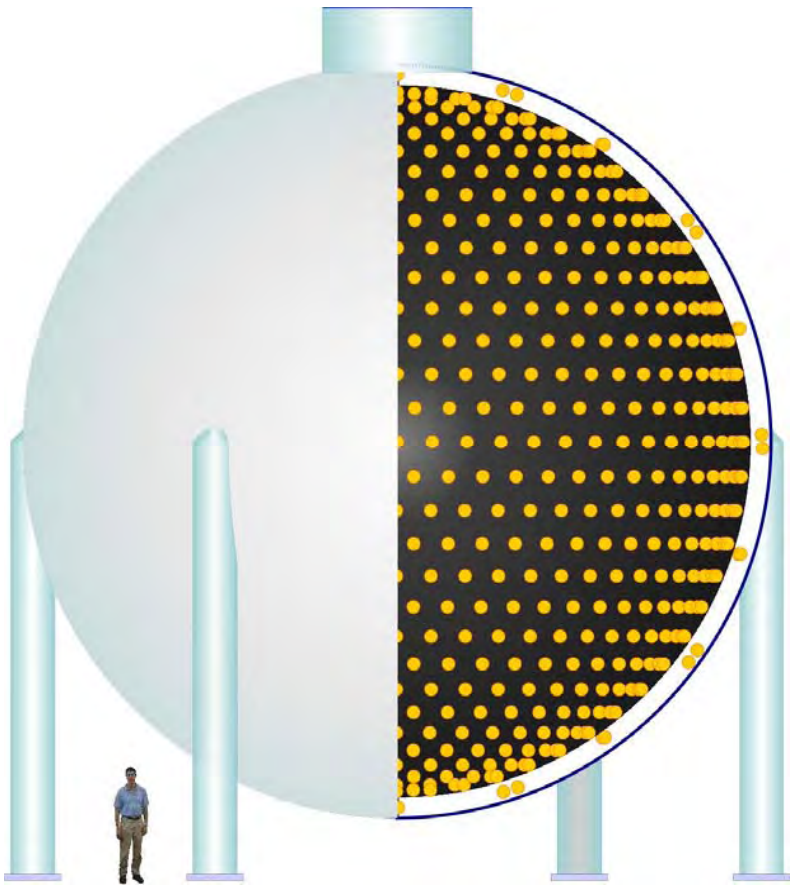




Observed and expected events per minute

Events in the MiniBooNE Detector

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

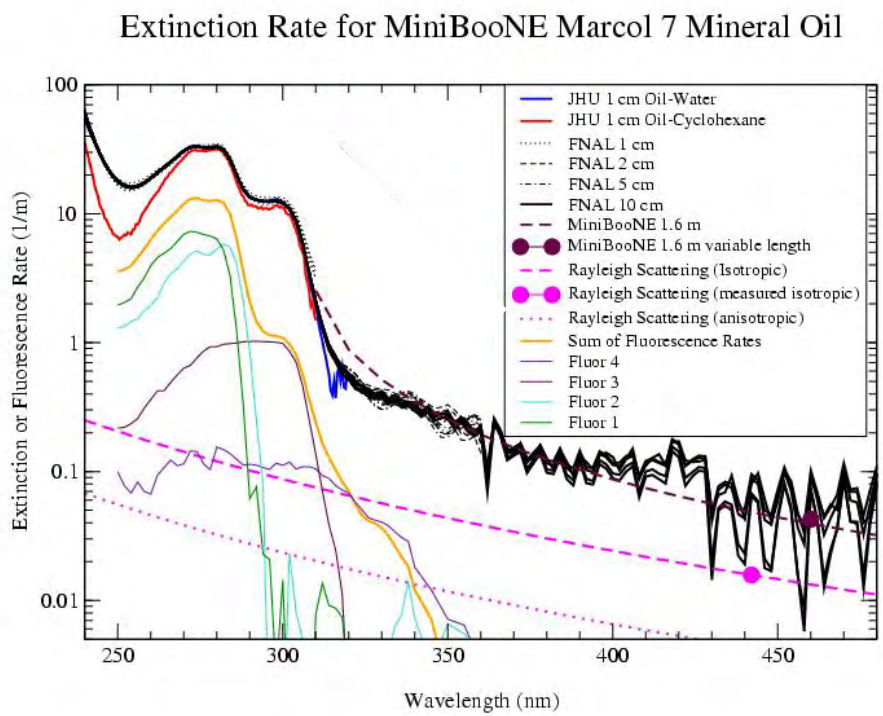
Optical Model

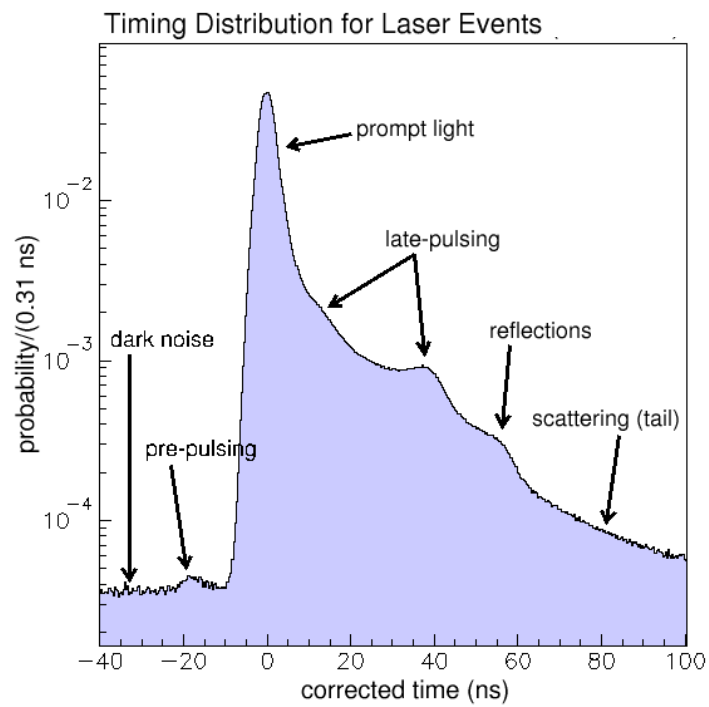
Attenuation length: >20 m @ 400 nm

Detected photons from
- Prompt light (Cherenkov)
- Late light (scintillation, fluorescence)

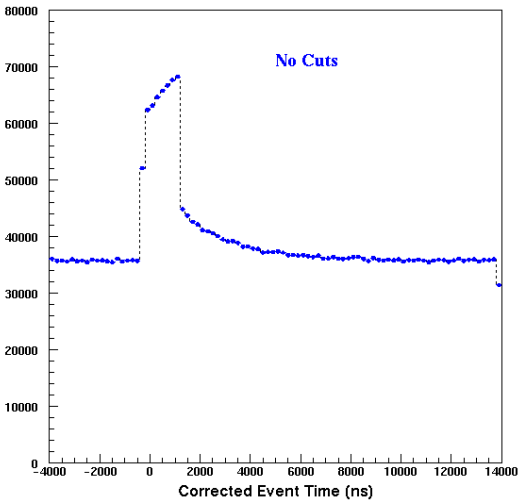
in a 3:1 ratio for β~1

We have developed 39-parameter "Optical Model" based on internal calibration and external measurement

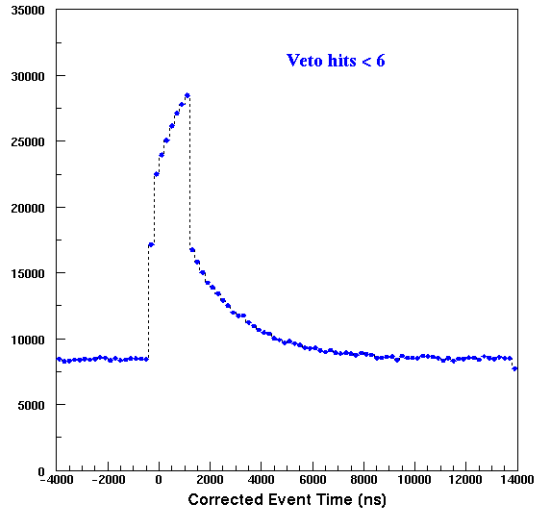




Events in the Beam Time Window

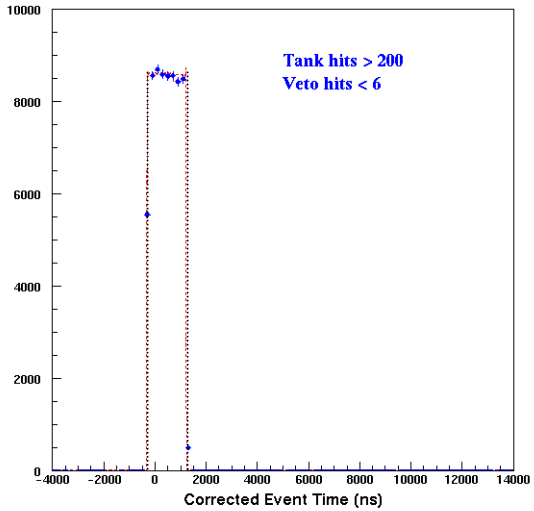


Raw data



Veto<6 removes through-going cosmics

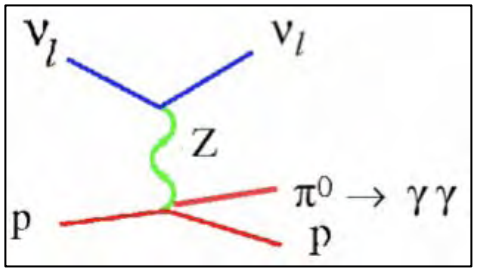
This leaves " Michel electrons" ($\mu \rightarrow \nu_\mu \nu_e e$) from cosmics

