Results of the MiniBooNE Oscillation Experiment

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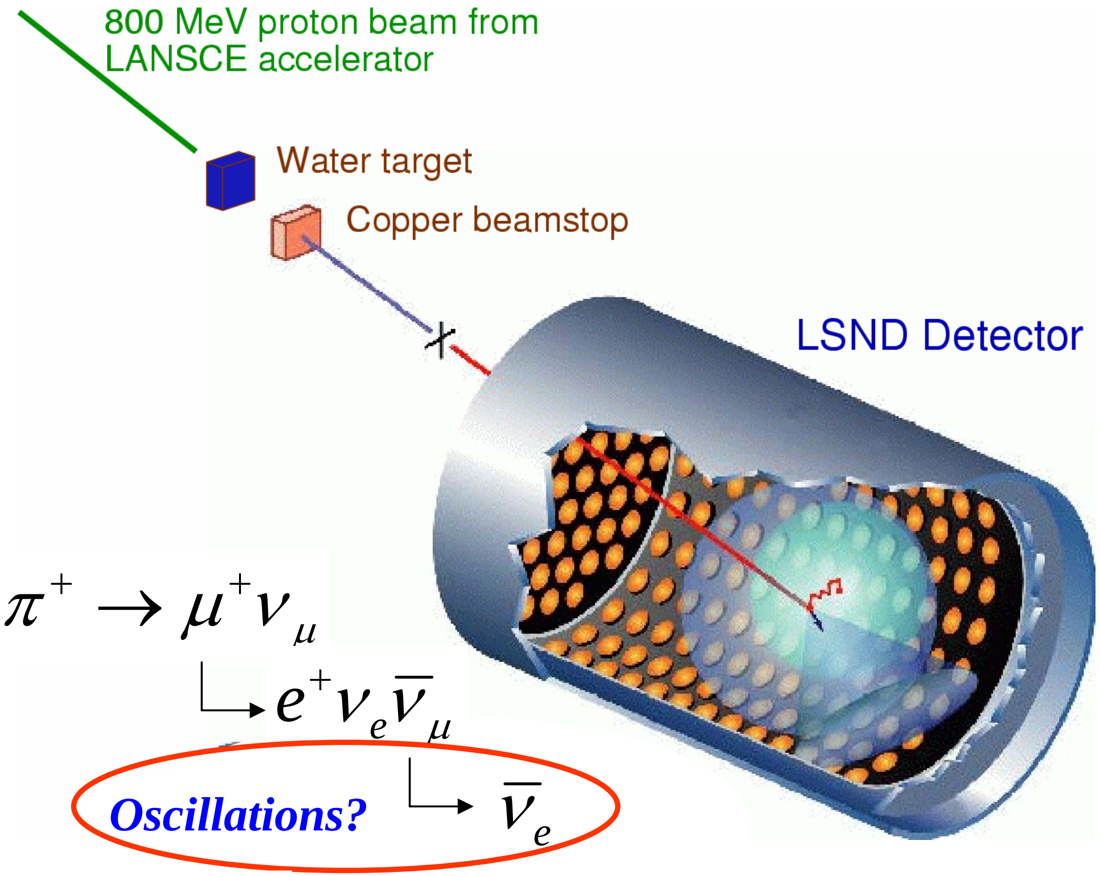
13th Lomonosov Conference on Elementary Particle Physics

