# Results of the MiniBooNE Oscillation Experiment

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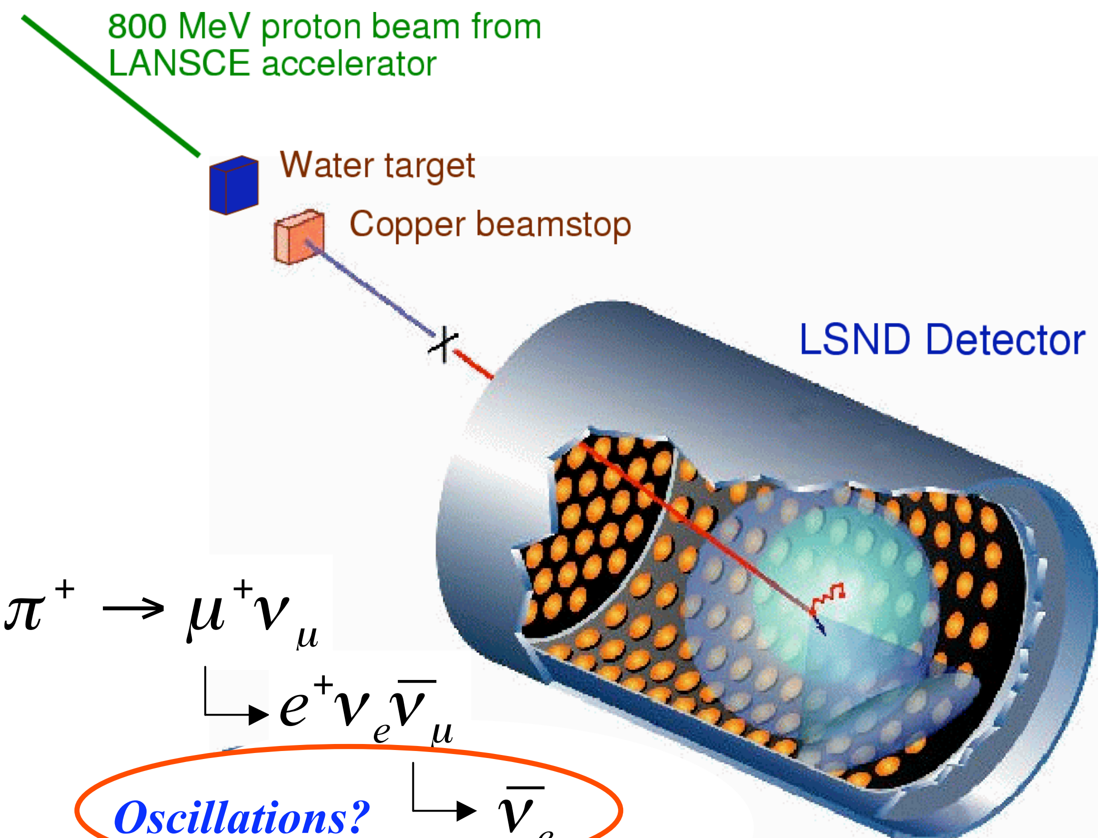
# *Before MiniBooNE*

# Before MiniBooNE: The LSND Experiment



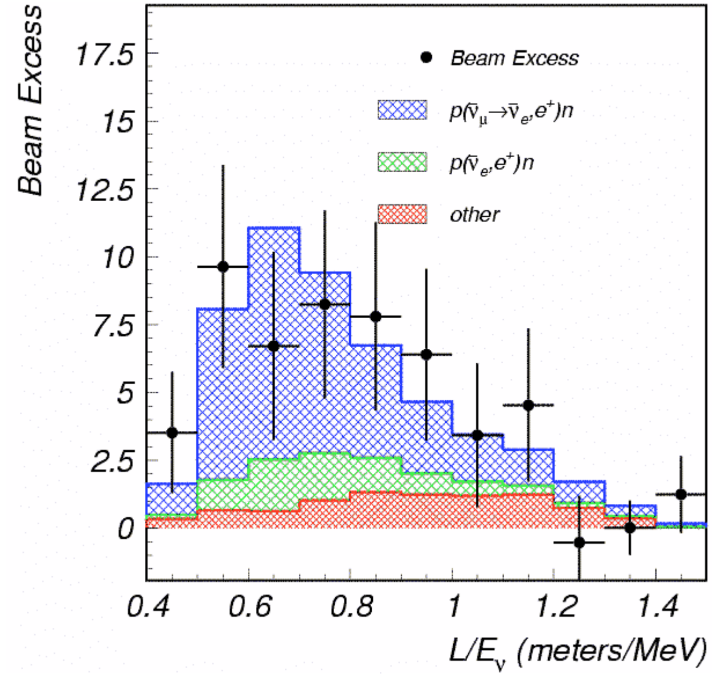

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

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

***Oscillations?*** $\hookrightarrow \bar{\nu}_e$

Signal: $\bar{\nu}_e\ p \rightarrow e^+\ n$

$n\ p \rightarrow d\ \gamma(2.2\mathrm{MeV})$



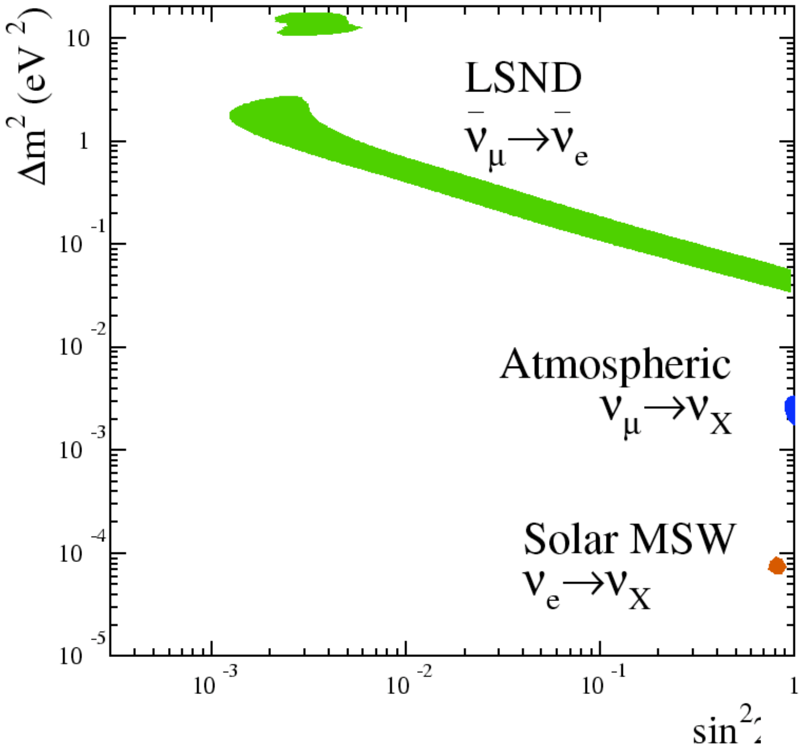

LSND took data from 1993-98
- 49,000 Coulombs of protons
- L = 30m and 20 < $E_\nu$ < 53 MeV

**Saw an excess of $\bar{\nu}_e$ :**
**87.9 ± 22.4 ± 6.0 events.**

**With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.**

**3.8 σ significance for excess.**

# Oscillation Status After LSND



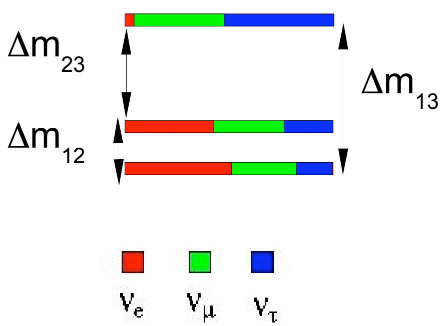

This signal looks very different from the others...

- Much higher $\Delta m^2 = 0.1 - 10$ eV$^2$
- Much smaller mixing angle
- Only one experiment!

Kamioka, IMB, Super K, Soudan II, Macro, K2K
$\Delta m^2 = 2.5\times10^{-3}$ eV$^2$

Homestake, Sage, Gallex, Super-K SNO, KamLAND
$\Delta m^2 = 8.2\times10^{-5}$ eV$^2$

In SM there are only 3 neutrinos




- Three distinct neutrino oscillation signals, with $\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- For three neutrinos, expect $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

## How can one get 3 distinct $\Delta m^2$ ?

- One of the experimental measurements is wrong
- One of the experimental measurements is not neutrino oscillations
  - Neutrino decay
  - Neutrino production from flavor violating decays
- Additional "sterile" neutrinos involved in oscillations
- CPT violation (or CP viol. and sterile $\nu$'s ) allows different mixing for $\nu$'s and $\bar{\nu}$'s