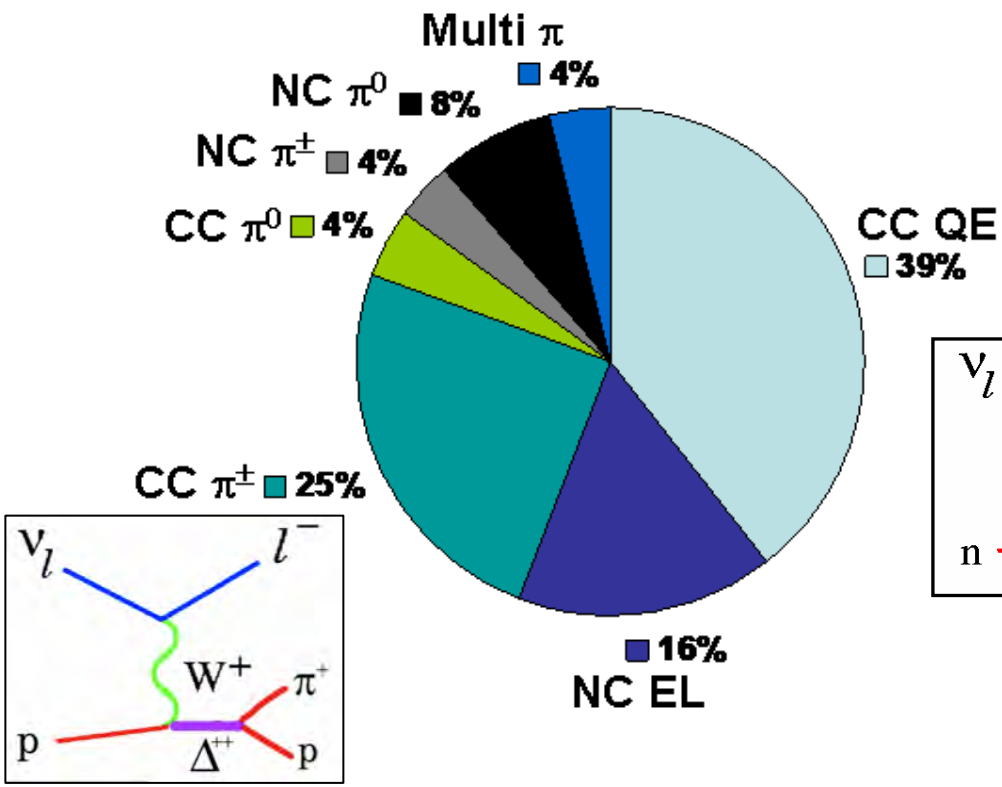


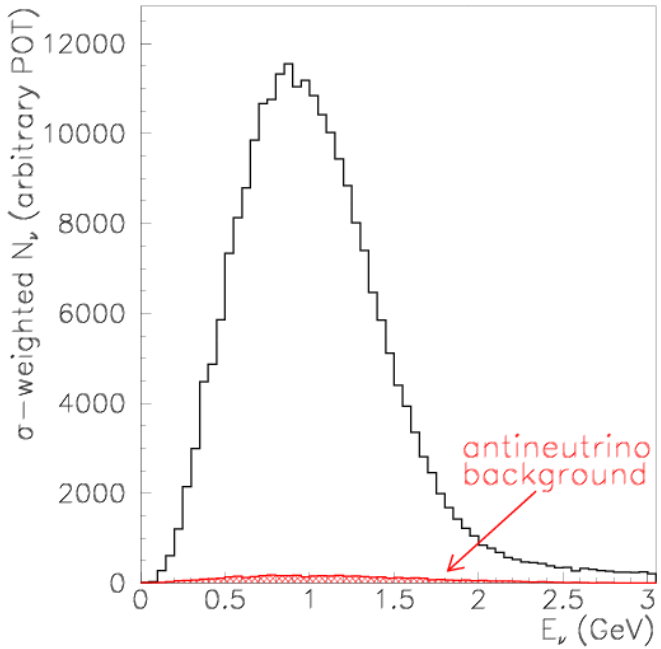
Tank Hits > 200 (equivalent to energy) removes Michel electrons, which have 52 MeV endpoint

Predicted event rates before cuts (NUANCE Monte Carlo)

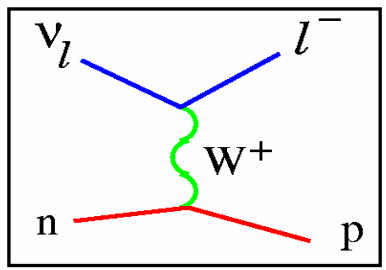
D. Casper, NPS, 112 (2002) 161



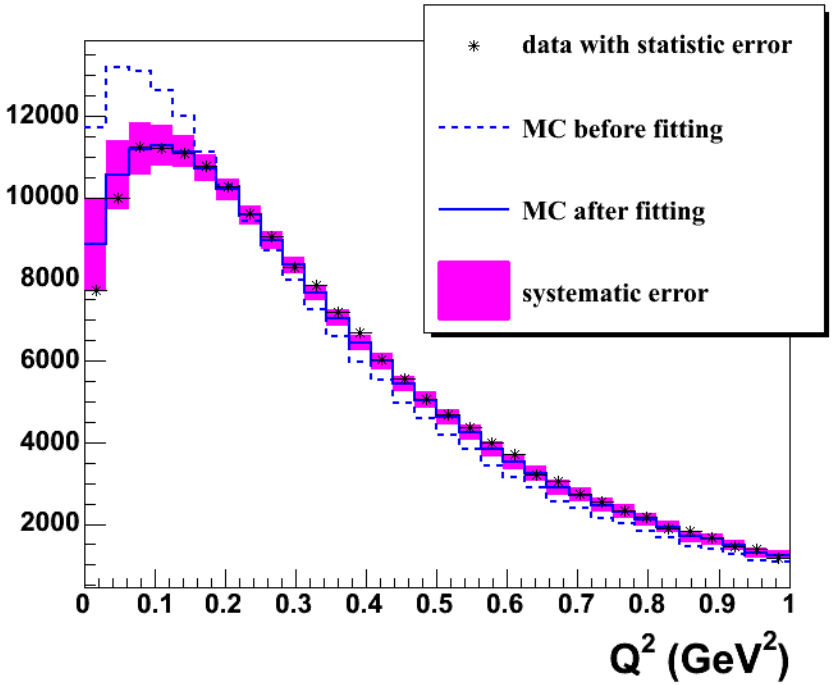




Event neutrino energy (GeV)



CCQE Scattering



From Q^2 fits to MB ν_μ CCQE data:

- M_A^{eff} -- effective axial mass
- E_{lo}^{SF} -- Pauli Blocking parameter

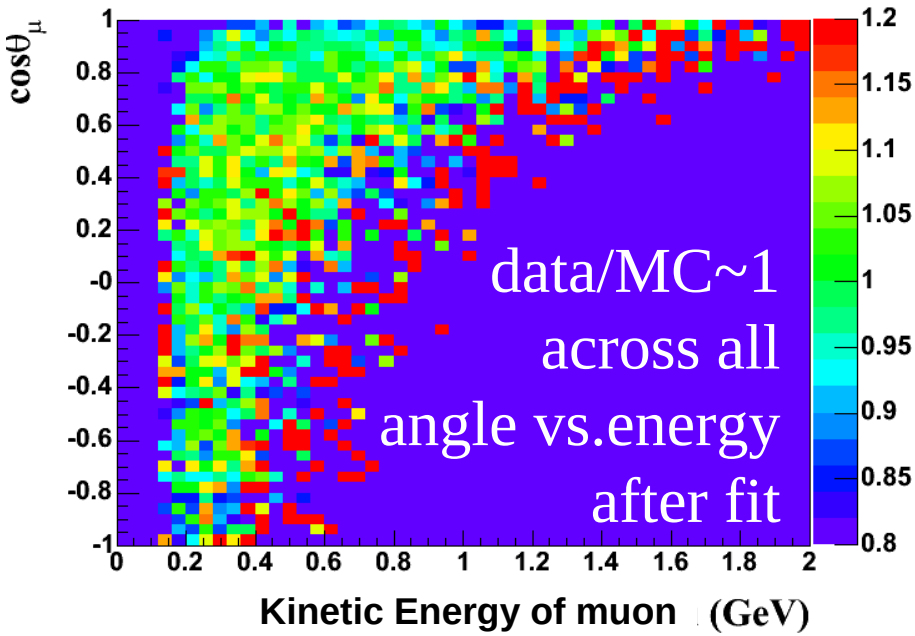
From electron scattering data:

- E_b -- binding energy
- p_f -- Fermi momentum

Model describes CCQE ν_μ data well

M_A = 1.23+-0.20 GeV

E_{lo} = 1.019+-0.011

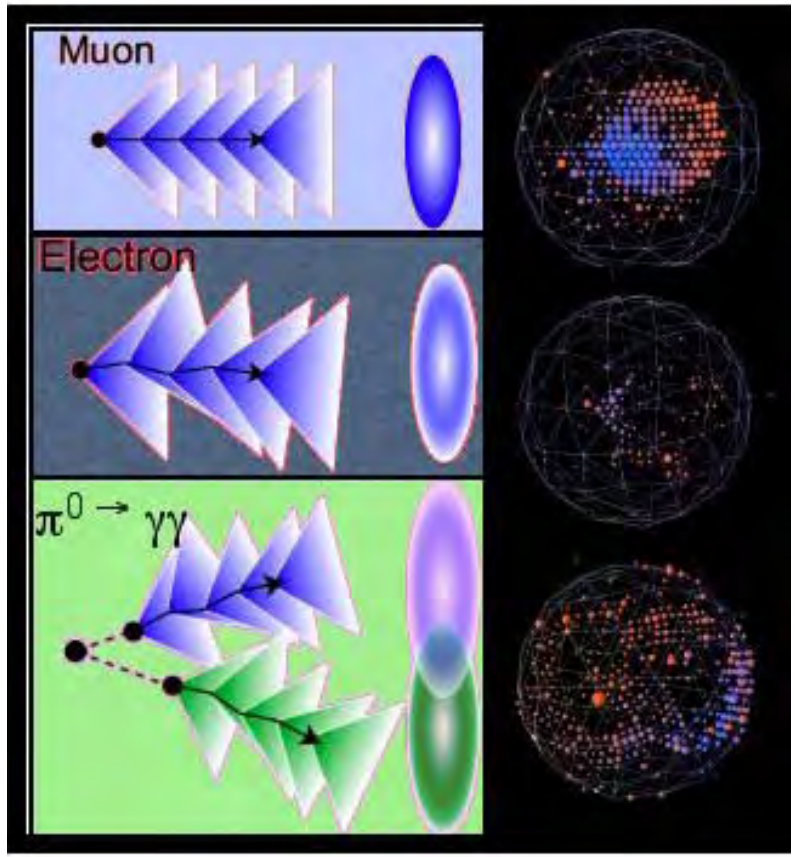


The types of particles these events produce:

Muons:
Produced in most CC events.
Usually 2 subevent or exiting.

Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

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



Data Analysis

“Track-Based” (TB) Analysis

Philosophy:

Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles.