Moscow State University 2007

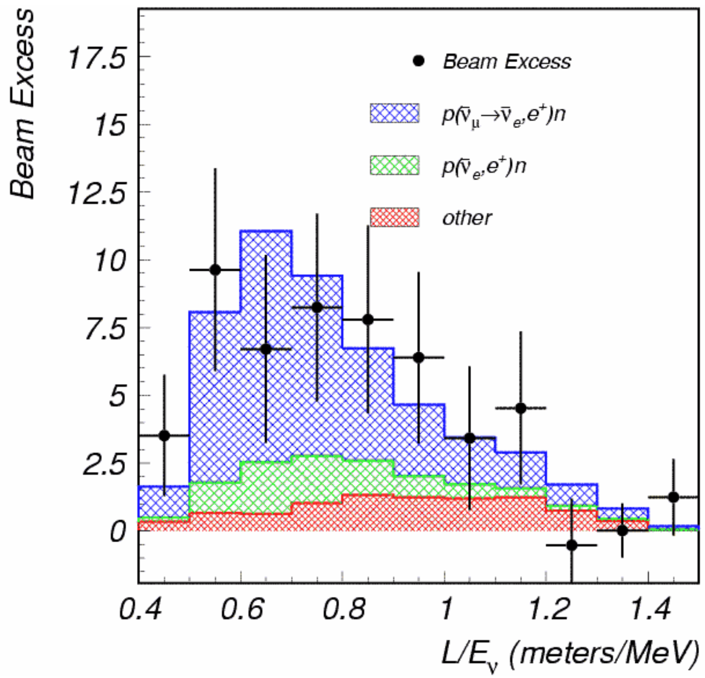
Before MiniBooNE

Before MiniBooNE: The LSND Experiment



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

n p $\rightarrow$ d γ(2.2MeV)



LSND took data from 1993-98

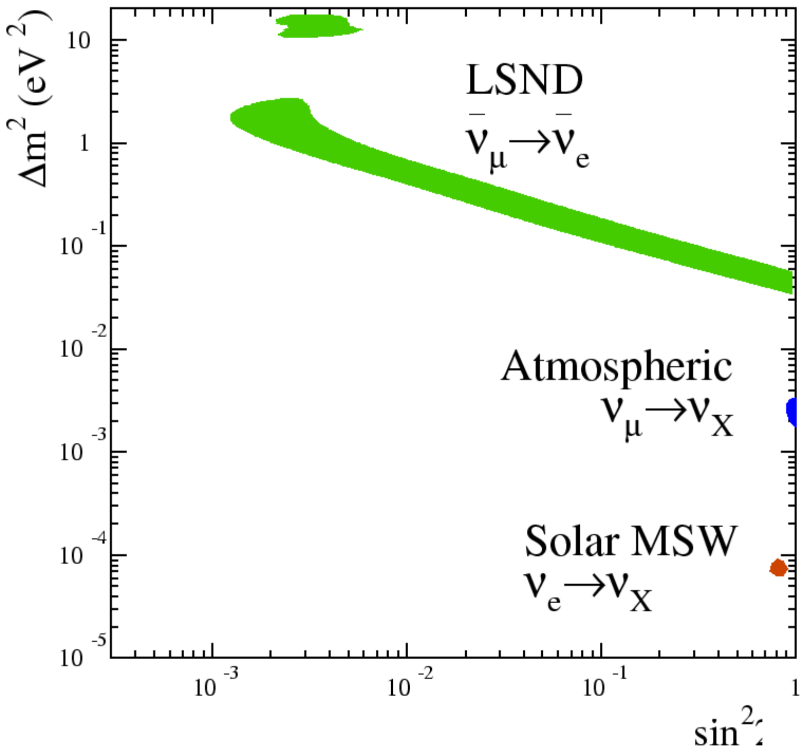
- 49,000 Coulombs of protons
- L = 30m and 20 < E_ν < 53 MeV

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



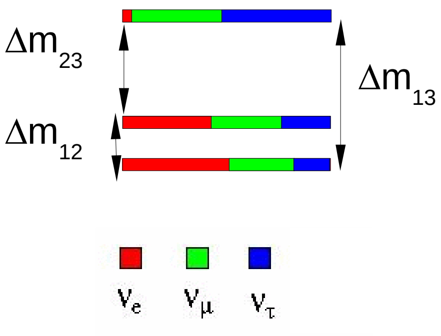
This signal looks very different from the others...

- Much higher Δm^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 Δm^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 ν's) allows different mixing for ν's and $\bar{\nu}$'s