# *MiniBooNE*

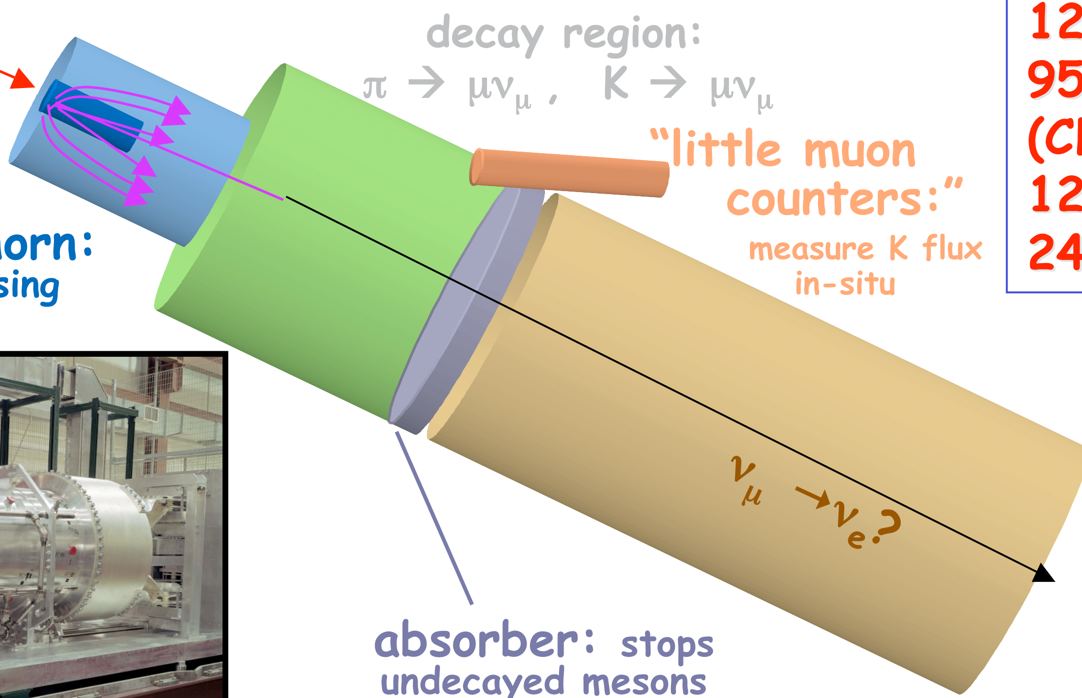
## *(Booster Neutrino Experiment)*

# Search for $\nu_e$ appearance in $\nu_\mu$ beam

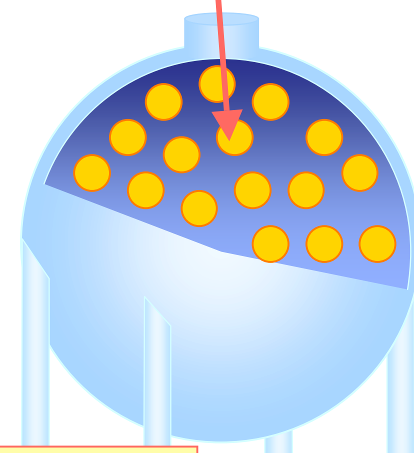
FNAL 8 GeV Beamline

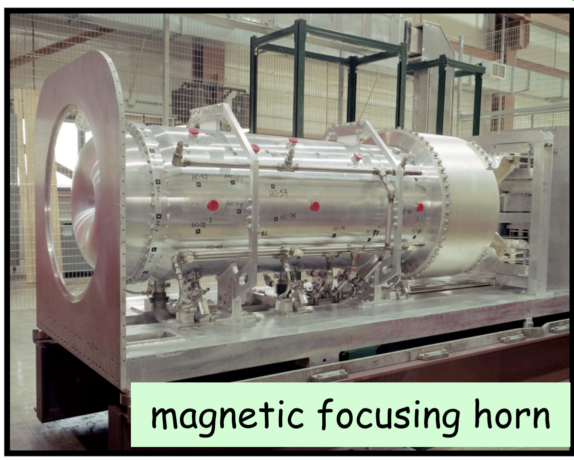
50 m decay pipe

Use protons from the 8 GeV booster
⇒ Neutrino Beam
$\langle E_\nu \rangle \sim 0.7$ GeV




**MiniBooNE Detector:**
- 12m diameter sphere
- 950000 liters of oil ($CH_2$)
- 1280 inner PMTs
- 240 veto PMTs





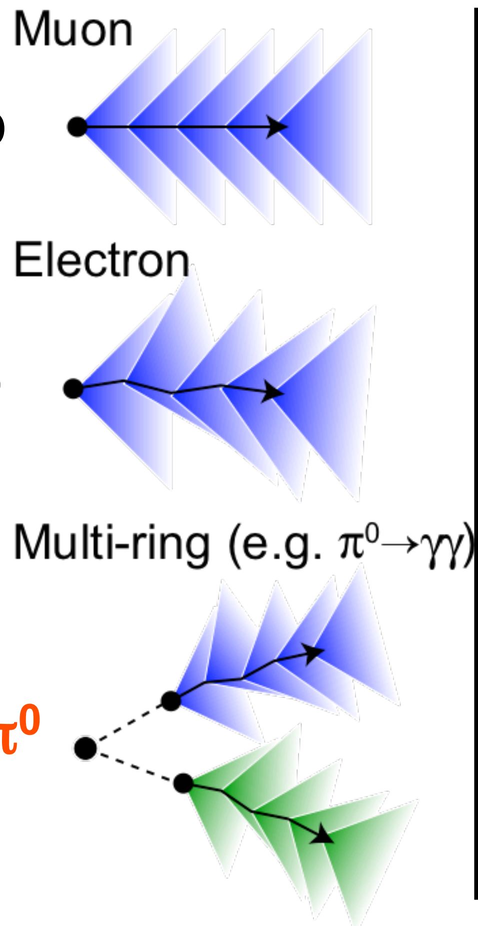
magnetic focusing horn

Same L/E~0.8m/MeV as LSND !

$\nu_\mu \rightarrow \nu_e$ ???

# Particle Identification

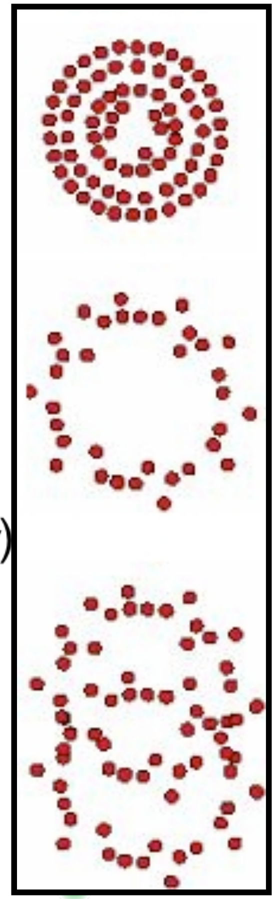
Čerenkov rings provide primary means of identifying products of $\nu$ interactions in the detector



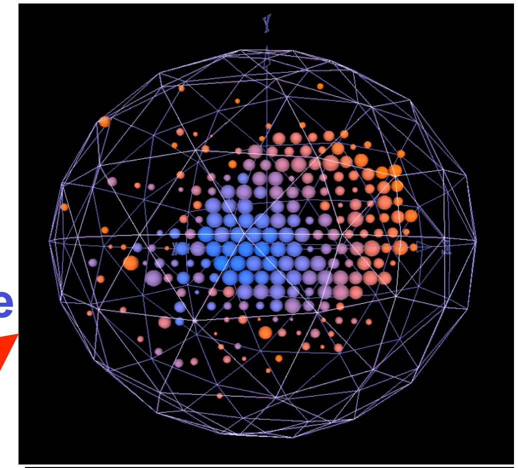

$\nu_\mu\, n \to \mu^-\, p$

$\nu_e\, n \to e^-\, p$

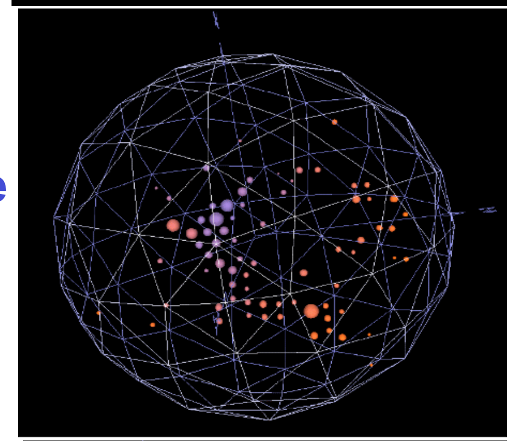
$\nu_\mu\, p\ n \to \nu_\mu\, p\ n\ \pi^0$