This algorithm was found to have the better sensitivity to $\nu_\mu \rightarrow \nu_e$ appearance.
Therefore, before unblinding,
this was the algorithm chosen for the “primary result”

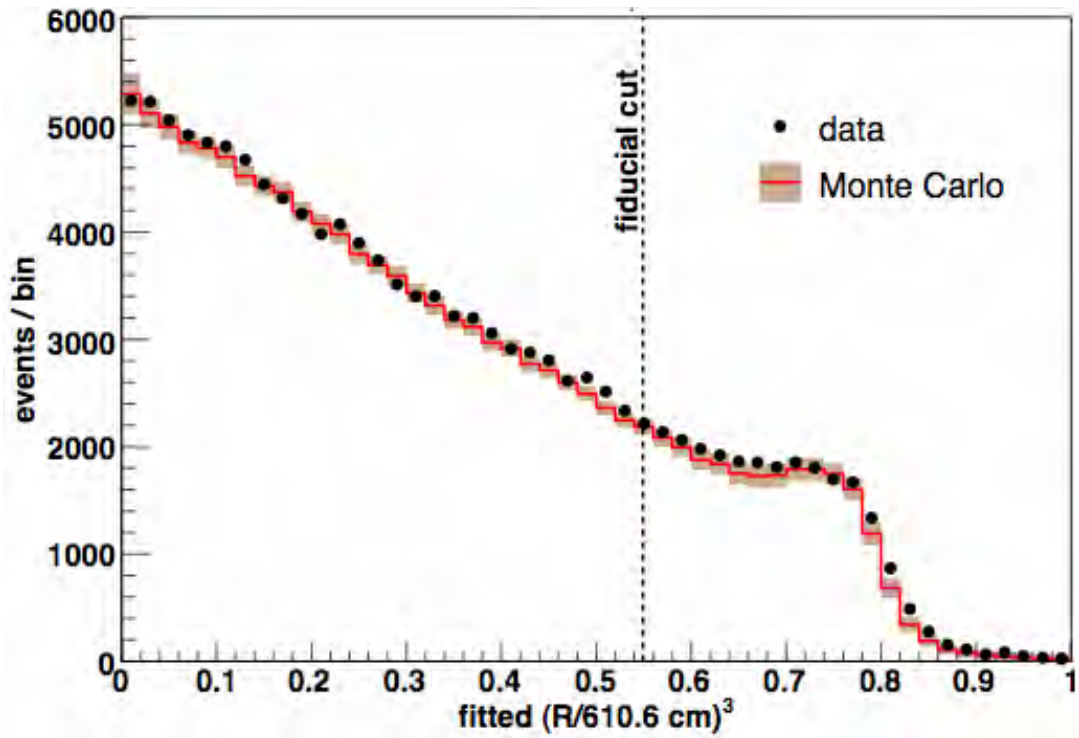
Each event is characterized by 7 reconstructed variables:

vertex (x,y,z), time, energy, and direction $(\theta,\phi)\Leftrightarrow(U_x, U_y, U_z)$.

Resolutions: vertex: 22 cm

direction: 2.8°

energy: 11%

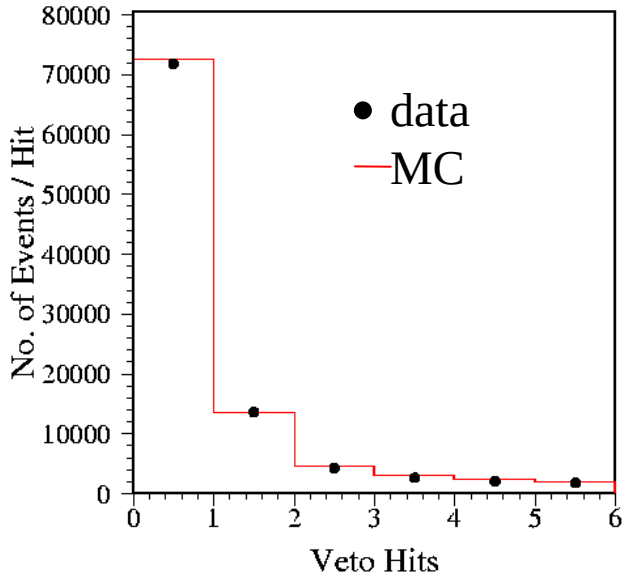


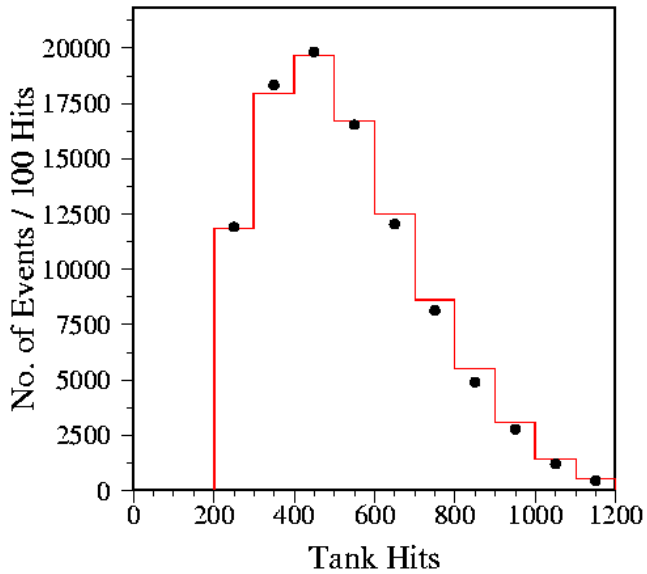
ν_μ CCQE events

2 subevents
Veto Hits<6
Tank Hits>200

Pre-Cuts

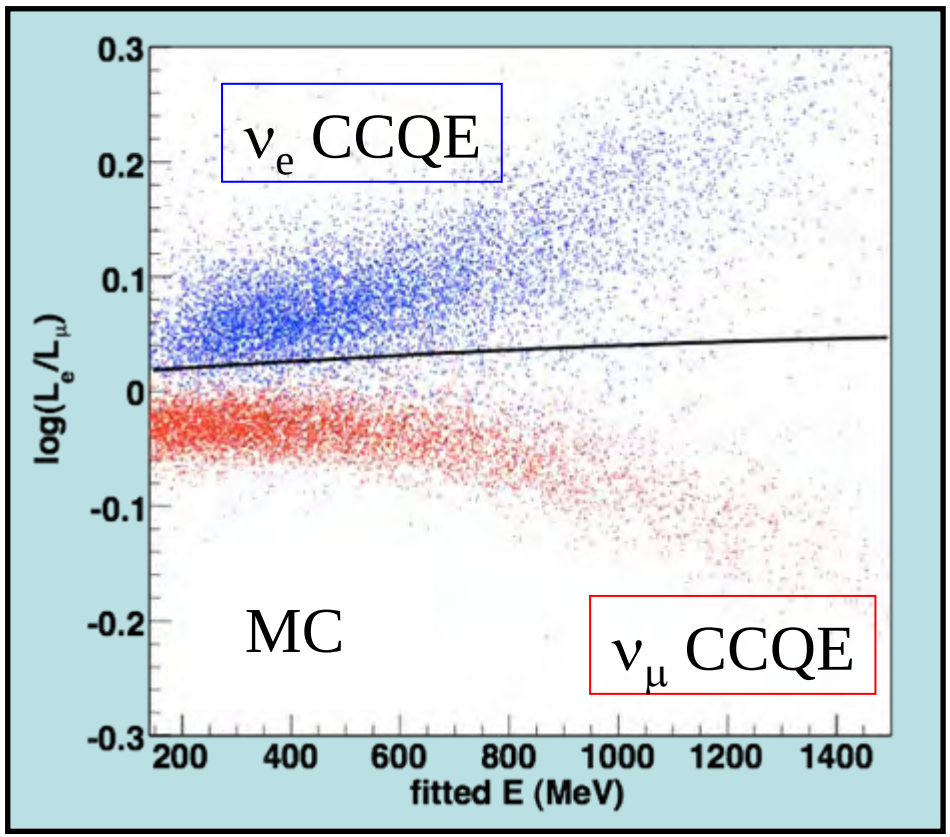
Event in time with beam
Only 1 subevent
Veto hits<6
Tank hits > 200
R<500 cm





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

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



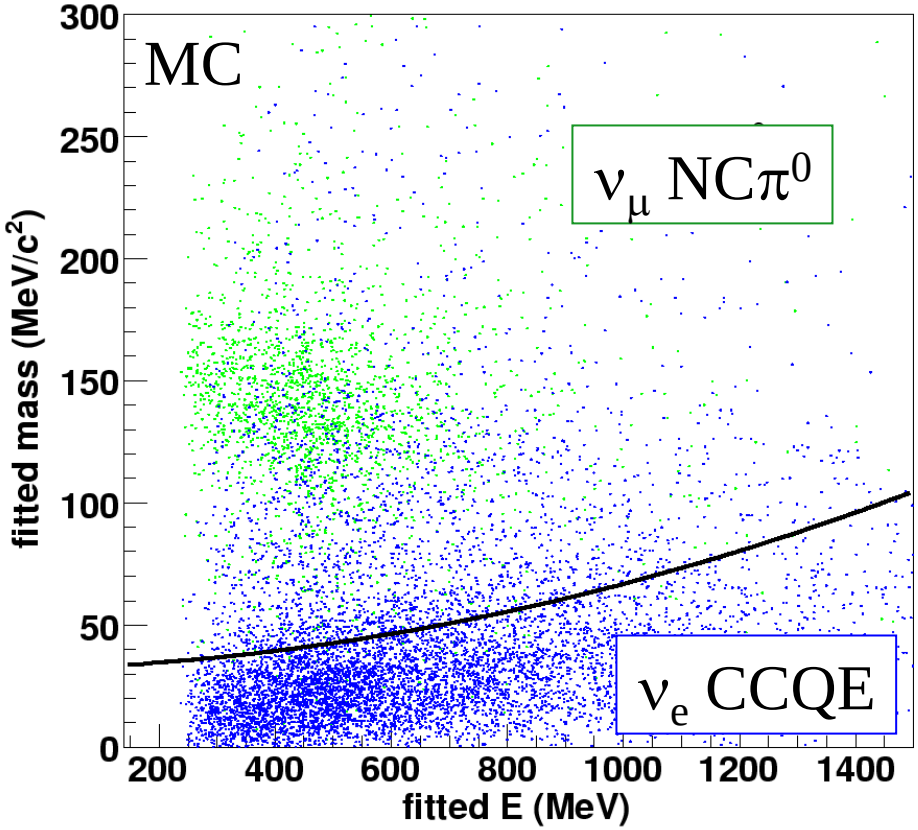
Note: photon conversions are electron-like.
This does not separate e/π^0.