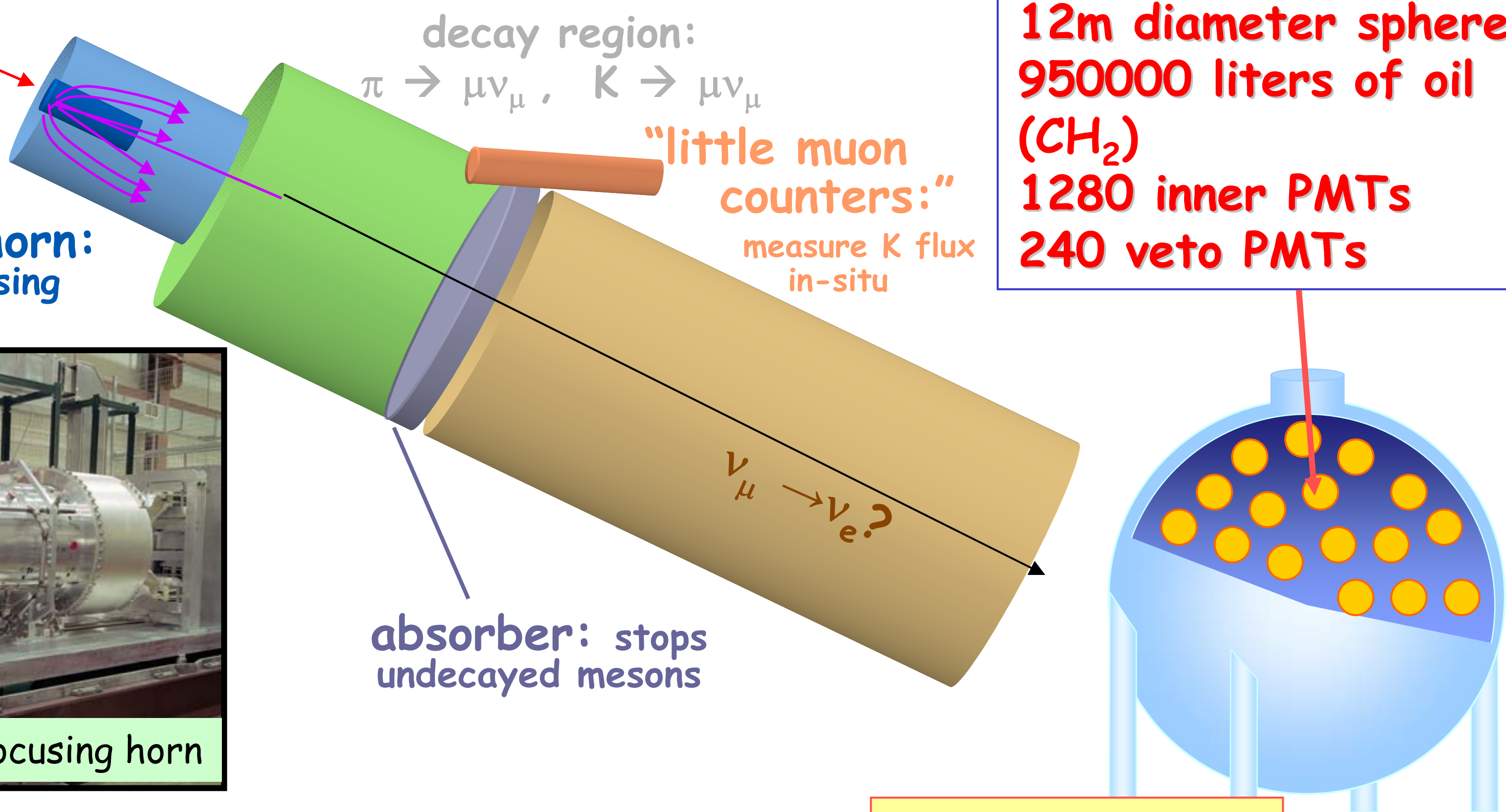
MiniBooNE

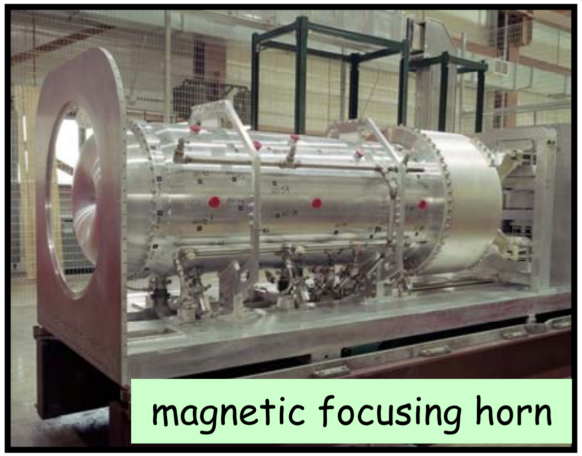
(Booster Neutrino Experiment)