**beam $\mu$ candidate**

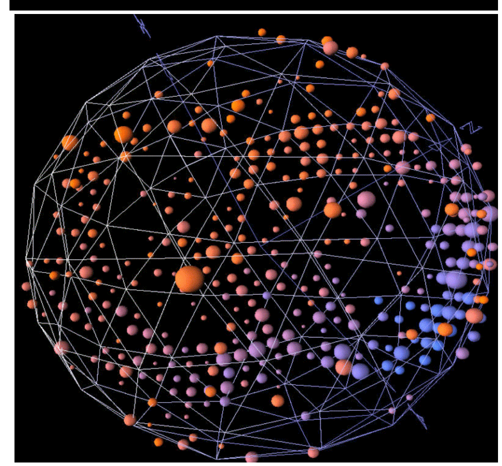


**Michel $e^-$ candidate**



**beam $\pi^0$ candidate**

$\pi^0 \to \gamma\gamma$



# *Oscillation Analysis*

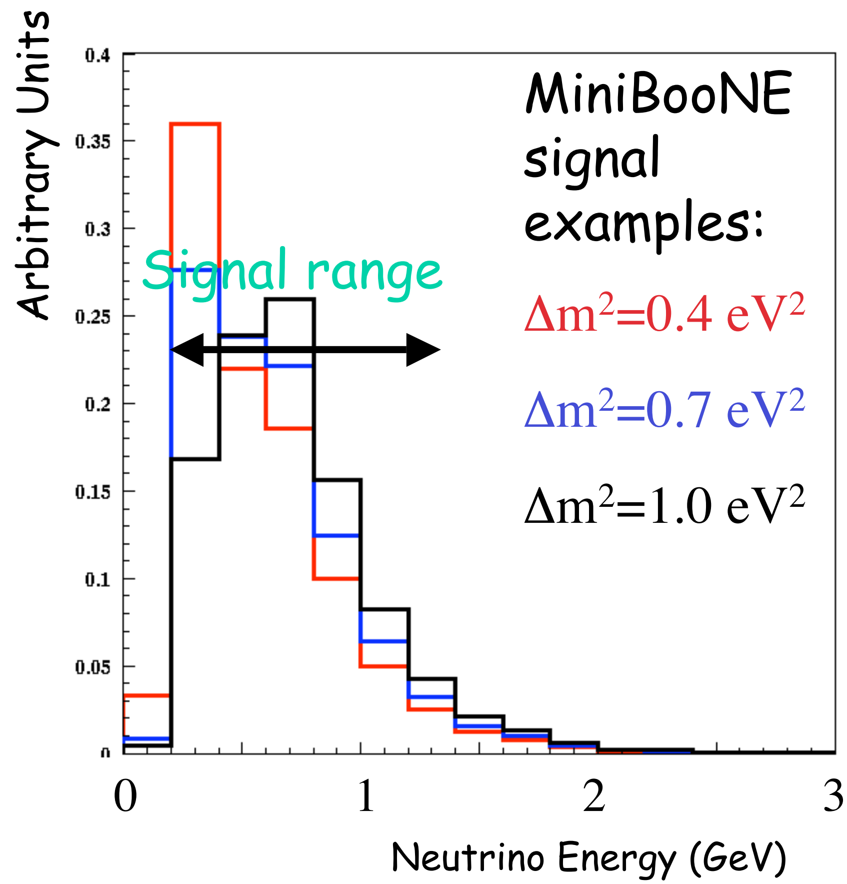
# Oscillation Analysis

Extract an oscillation signal.

"Signal range" is approximately
300 MeV < $E_\nu^{QE}$ < 1500 MeV.

One has to:
-to minimize background
-maximize signal efficiency

Then:
- look for a total excess ("counting exeriment")
- fit for both an excess and energy dependence ("energy fit")




**Blind analysis conducted: not looked into signal region("closed box")**

# Analysis Method

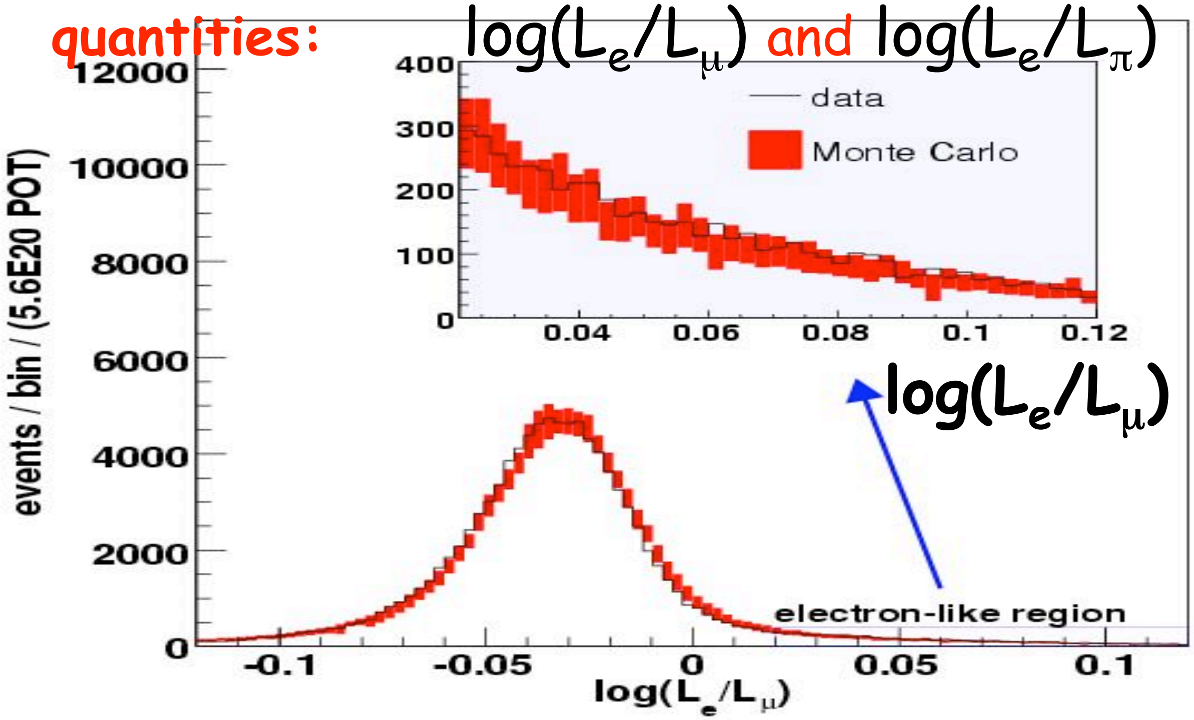
**Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles.**

**Apply likelihood fits to three hypotheses:**
**-single electron track**
**-single muon track**
**-two electron-like rings ($\pi^0$ event hypothesis )**

Compare observed light distribution to fit prediction:

Does the track actually look like an electron?

Form likelihood differences using minimized −logL quantities: $\log(L_e/L_\mu)$ and $\log(L_e/L_\pi)$

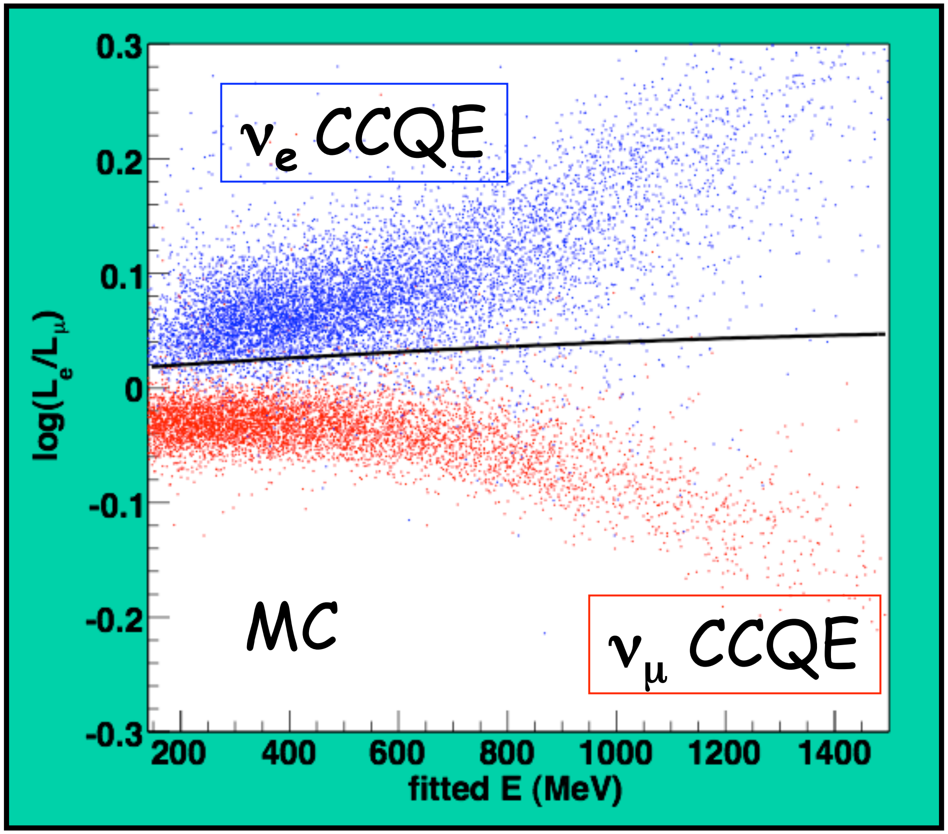



$\log(L_e/L_\mu)<0$ μ-like events

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

# Rejecting "μ-like" events

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

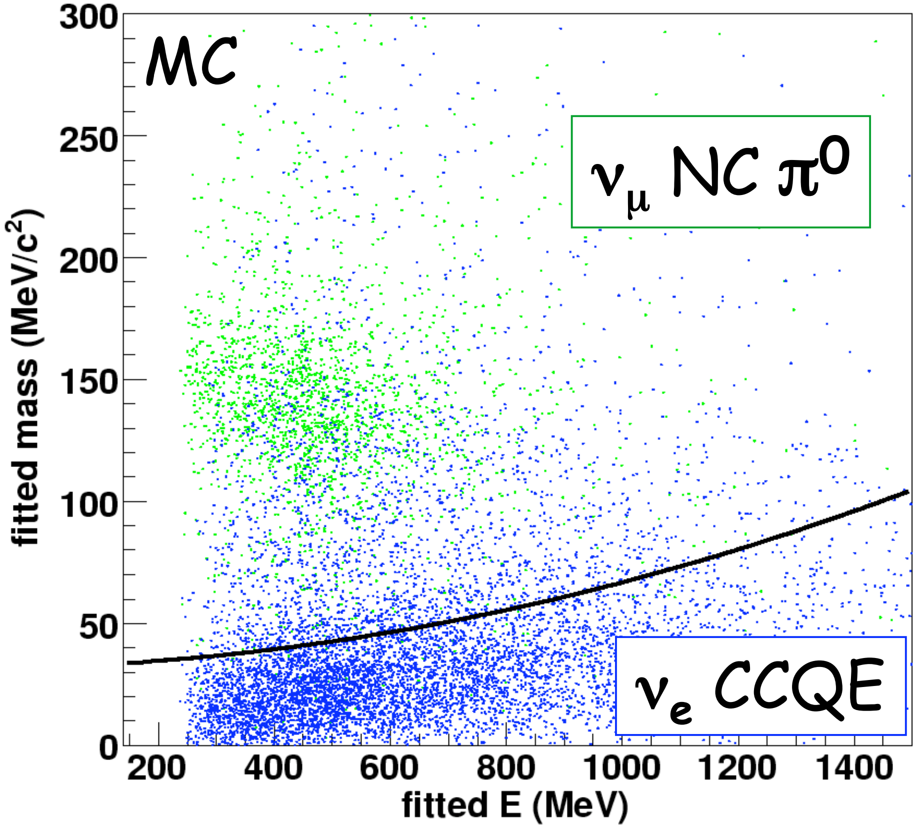



Separation is clean at high energies where muon-like events are long.