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

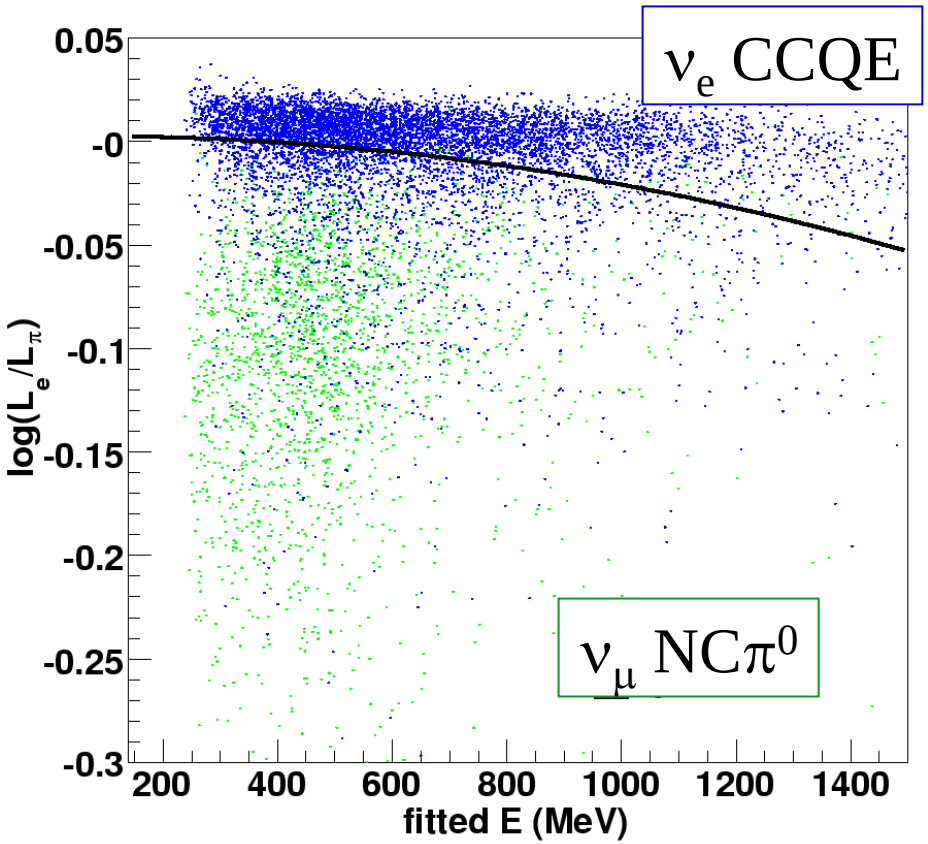
Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

Rejecting "π^0-like" events

Using a mass cut



Using $\log(L_e/L_\pi)$



Cuts were chosen to maximize $\nu_\mu \rightarrow \nu_e$ sensitivity

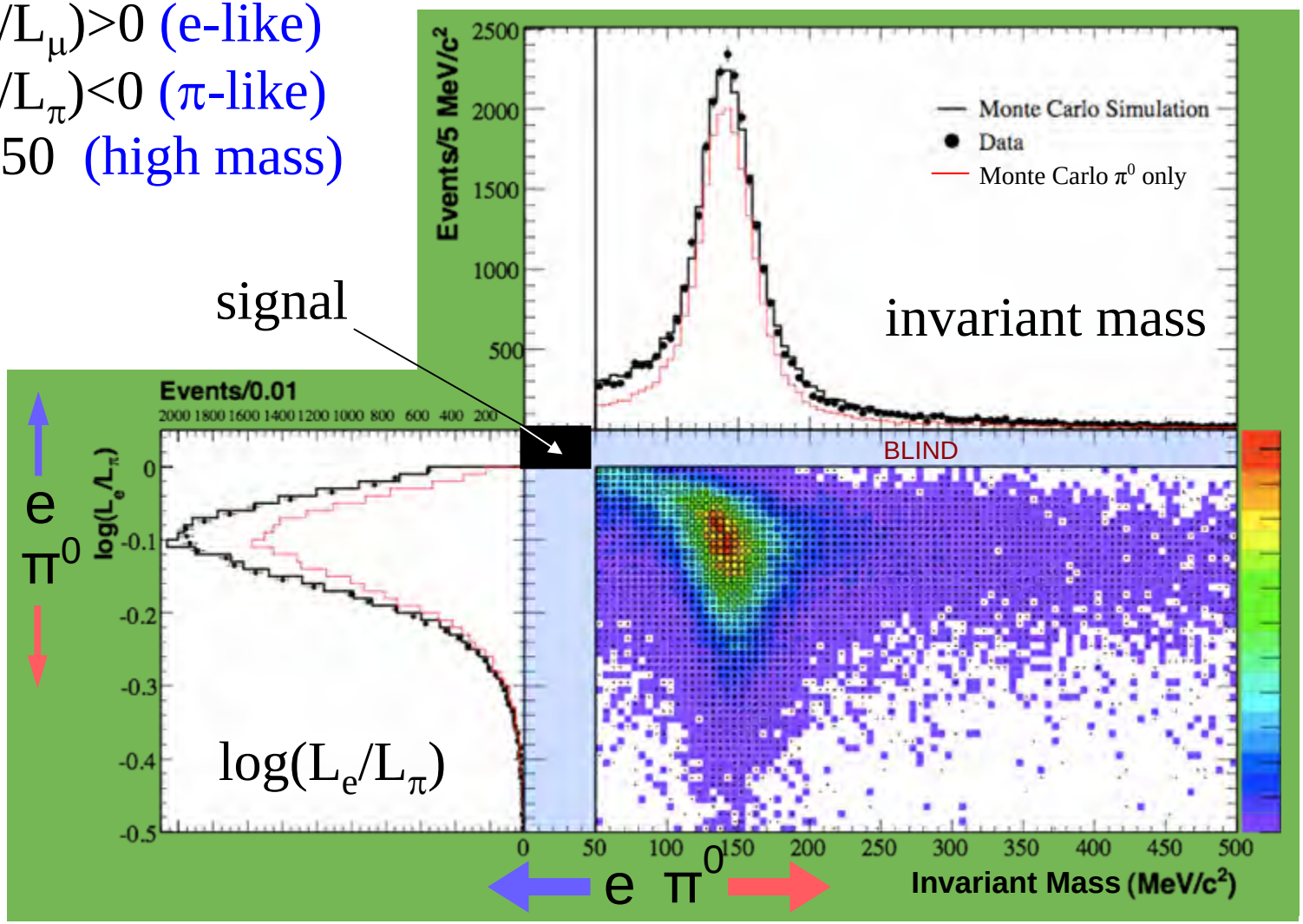
Testing e-π^0 separation using ***data***

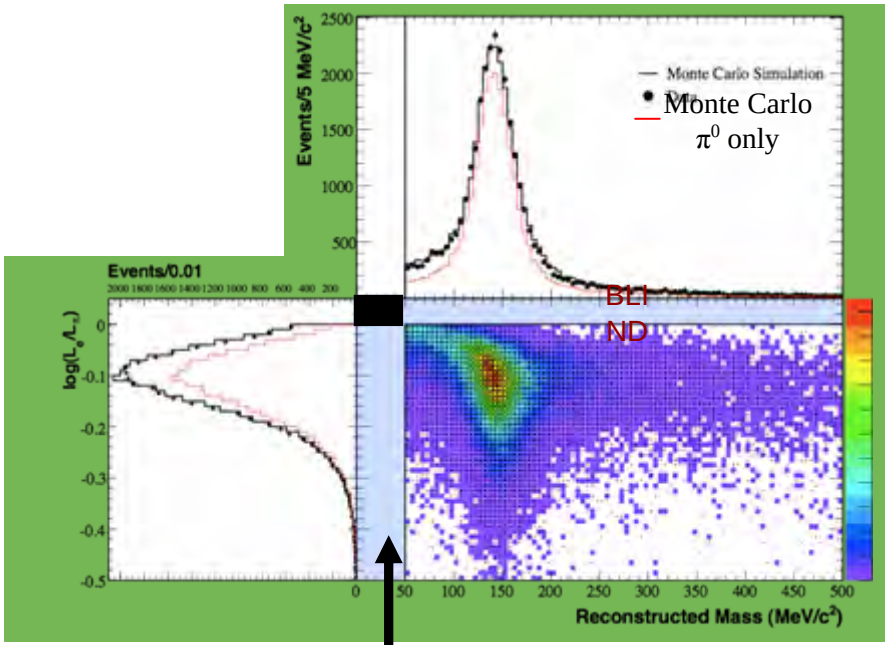
1 subevent

$\log(L_e/L_\mu)>0$ (e-like)

$\log(L_e/L_\pi)<0$ (π-like)

mass>50 (high mass)





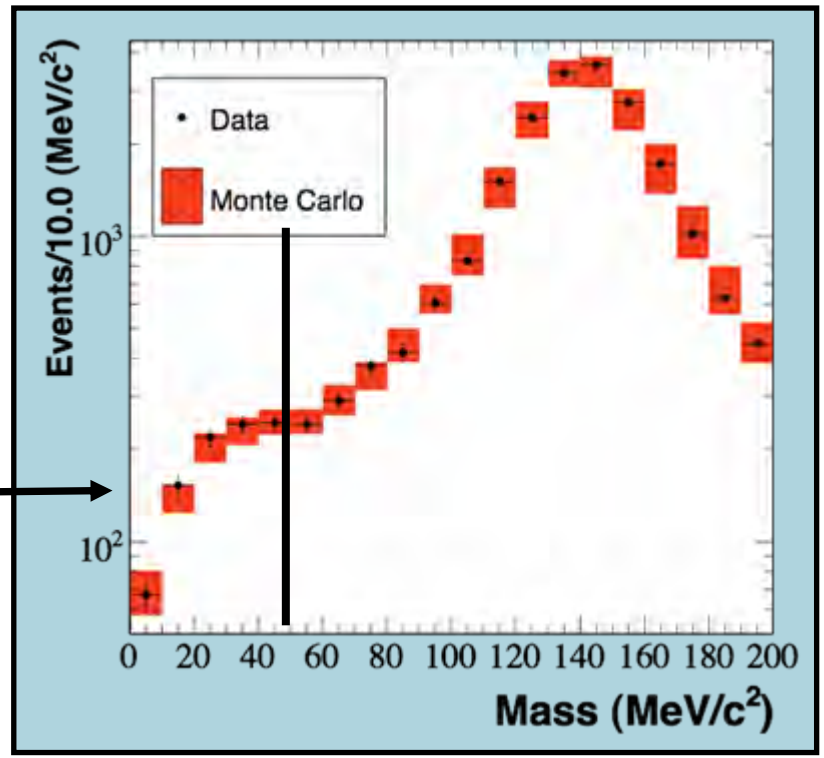
1 subevent

$\log(L_e/L_\mu)>0$ (e-like)

$\log(L_e/L_\pi)<0$ (π-like)

mass<200 (low mass)

Next: look here....