Search for ν_e appearance in ν_μ beam

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





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

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

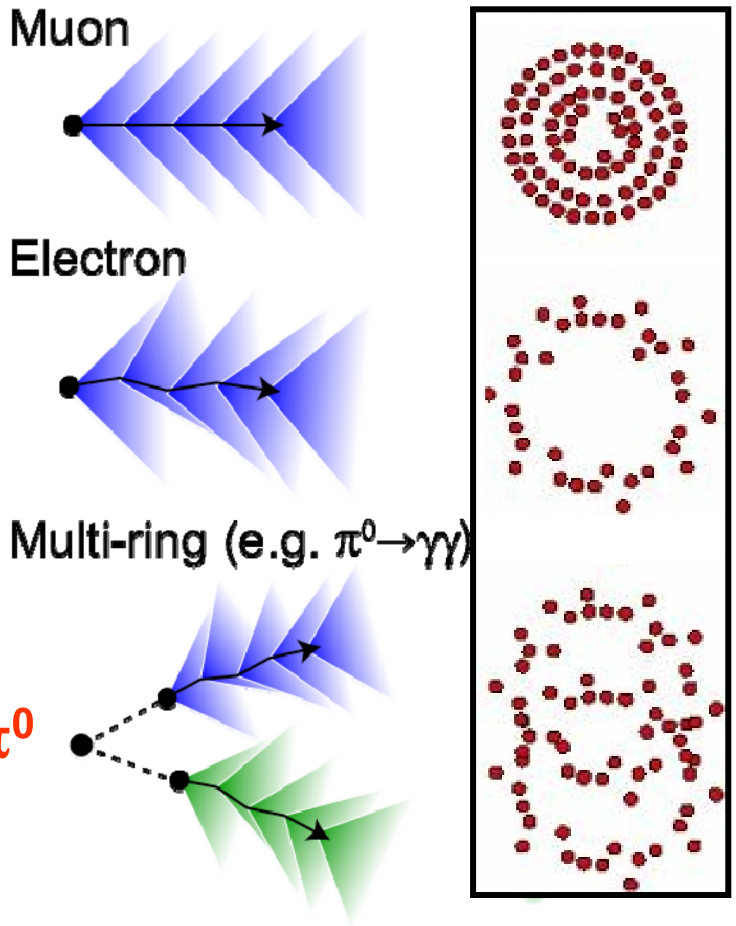
Particle Identification

Čerenkov rings provide primary means of identifying products of ν interactions in the detector

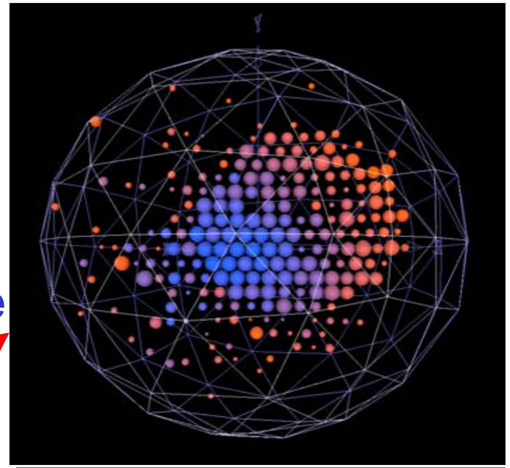
$\nu_\mu\, n \rightarrow \mu^-\, p$

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

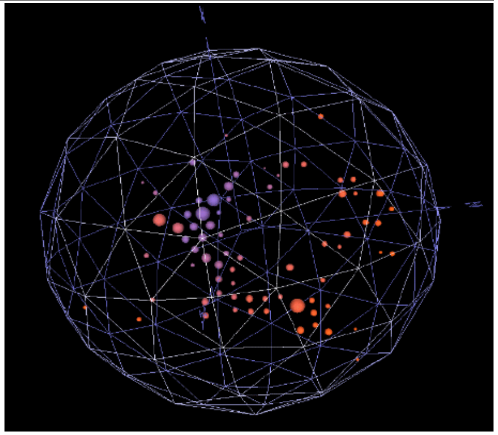
$\nu_\mu\, p\,(n) \rightarrow \nu_\mu\, p\,(n)\, \pi^0$