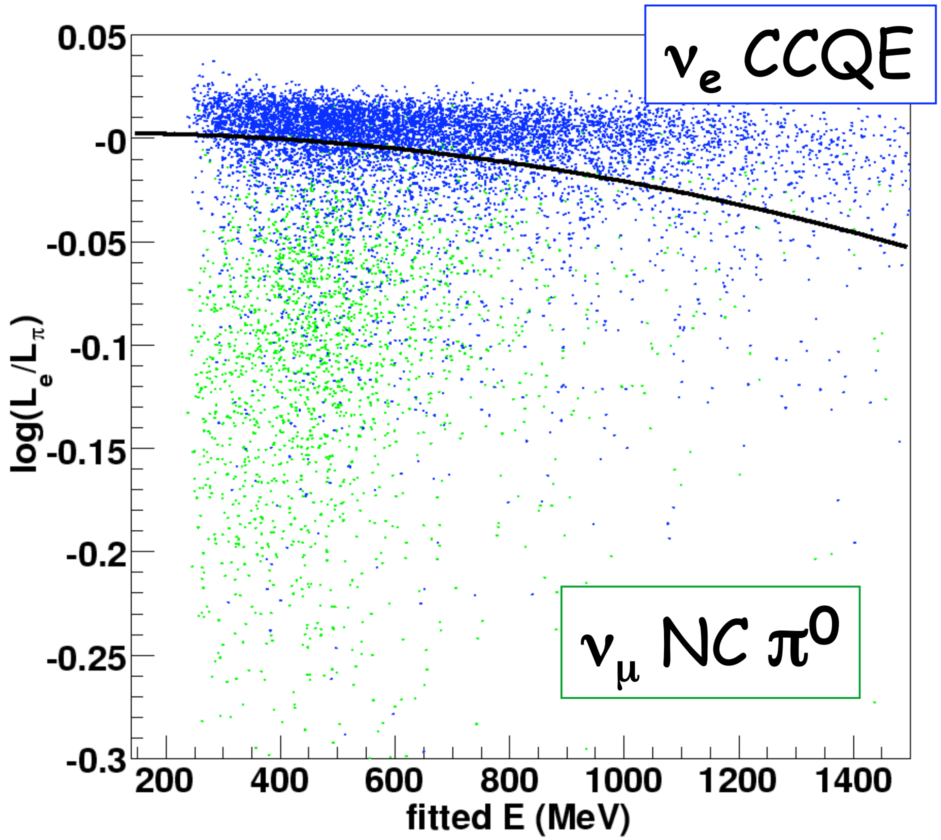
This does not separate e/$\pi^0$ as photon conversions are electron-like.

# Rejecting "$\pi^0$-like" events

## $\pi^0$ mass cut




## $\log(L_e/L_\pi)$ cut

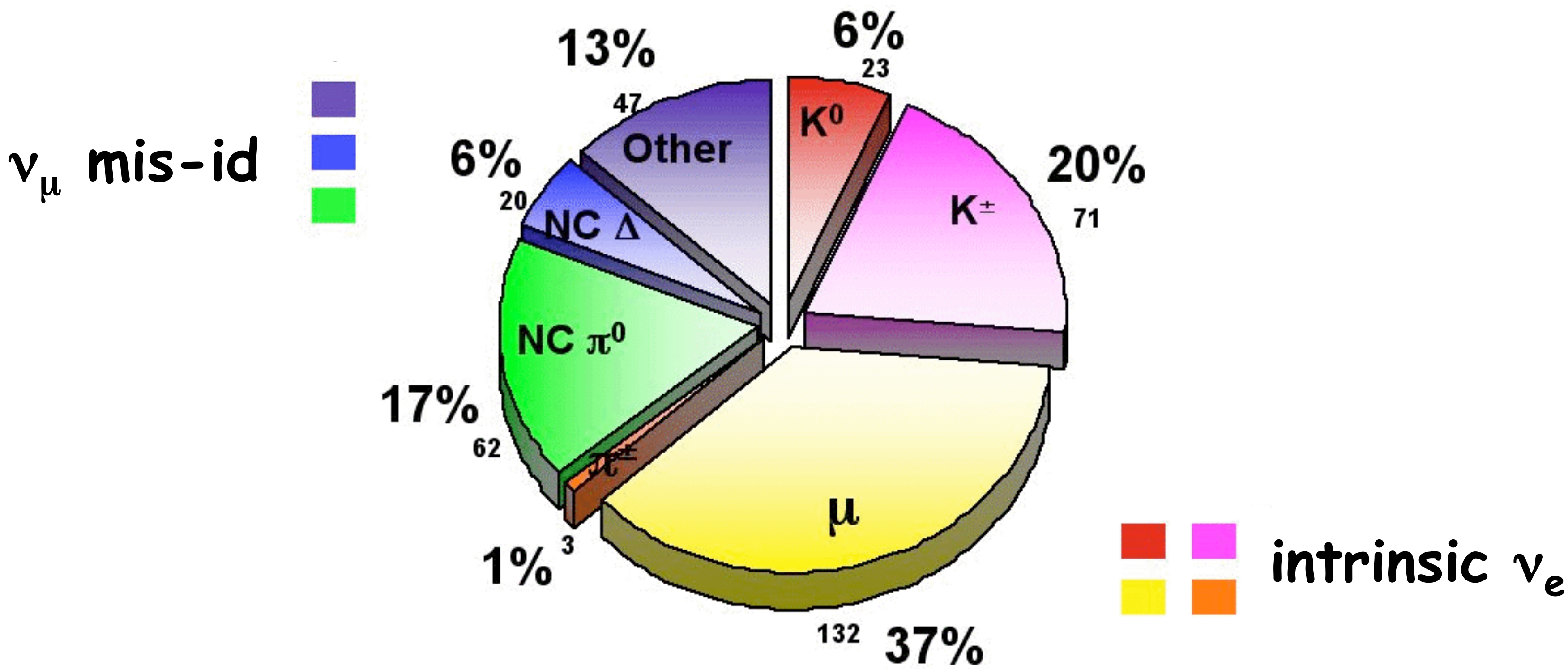


# *Backgrounds*

# Break-up of the backgrounds

Two main categories of backgrounds:

$\nu_\mu$ mis-ids and intrinsic $\nu_e$



# Summary of the backgrounds

Predicted backgrounds passing analysis cuts:

| Process | Number of Events |
|---|---|
| $\nu_\mu$ CCQE | 10 |
| $\nu_\mu e \to \nu_\mu e$ | 7 |
| Miscellaneous $\nu_\mu$ Events | 13 |
| NC $\pi^0$ | 62 |
| NC $\Delta \to N\gamma$ | 20 |
| NC Coherent & Radiative $\gamma$ | $< 1$ |
| Dirt Events | 17 |
| $\nu_e$ from $\mu$ Decay | 132 |
| $\nu_e$ from $K^+$ Decay | 71 |
| $\nu_e$ from $K^0_L$ Decay | 23 |
| $\nu_e$ from $\pi$ Decay | 3 |
| Total Background | 358 ±35(syst) |
| 0.26% $\nu_\mu \to \nu_e$ | 163 |

If LSND correct

# The Box Opening: What we found

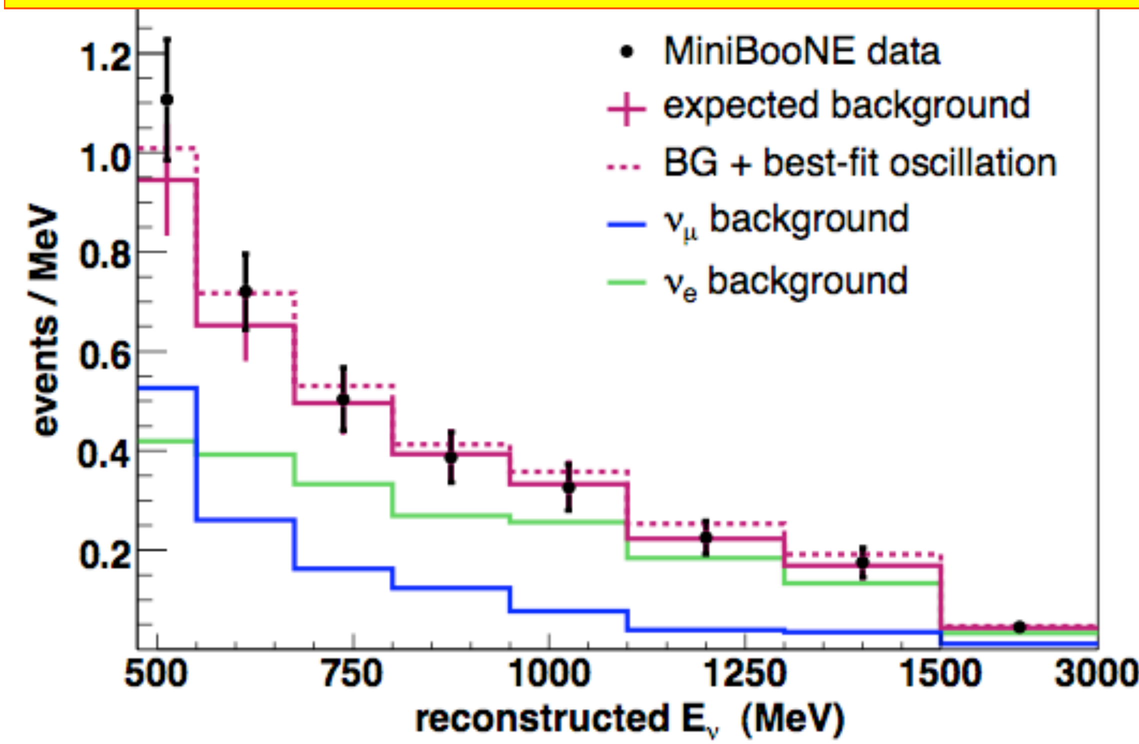
Open the box and look into $E_\nu^{QE}$ :Return the fit parameters.