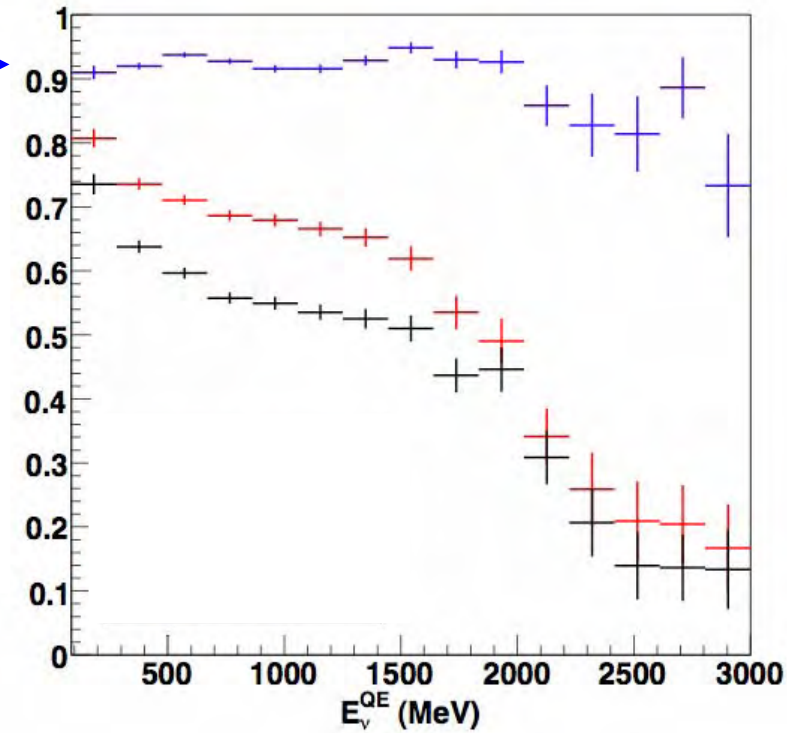
χ^2 Prob for mass<50 MeV ("most signal-like"): 69%

Summary of Track Based cuts

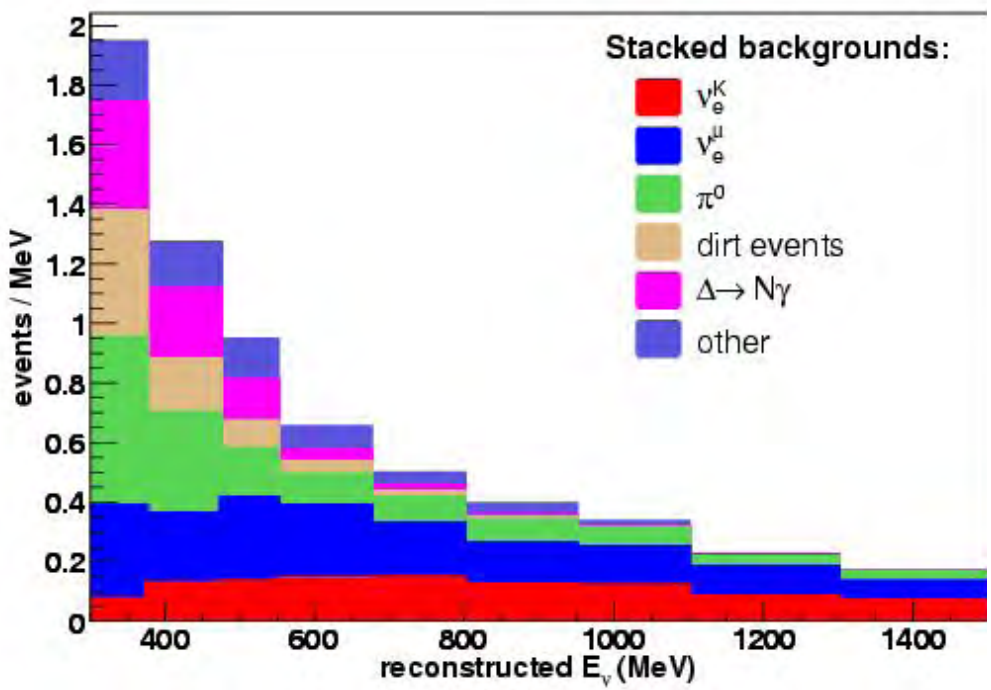
"Precuts" +

$\mathrm{Log}(L_e/L_\mu)$
+ $\mathrm{Log}(L_e/L_\pi)$
+ invariant mass

Efficiency:



Backgrounds after cuts



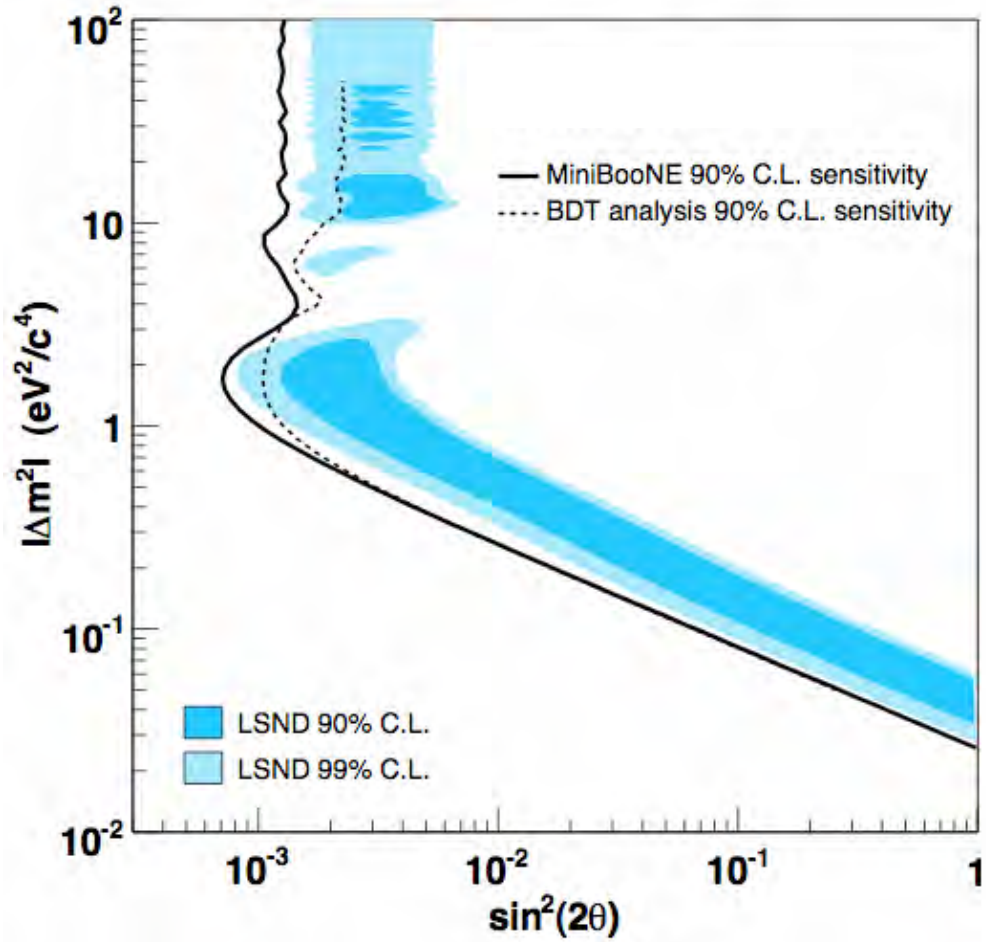
Summary of predicted backgrounds for the final MiniBooNE result (475<E_ν^{QE}<1250 MeV) (Track Based Analysis):

Process	Number of Events
ν_μ CCQE	10
$\nu_\mu e \rightarrow \nu_\mu e$	7
Miscellaneous ν_μ Events	13
NC π^0	62
NC $\Delta \rightarrow N\gamma$	20
NC Coherent & Radiative γ	< 1
Dirt Events	17
ν_e from μ Decay	132
ν_e from K^+ Decay	71
ν_e from K_L^0 Decay	23
ν_e from π Decay	3
Total Background	358
0.26% $\nu_\mu \rightarrow \nu_e$	(example signal) 163

Source of Uncertainty On ν_e background	Track Based error in %	Checked or Constrained by MB data	Further reduced by tying ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2	√	√
Flux from K^+ decay	3.3	√	√
Flux from K^0 decay	1.5	√	√
Target and beam models	2.8	√	
ν-cross section	12.3	√	√
NC π^0 yield	1.8	√	
External interactions (“Dirt”)	0.8	√	
Optical model	6.1	√	√
DAQ electronics model	7.5	√	

Sensitivity of the two analyses

The Track-based sensitivity is better,
thus this becomes the pre-determined default algorithm



Set using $\Delta\chi^2$=1.64 @ 90% CL

The Initial Results

Box Opening Procedure

Progress cautiously,
in a
step-wise fashion

After applying all analysis cuts:

1. Fit sequestered data to an oscillation hypothesis, returning no fit parameters. Return the χ^2 of the data/MC comparison for a set of diagnostic variables.

   (Bad E_{vis} χ^2 => Increase E_ν^{QE} threshold from 300 to 475 MeV for osc. fit)

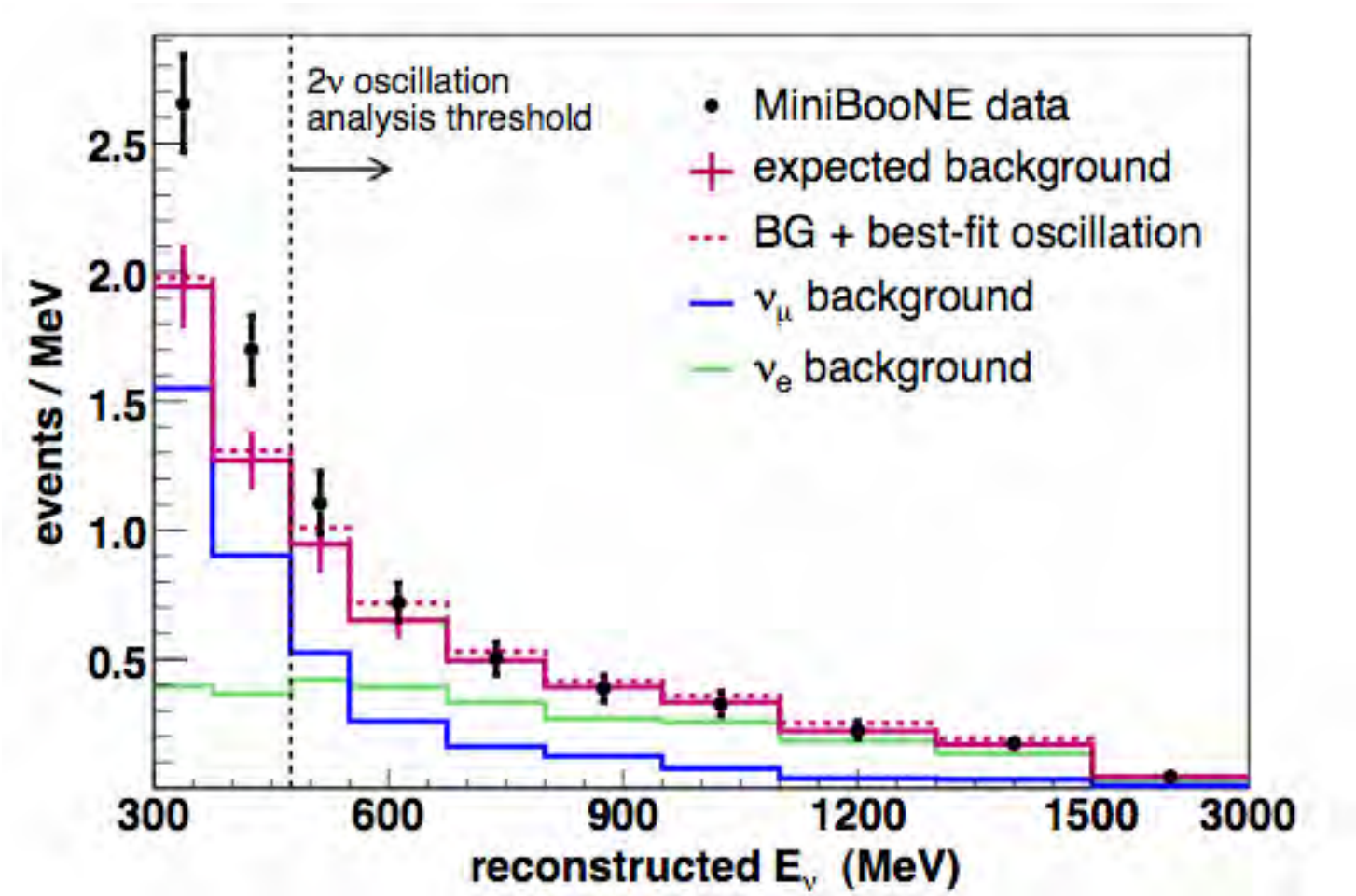
2. Open up the plots from step 1. The Monte Carlo has unreported signal. Plots chosen to be useful diagnostics, without indicating if signal was added.