beam μ candidate

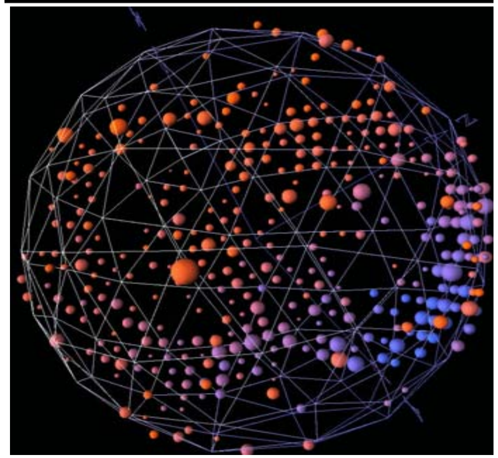


Michel e^- candidate



beam π^0 candidate

$\pi^0 \longrightarrow \gamma\gamma$



Oscillation Analysis

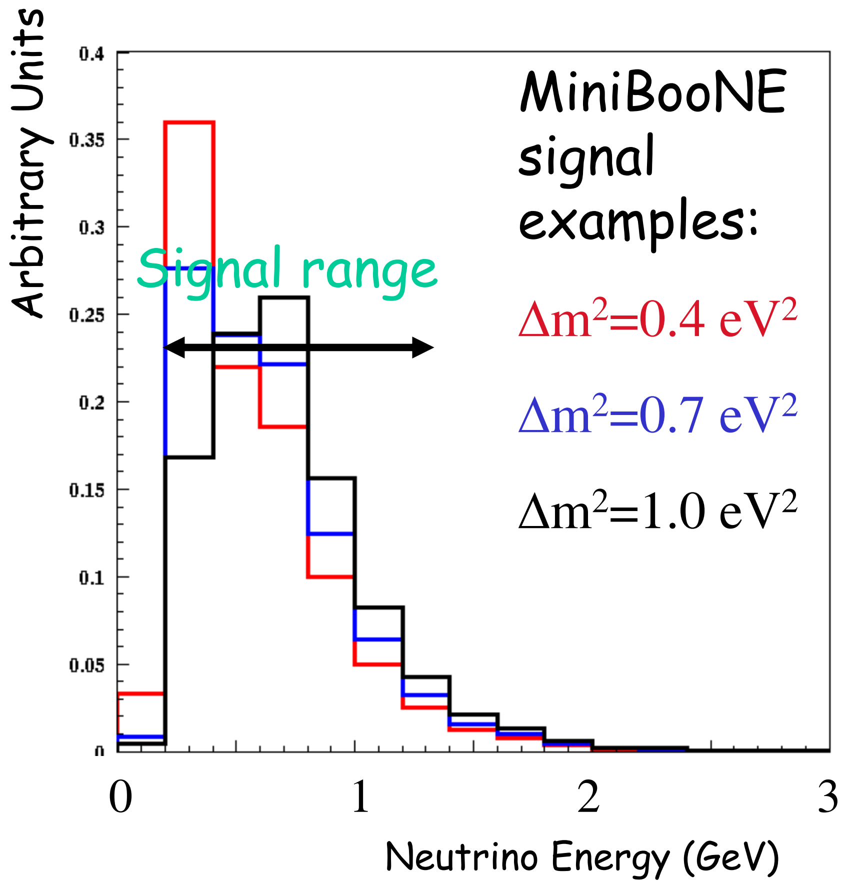
Oscillation Analysis

Extract an oscillation signal.

"Signal range" is approximately
300 MeV < E_ν^{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