**Is there an oscillation signal?**

The Track-based $\nu_\mu \rightarrow \nu_e$ **appearance-only** result:

Counting Experiment: $475 < E_\nu^{QE} < 1250$ MeV
Data: 380 events
Expectation: 358 ±19 (stat) ± 35 (sys) events

Significance: 0.55 $\sigma$




Best Fit (dashed):
$(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ eV^2)$

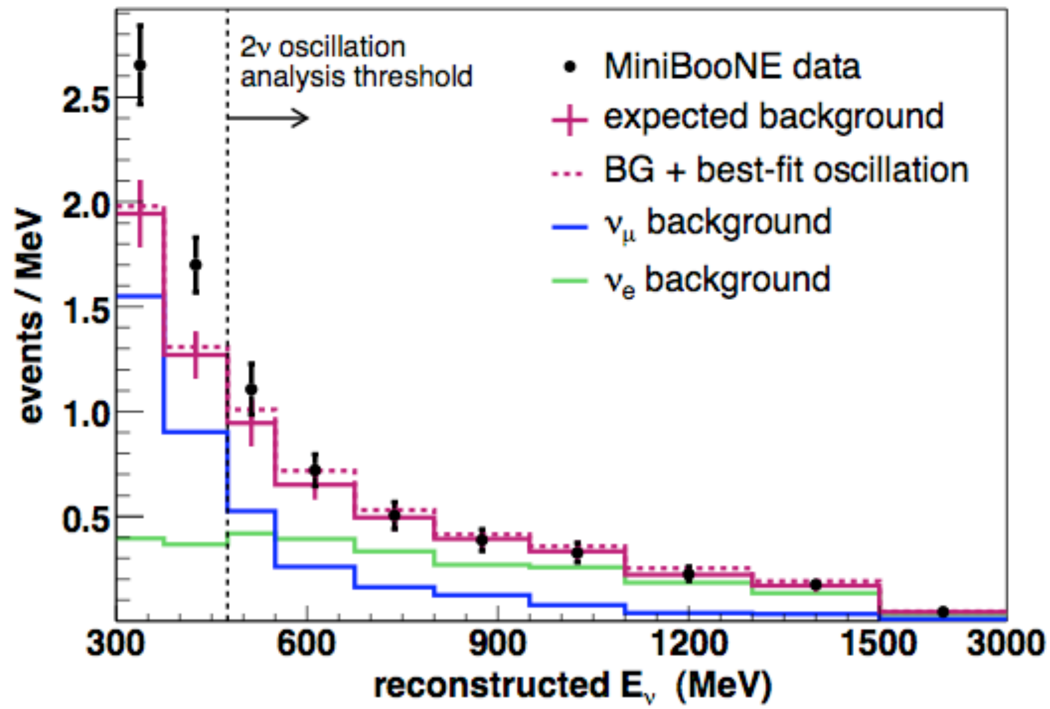
Probability of Null Fit: 93%
Probability of Best Fit: 99%

# Full Energy Range

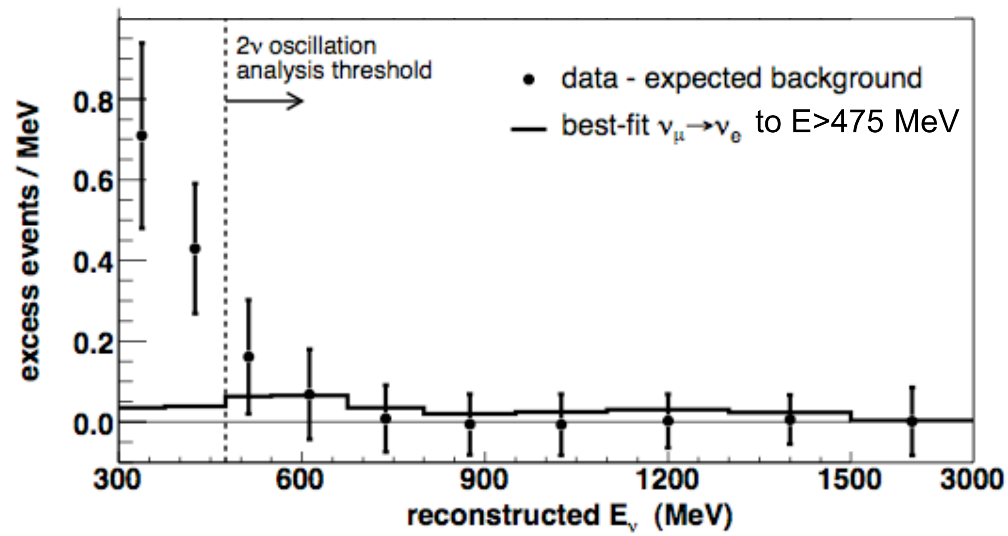
Report the full range:
$300 < E_\nu^{QE} < 3000$ MeV

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

Deviation: 3.7 $\sigma$

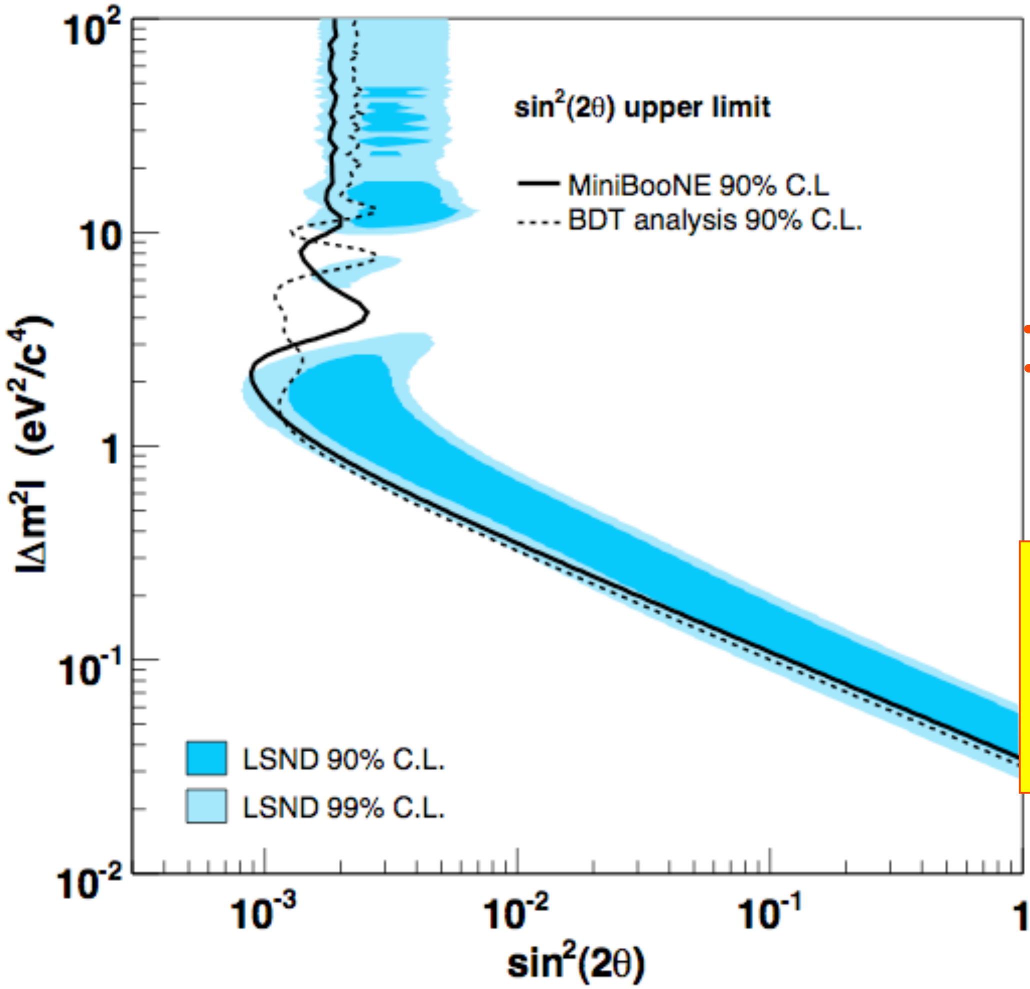



Background-subtracted:



# Analysis Results

Main Conclusion: The observed reconstructed energy distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ 2-neutrino model.