3. Report the χ^2 for a fit to E_ν^{QE}, without returning fit parameters.

4. Compare E_ν^{QE} in data and Monte Carlo, returning the fit parameters. At this point, the box is open (March 26, 2007)

5. Present results two weeks later.

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

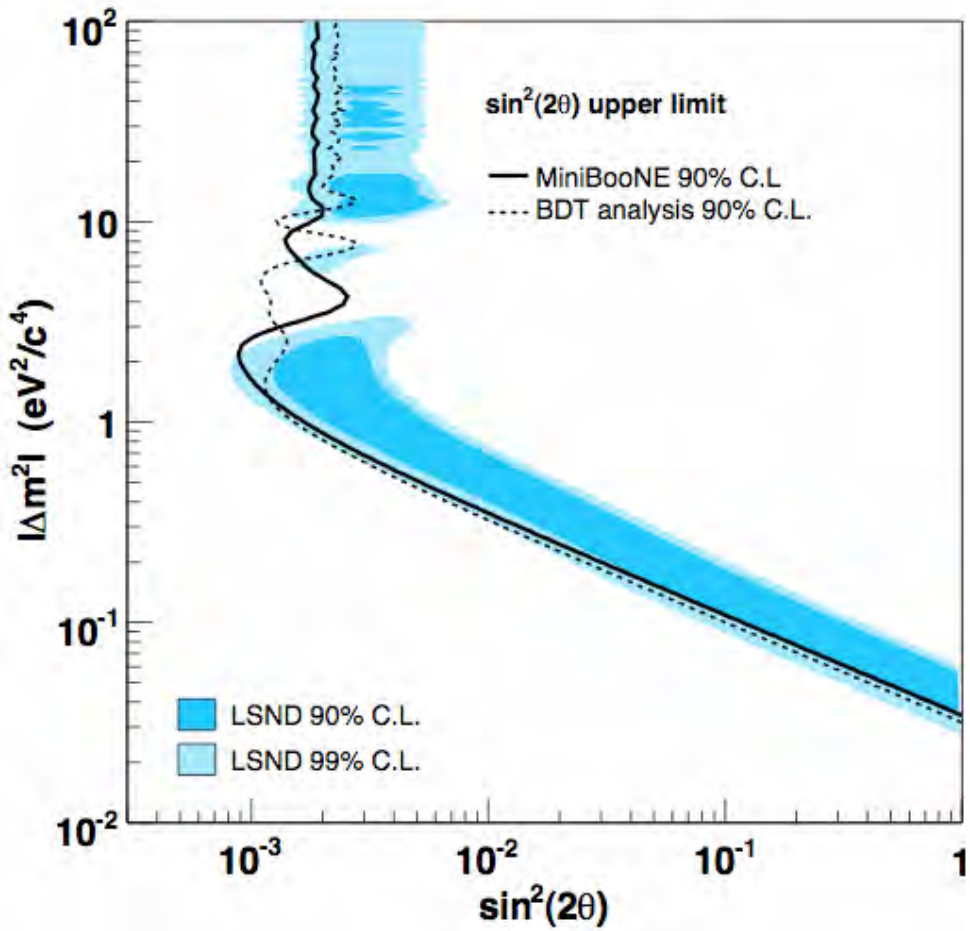


$300 < E_\nu^{QE} < 1250$ MeV : data: 749 events, MC: 631 ±25 ±45 events, 2.3 σ

$475 < E_\nu^{QE} < 1250$ 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

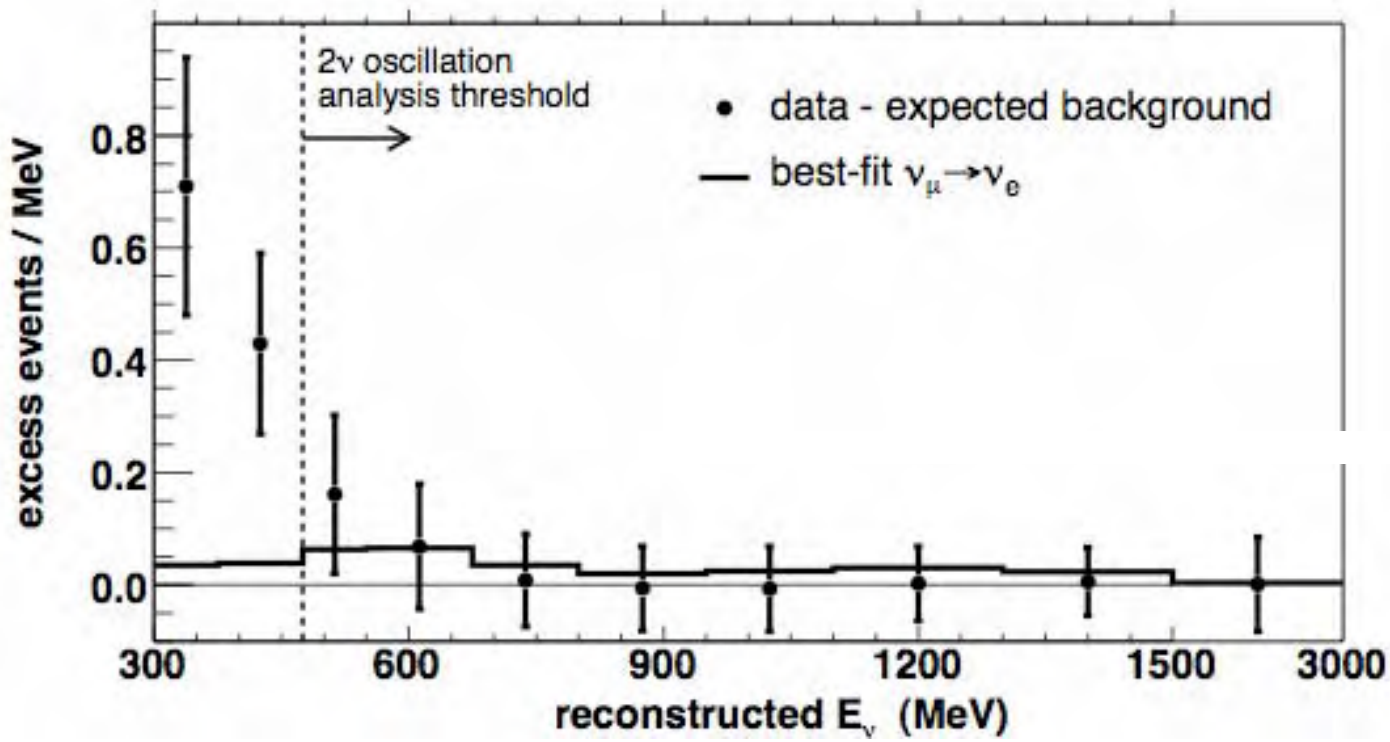
The result of
the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis
is a <u>limit</u> on oscillations:



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

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

Background Subtracted

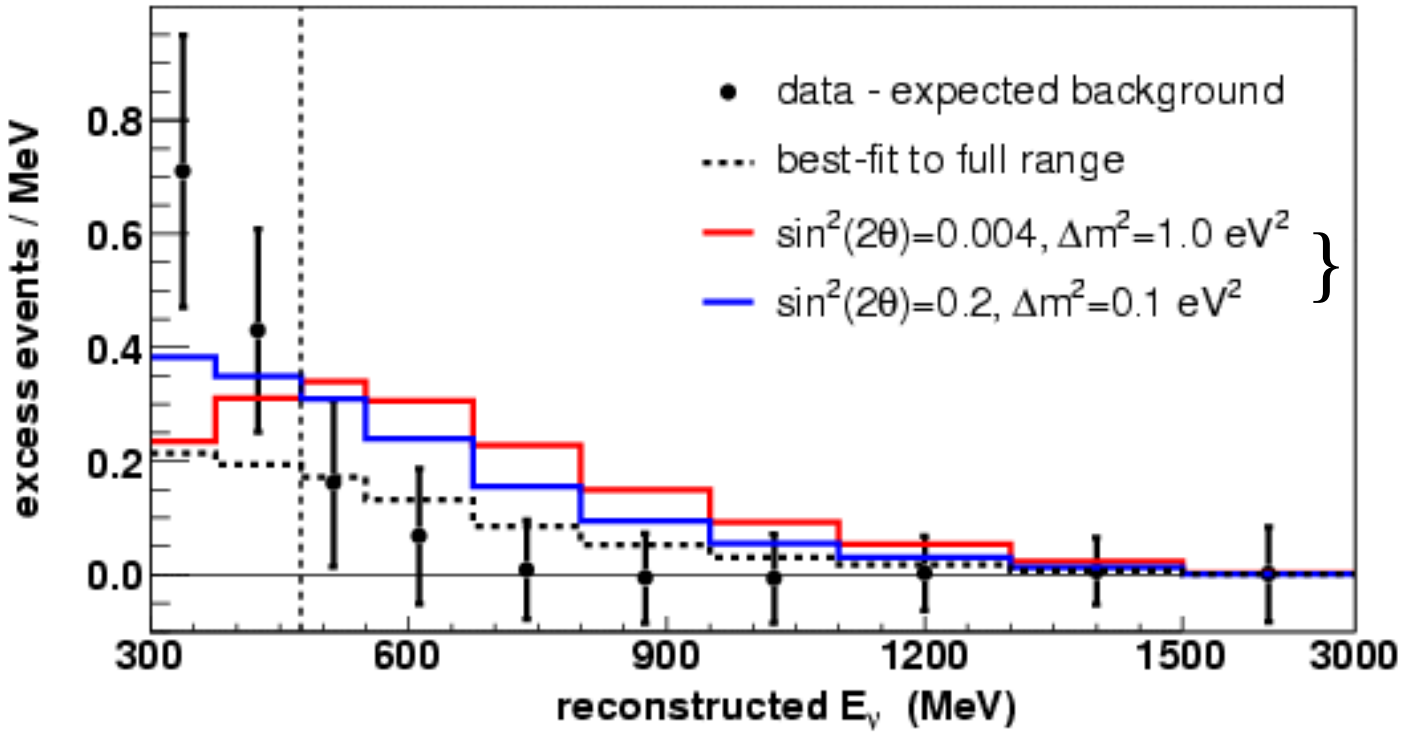


96 ± 17 ± 20 events above background, for $300<E_\nu^{QE}<475$MeV

Deviation: 3.7σ

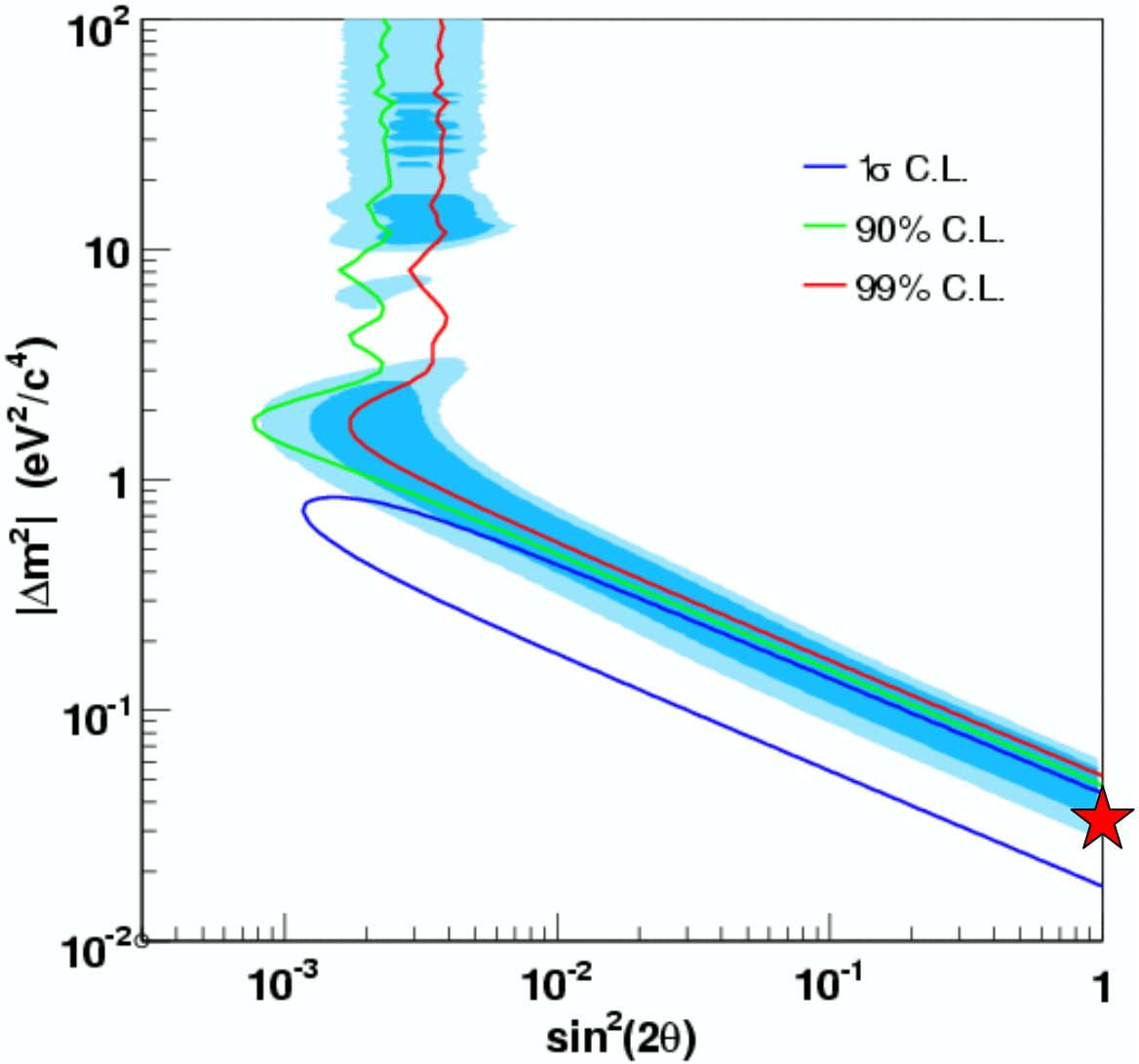
Fit to the > 300 MeV range:

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



Allowed Region

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



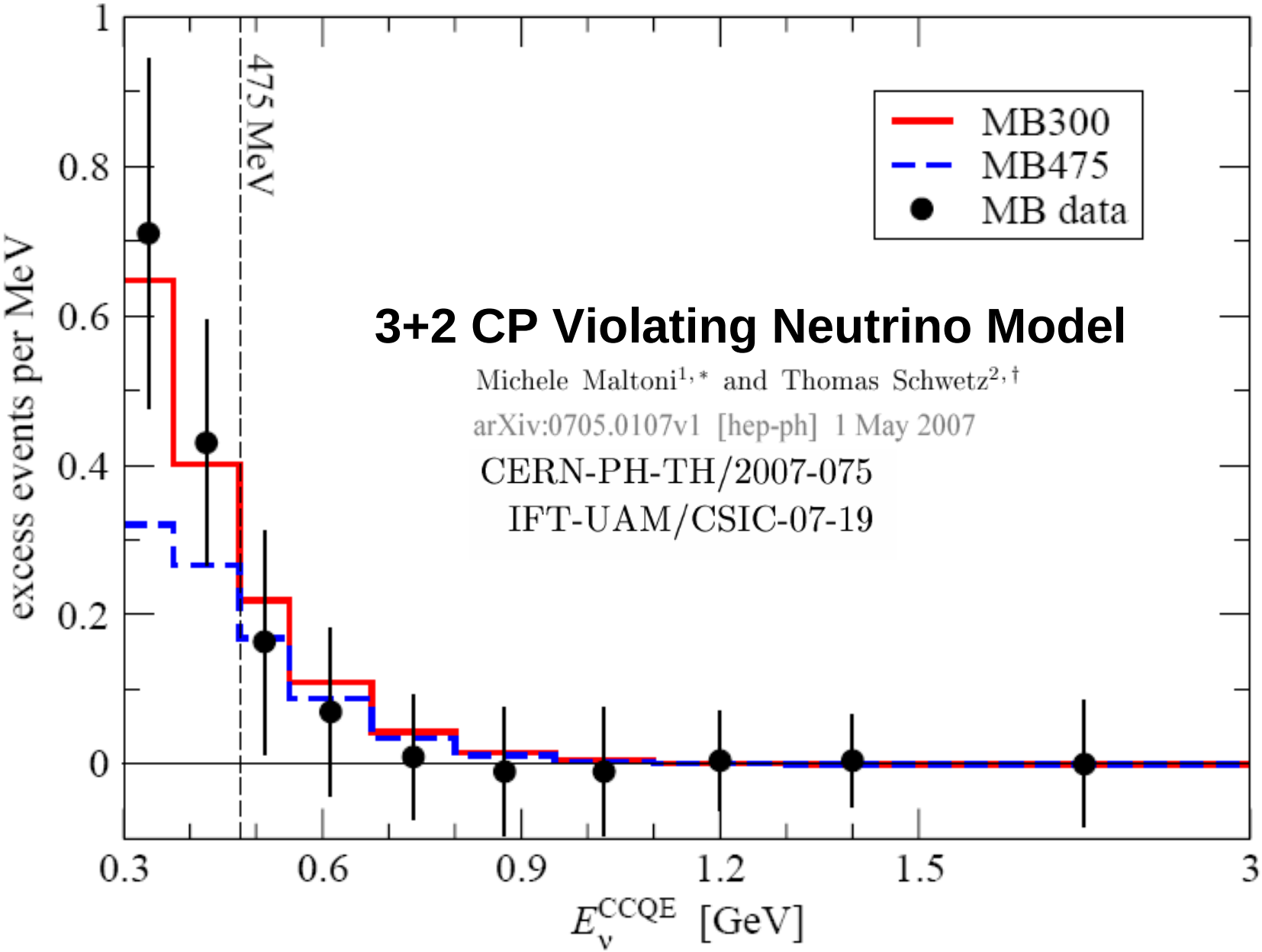
Interpretations of Low-Energy Excess

Background?

- Is low-energy excess due to background?
- e.g. some NC gamma production or other electromagnetic process?

Signal?