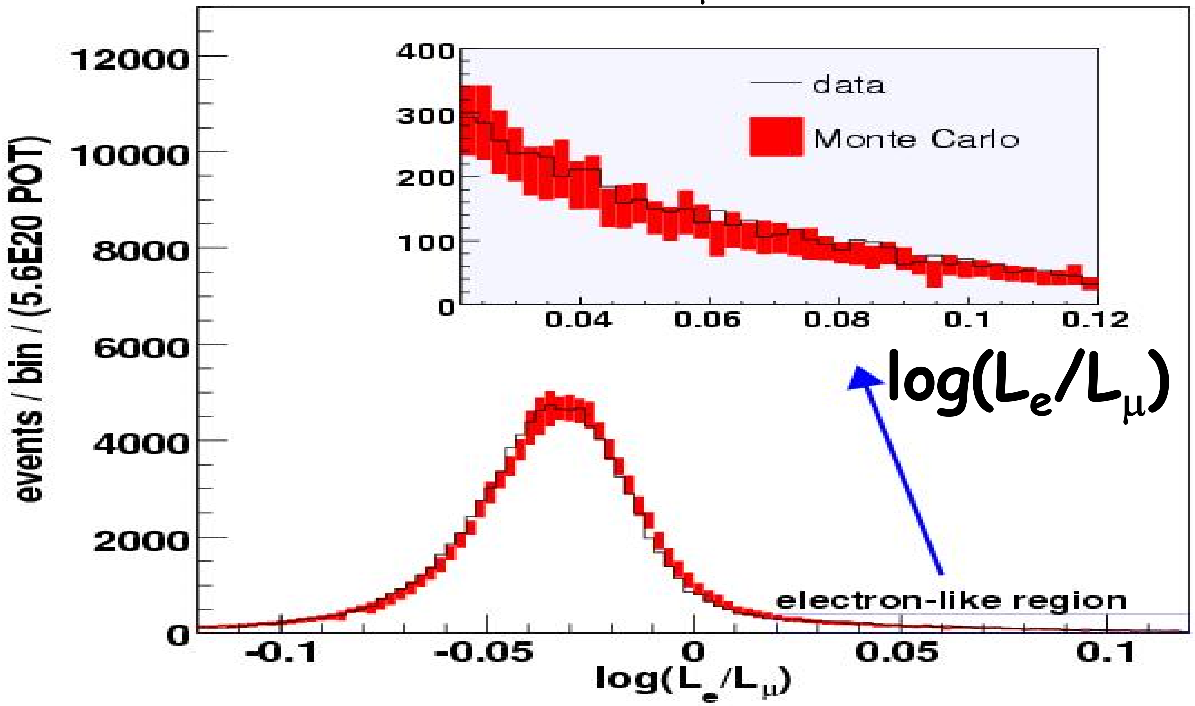
Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles.

Apply likelihood fits to three hypotheses:
- single electron track
- single muon track
- two electron-like rings (π^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 $\log(L_e/L_\pi)$