Energy-fit analysis:
Solid: Analysis I
Dashed: Analysis II

**Independent analyses are in good agreement.**

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

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

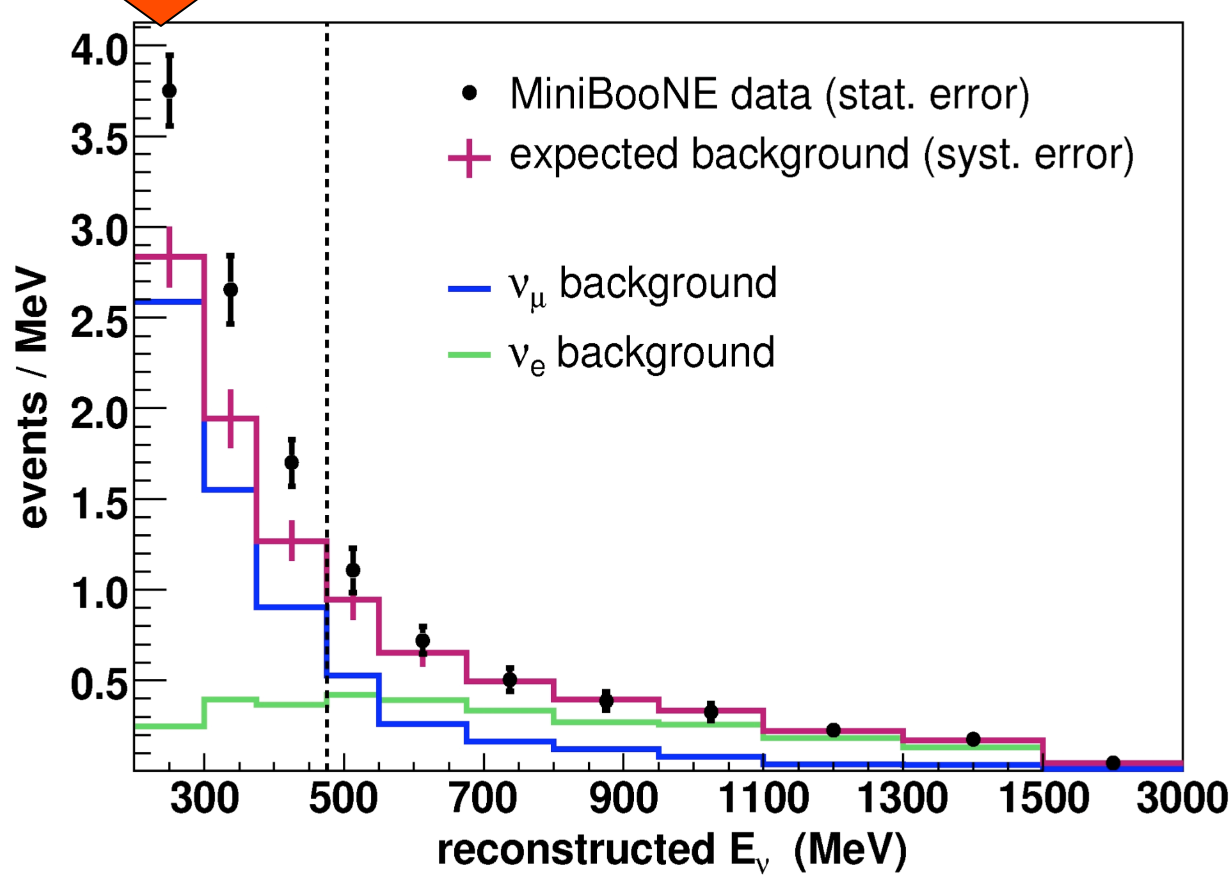
**Details:**

Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex]

# ***What is New?***

# Investigation of observed low-energy excess

Lower the energy: to $E_\nu^{QE}$ = 200 MeV!



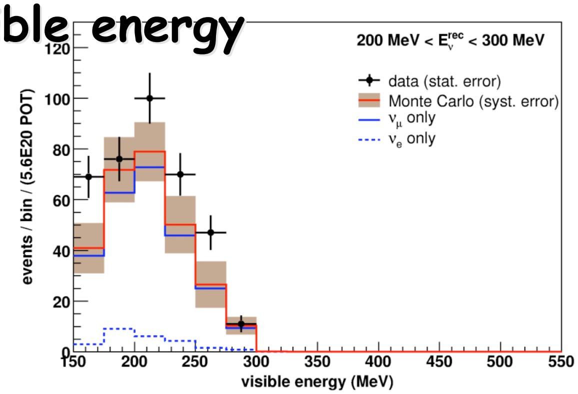

Reconstructed $E_\nu^{QE}$: from $E_{lepton}$ ("visible energy") and lepton angle wrt neutrino direction

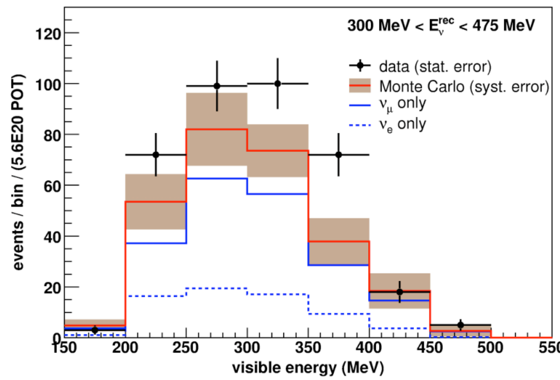
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$

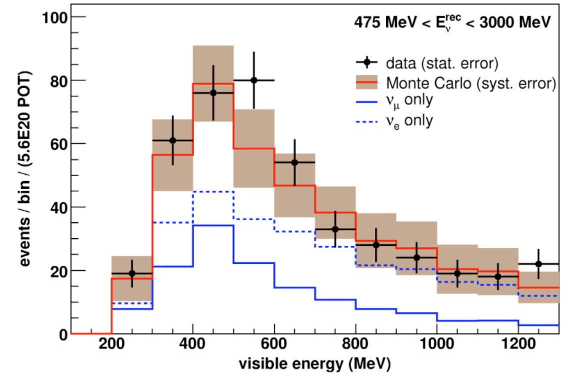
# Visible energy and angle in $E_\nu^{QE}$ bins

| $200<E_\nu<300$ MeV | $300<E_\nu<475$ MeV | $475<E_\nu<3000$ MeV |
|---|---|---|

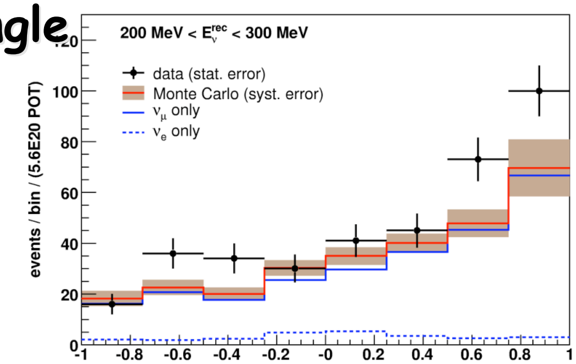
## Visible energy



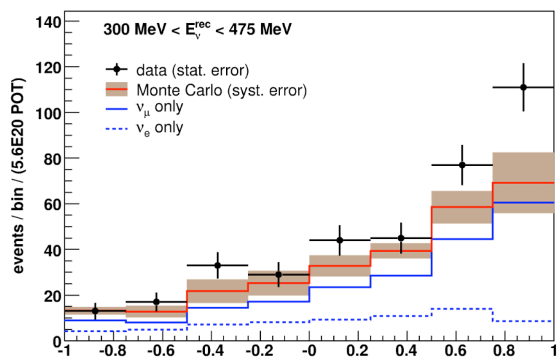



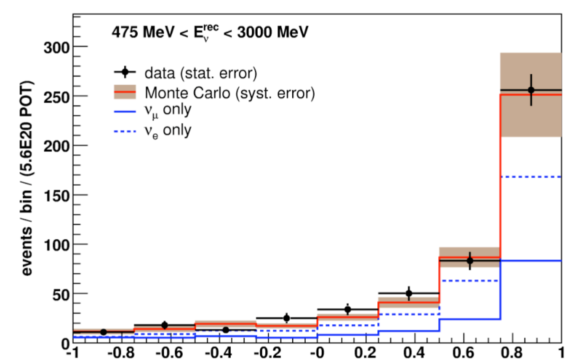

## Angle




$\cos\theta$




$\cos\theta$




$\cos\theta$

-Low Energy: Excess distributed among visible E, cos Θ bins.
-High Energy:Predicted background agrees with data.

# Summary of estimated backgrounds vs data

| $E_\nu^{QE}$ [MeV] | 200-300 | 300-475 | 475-1250 |
|---|---|---|---|
| total background | 284±25 | 274±21 | 358±35 |
| $\nu_e$ intrinsic | 26 | 67 | 229 |
| $\nu_\mu$ induced | 258 | 207 | 129 |
| NC $\pi^0$ | 115 | 76 | 62 |
| NC $\Delta \rightarrow N\gamma$ | 20 | 51 | 20 |
| Dirt | 99 | 50 | 17 |
| other | 24 | 30 | 30 |
| Data | 375±19 | 369±19 | 380±19 |
| Data-MC | 91±31 | 95±28 | 22±40 |

- Low Energy: largest backgrounds a are $\nu_\mu$-induced, in particular:
  - NC $\pi^0$
  - NC $\Delta \rightarrow N\gamma$
  - Dirt

-High Energy: no significant excess with $\nu_e$ bkgd dominant

Currently re-checking these processes.