- 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



3+2 CP Violating Neutrino Model

Michele Maltoni[1,*] and Thomas Schwetz[2,†]

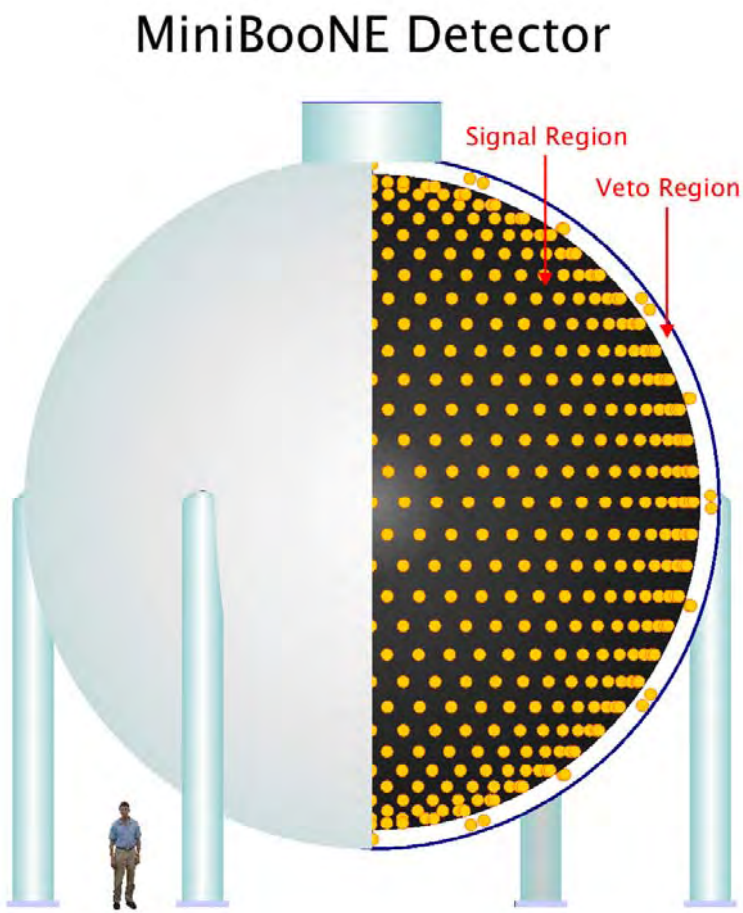
arXiv:0705.0107v1 [hep-ph] 1 May 2007
CERN-PH-TH/2007-075
IFT-UAM/CSIC-07-19

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



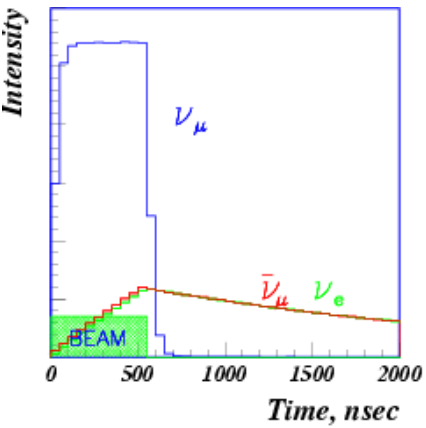
BooNE at FNAL

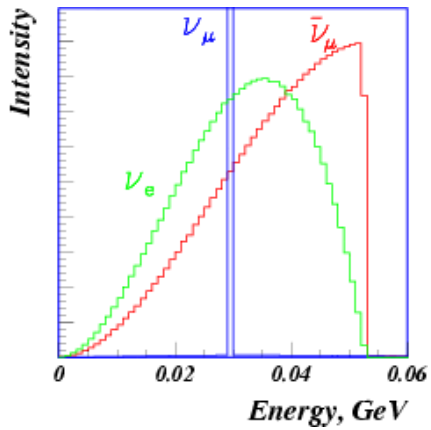
Two identical detectors at different distances

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

Problem: imprecise ν energy determination smears oscillations!

OscSNS at ORNL





SNS: ~1 GeV, ~1.4 MW

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

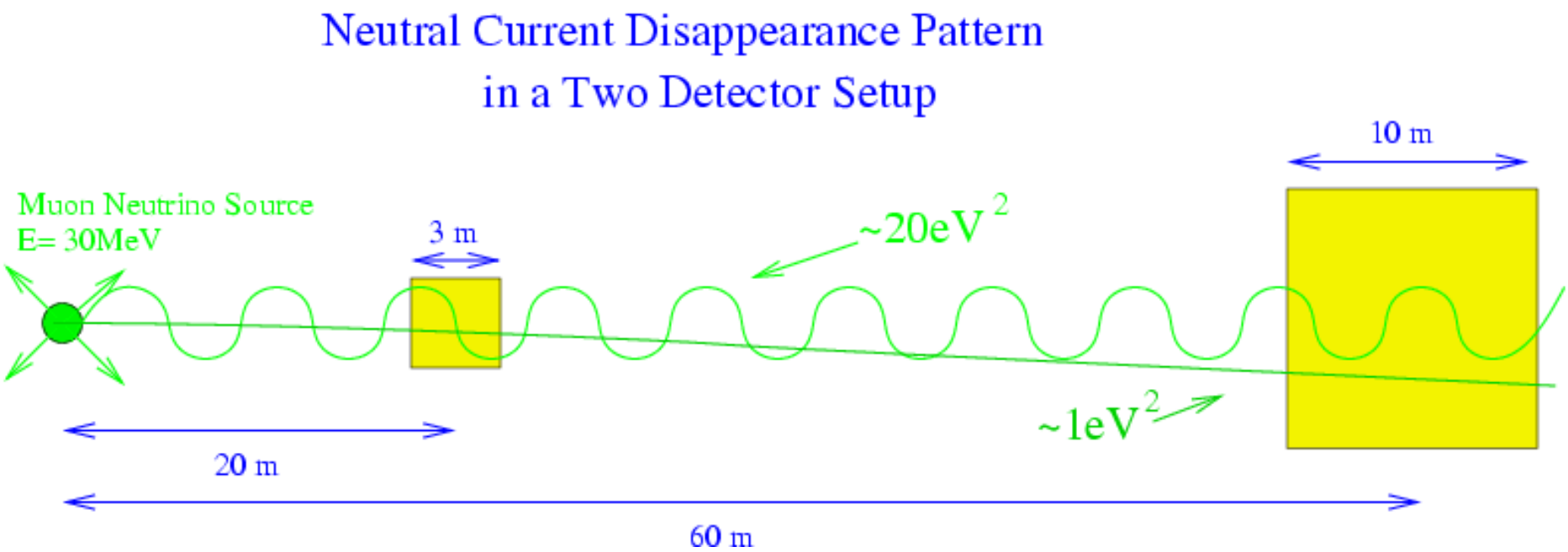
$\nu_\mu \to \nu_s$ $\Delta(L/E) < 1\%$; **Monoenergetic** ν_μ !; $\nu_\mu\, C \to \nu_\mu\, C^*(15.11)$

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)). Flux shapes are known perfectly and cross sections are known very well

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

ν_μ C -> ν_μ C*(15.11)

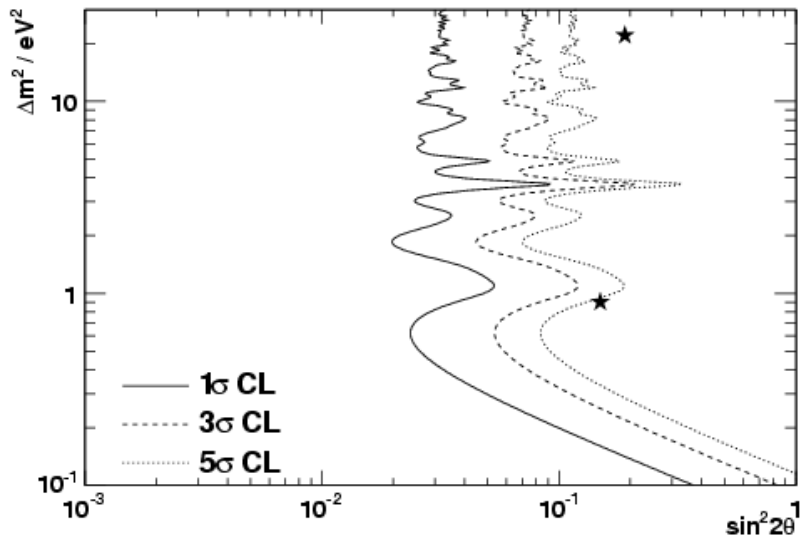
Garvey et al., Phys. Rev. D72 (2005) 092001

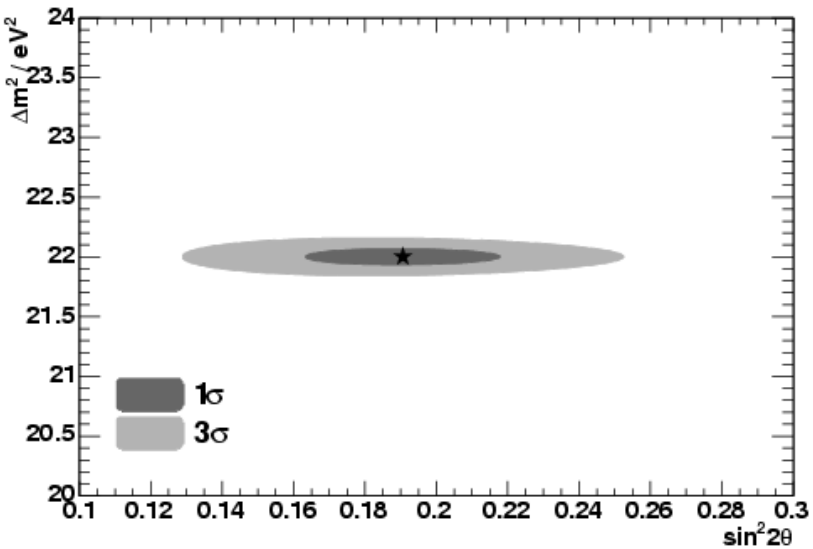


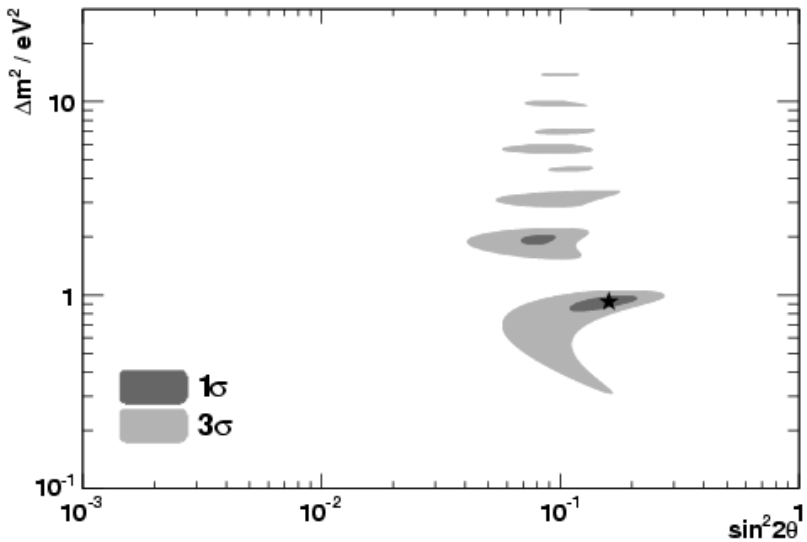
Measurement of 3+2 Model with OscSNS

(Sorel et al., Phys. Rev. D70 (2004) 073004)

$\nu_\mu \rightarrow \nu_s$







Conclusions

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

The observed reconstructed energy distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ appearance-only model, & MiniBooNE rules out this model as an explanation of the LSND excess at 98% CL.

However, more events are observed than expected at low energy $300<E_\nu^{QE}<475$MeV.

This unexplained deviation is under investigation.

Future

- Understand the low-energy excess of events!
- Extend threshold to lower energies.
- Analyze antineutrino data, NuMI data, & SciBooNE data.
- If low-energy excess is consistent with electron neutrinos, new experiments at FNAL (BooNE) and/or SNS (OscSNS) will be proposed to explore physics Beyond the Standard Model.