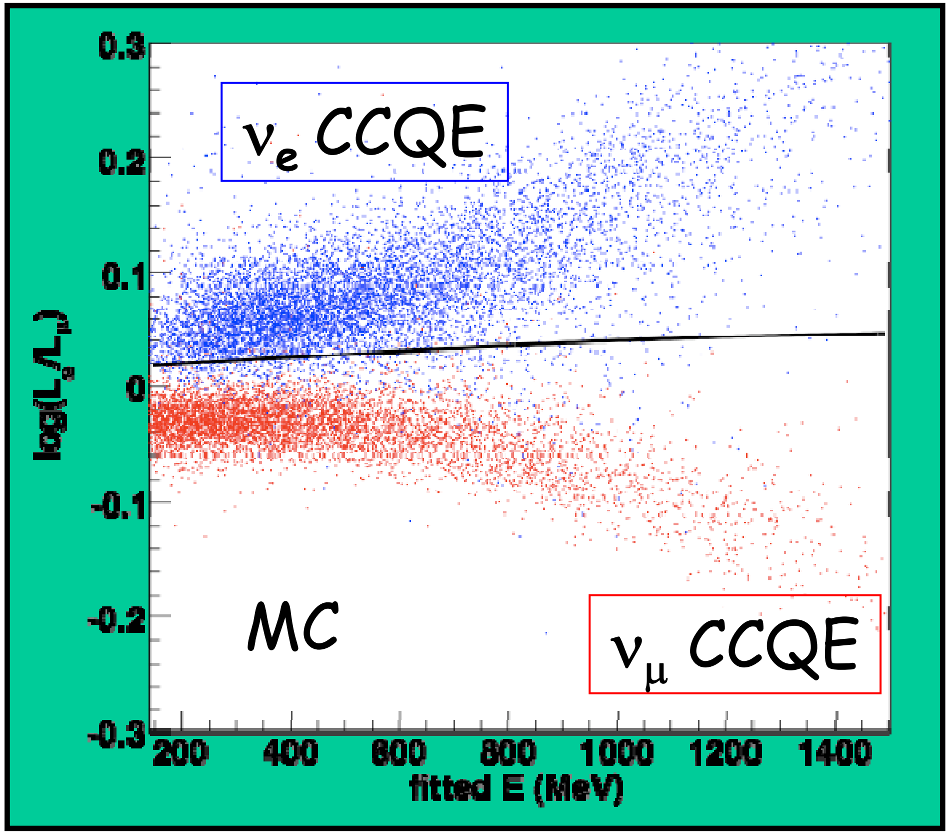


$\log(L_e/L_\mu)<0$ μ-like events

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

Rejecting "μ-like" events

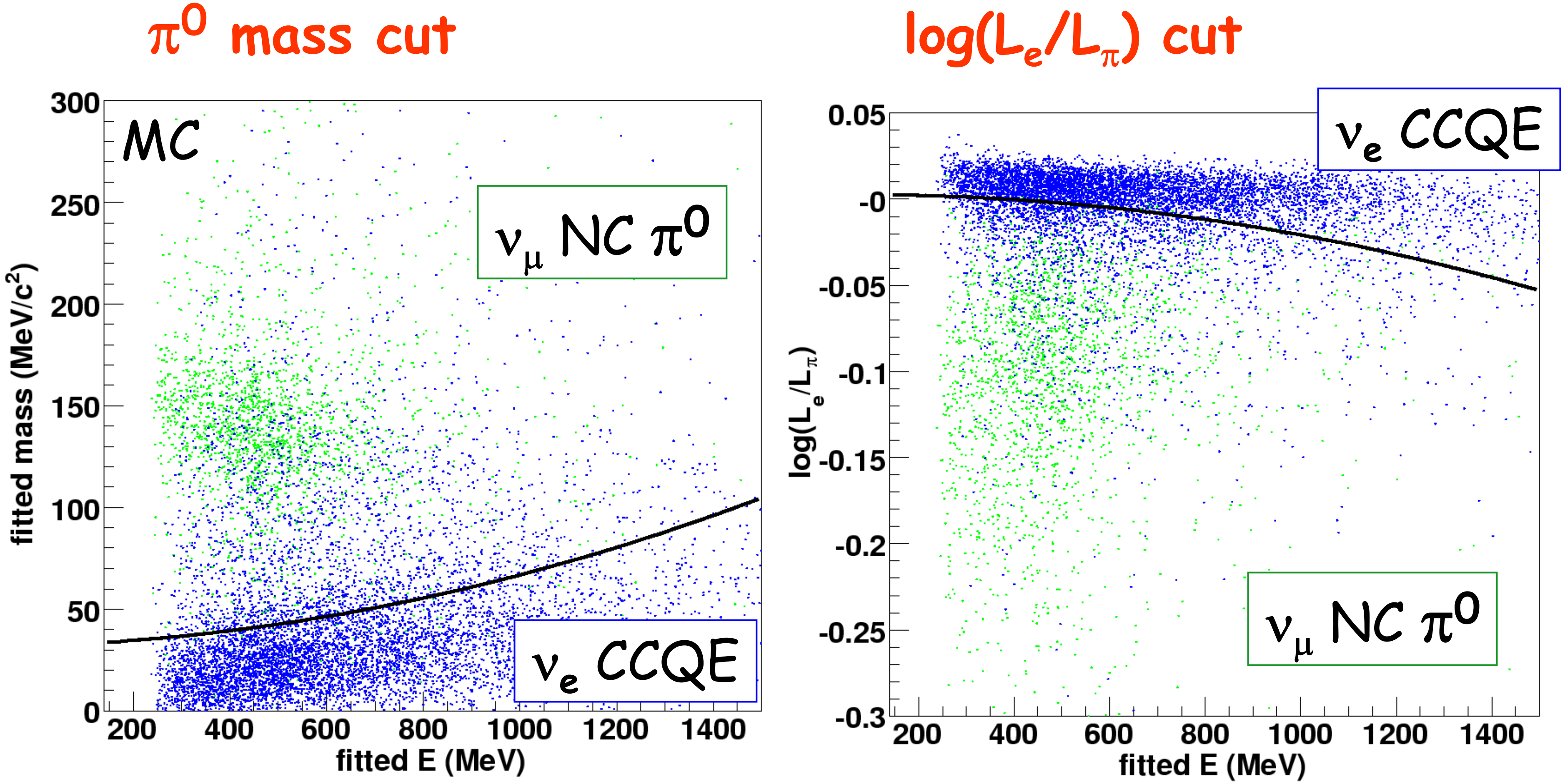
$\log(L_e/L_\mu)>0$ favors electron-like hypothesis