In addition, new processes being considered:

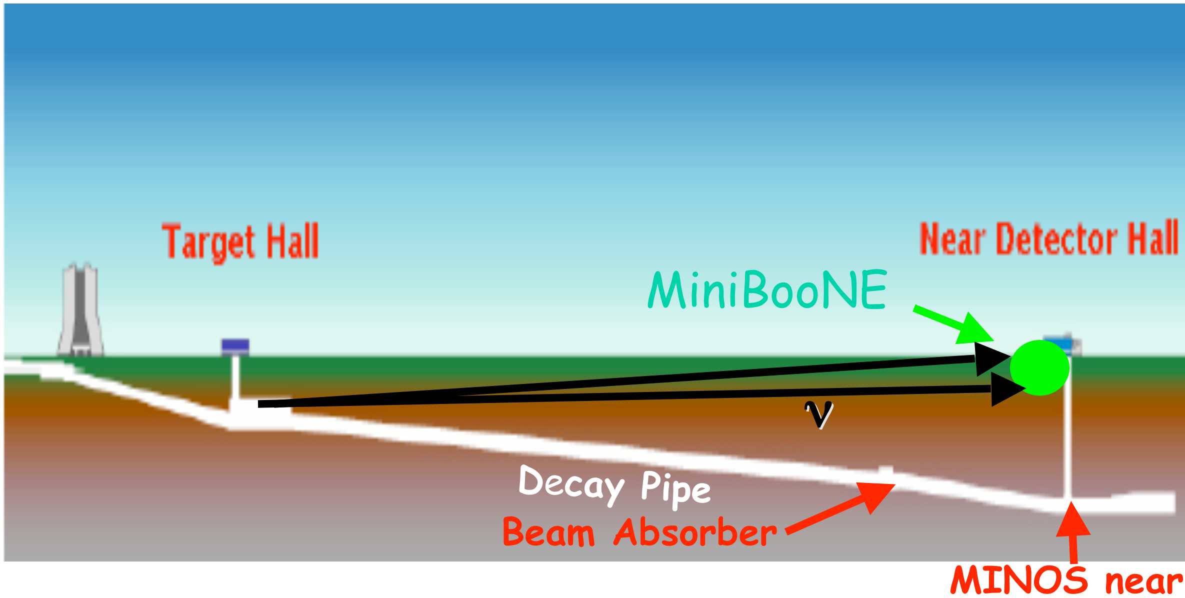
- $\nu_\mu$-induced NC $\pi^0$ with photonuclear absorption of $\pi^0$ photon

- new $\nu_\mu$-induced NC photon production (eg: hep-ex:0708.1281v2)

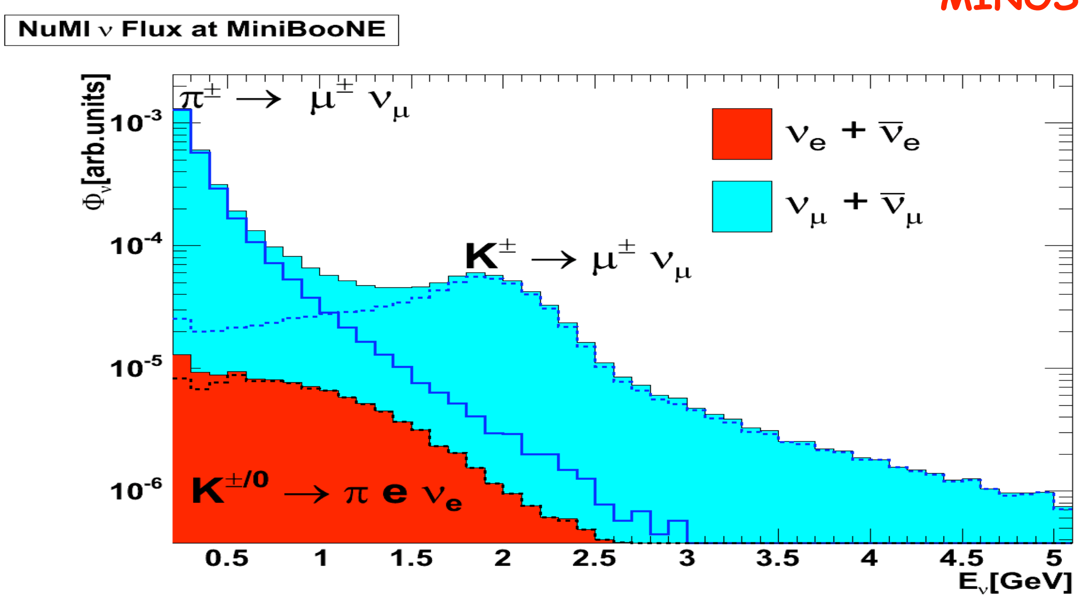
Other data sets available to check signal vs background hypotheses:
**NuMI neutrinos in MB**, MB anti-$\nu$ **run (started Jan06).**

# Analysis of the events from NuMI beam

NuMI events (for MINOS) detected in MiniBooNE detector!

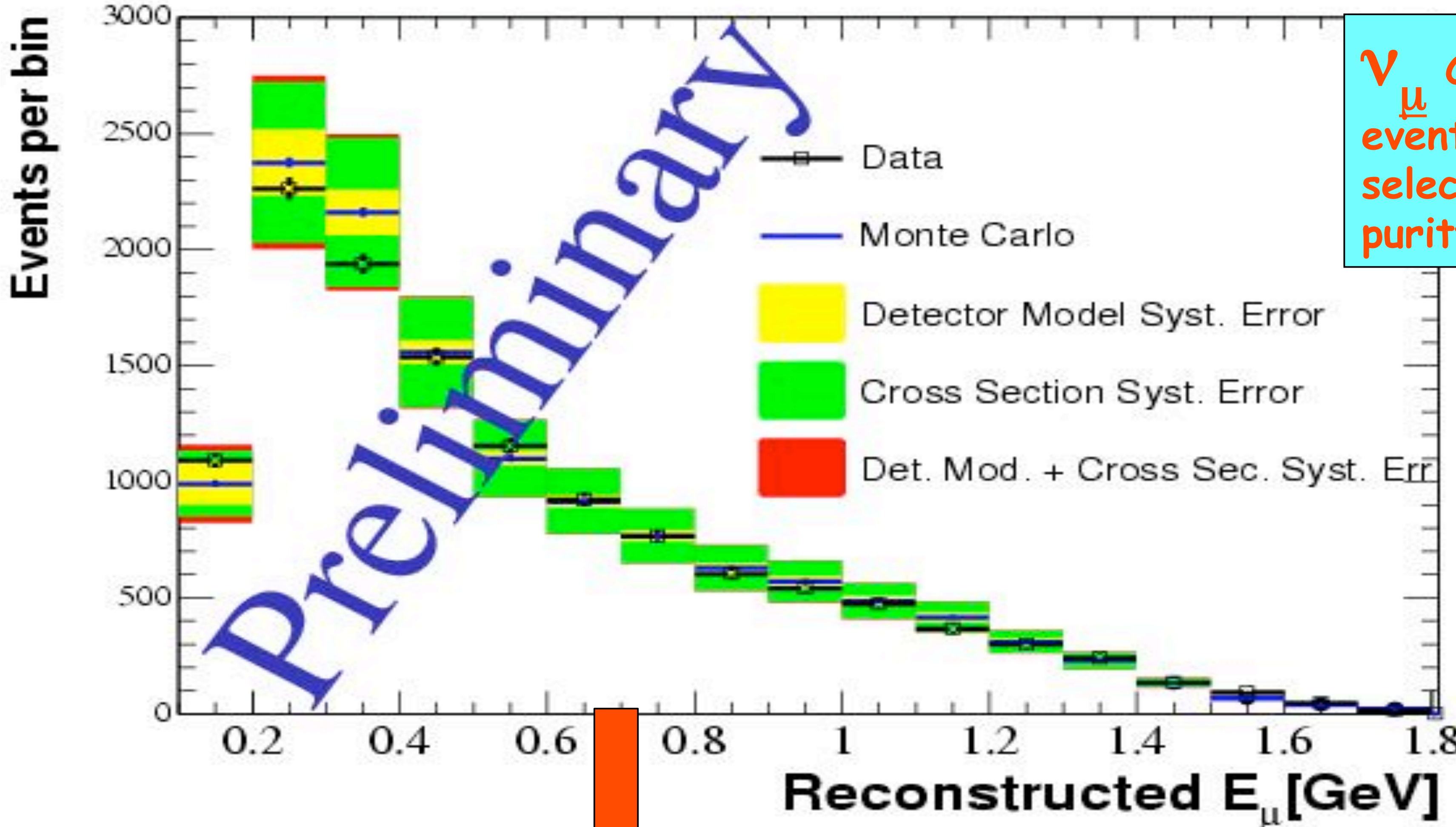



**NuMI event composition:**
$\nu_\mu$-81%, $\nu_e$-5%,$\bar{\nu}_\mu$-13%,$\bar{\nu}_e$-1%




The beam at MiniBooNE from NuMI is significantly enhanced in $\nu_e$ from K decay because of the off-axis position.

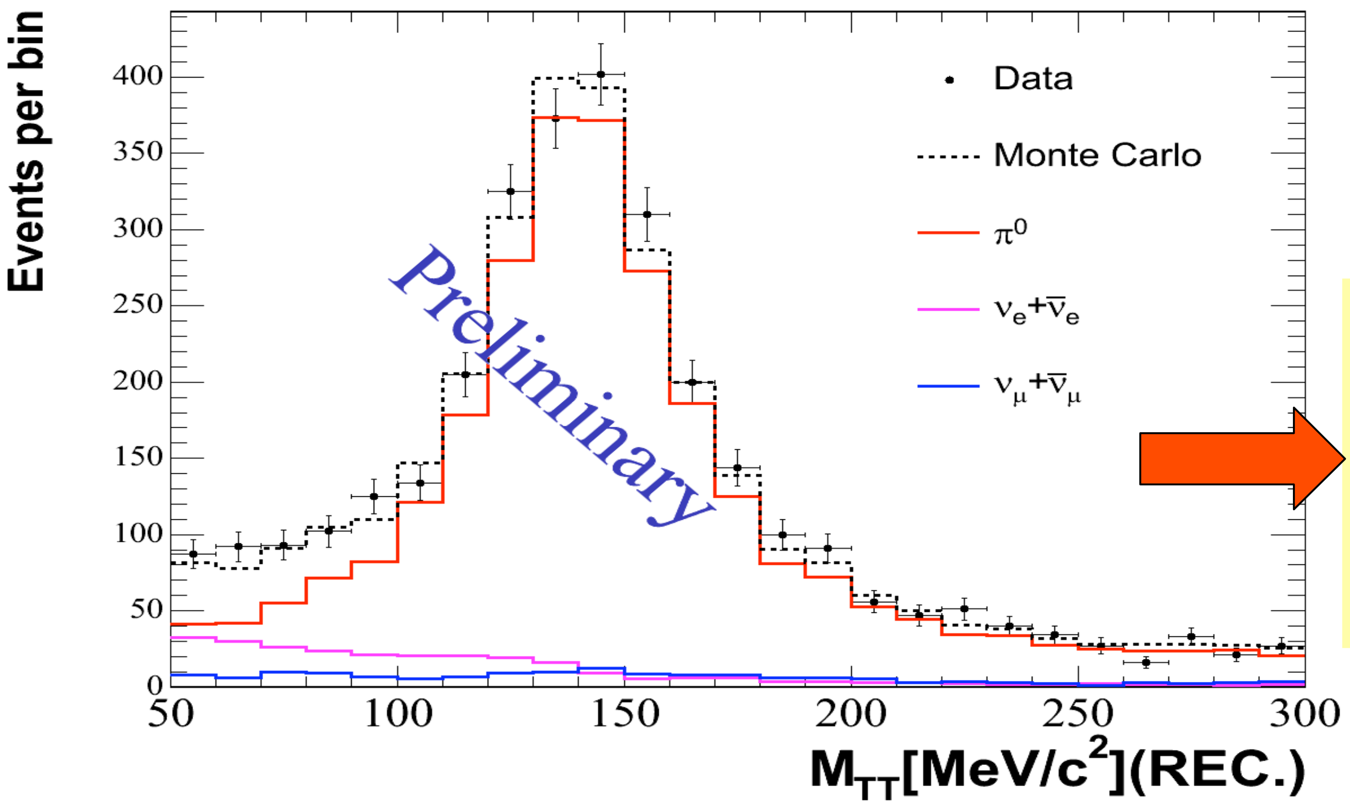
# Analysis of the CCQE events from NuMI beam




$\nu_\mu$ CCQE events selection: purity 70% .

Step I: Understanding of the beam demonstrated:
**Absolute normalization of MC to data POT number!**

# Analysis of $\pi^0$ events from NuMI beam




$\pi^0$ events selection: purity 87% .

Step II: Understanding of the bkgds to $\nu_e$ search: Good data/MC agreement with $\pi^0$ events!

Step III: Analysis of $\nu_e$ events: do we see a similar excess?
Search for low energy excess at MiniBooNE with NuMI beam: Ongoing!
Please, stay tuned!

# Summary

MiniBooNE is incompatible with an oscillation $\nu_\mu \rightarrow \nu_e$ appearance-only interpretation of LSND at 98% CL.

Observed deviation of MiniBooNE data from prediction at low energy might be a background: interesting for future $\nu_\mu \rightarrow \nu_e$ searches in same energy region.

It might be a new interesting physics → see next talk!

Currently searching for low energy excess at MiniBooNE with NuMI beam with high priority.

# MiniBooNE Collaboration

A. A. Aguilar-Arevalo, A. O. Bazarko, S. J. Brice, B. C. Brown, L. Bugel, J. Cao, L. Coney, J. M. Conrad, D. C. Cox, A. Curioni, Z. Djurcic, D. A. Finley, B. T. Fleming, R. Ford, F. G. Garcia, G. T. Garvey, J. A. Green, C. Green, T. L. Hart, E. Hawker, R. Imlay, R. A. Johnson, P. Kasper, T. Katori, T. Kobilarcik, I. Kourbanis, S. Koutsoliotas, J. M. Link, Y. Liu, Y. Liu, W. C. Louis, K. B. M. Mahn, W. Marsh, P. S. Martin, G. McGregor, W. Metcalf, P. D. Meyers, F. Mills, G. B. Mills, J. Monroe, C. D. Moore, R. H. Nelson, P. Nienaber, S. Ouedraogo, R. B. Patterson, D. Perevalov, C. C. Polly, E. Prebys, J. L. Raaf, H. Ray, B. P. Roe, A. D. Russell, V. Sandberg, R. Schirato, D. Schmitz, M. H. Shaevitz, F. C. Shoemaker, D. Smith, M. Sorel, P. Spentzouris, I. Stancu, R. J. Stefanski, M. Sung, H. A. Tanaka, R. Tayloe, M. Tzanov, M. O. Wascko, R. Van de Water, D. H. White, M. J. Wilking, H. J. Yang, G. P. Zeller, E. D. Zimmerman

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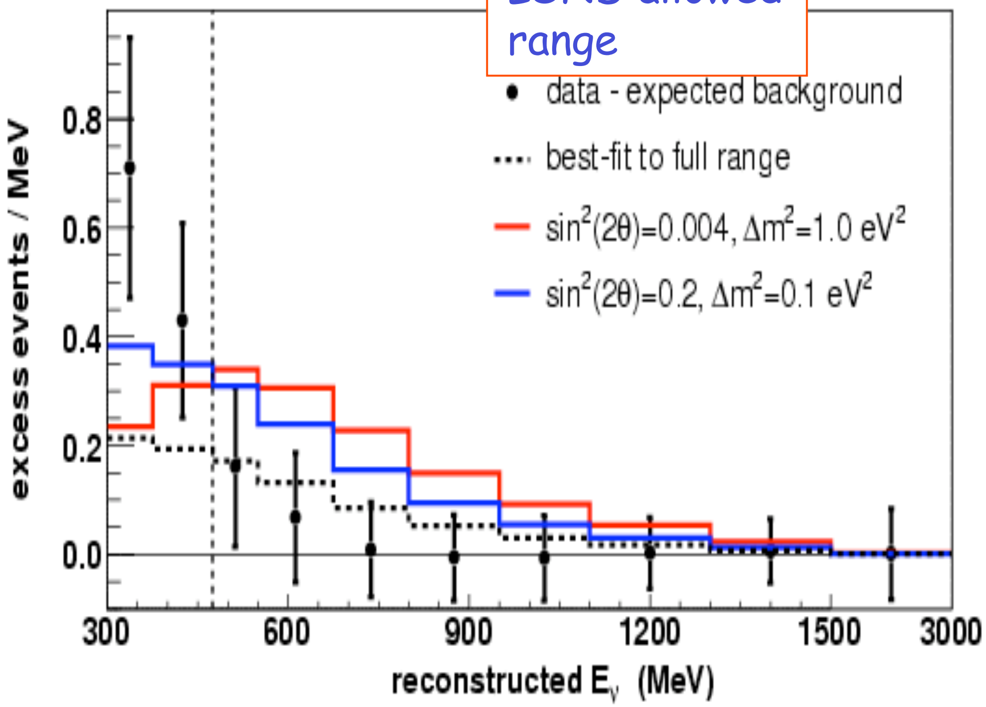
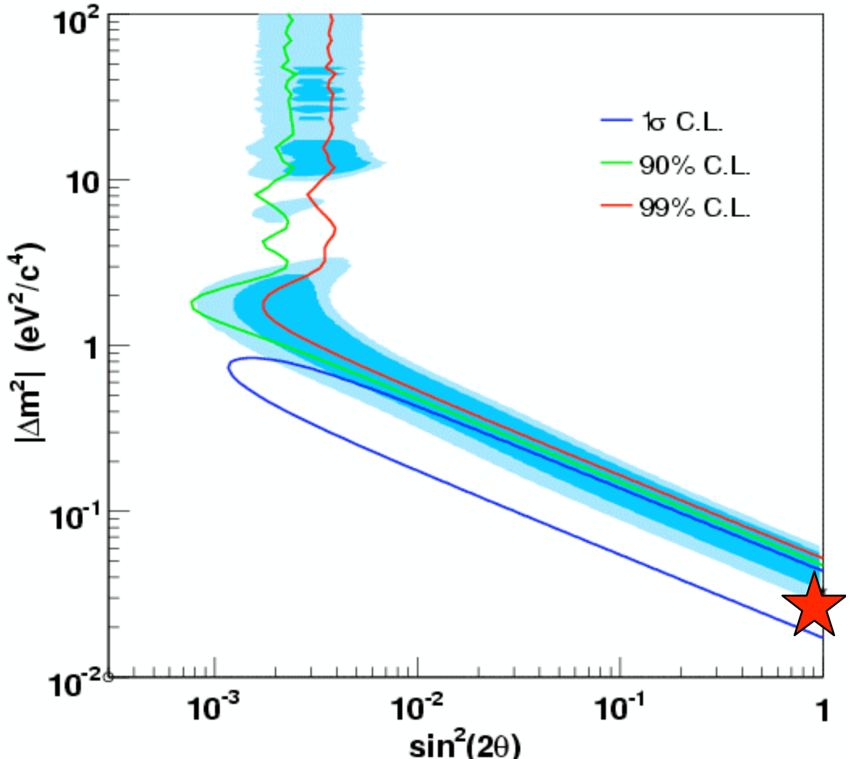
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

# *Backups*

# Full Energy Range Fit 300< $E_\nu^{QE}$< 3 GeV

Examples in LSND allowed range




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

The best falls into region excluded by other Experiments (i.e. Bugey)

# Testing e-$\pi^0$ separation using the data

What is applied:

Event pre-selection

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

$\log(L_e/L_\pi)<0$ ($\pi^0$-like)

mass>50