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

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

Rejecting "π^0-like" events

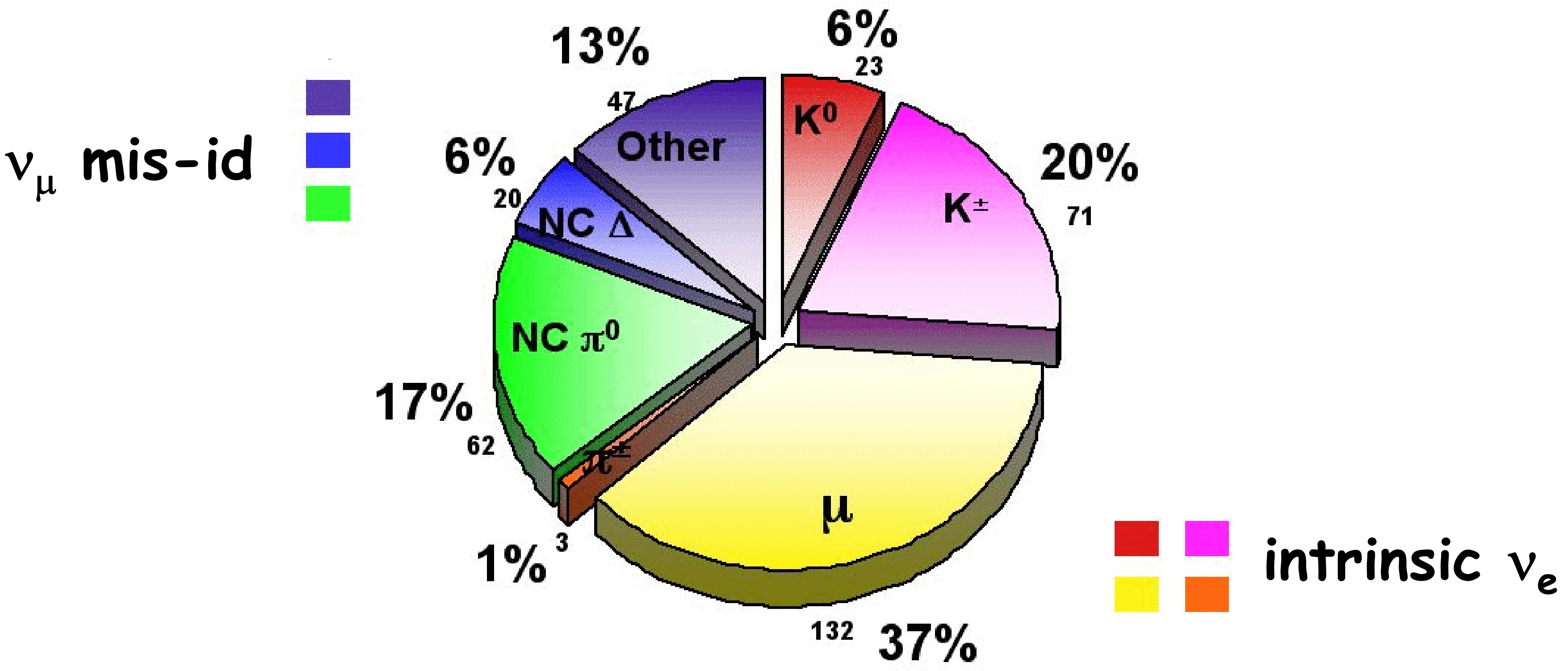


Backgrounds

Break-up of the backgrounds

Two main categories of backgrounds:

ν_μ **mis-ids** and **intrinsic** ν_e



Summary of the backgrounds

Predicted backgrounds passing analysis cuts:

Process	Number of Events
ν_μ CCQE	10
$\nu_\mu e \to \nu_\mu e$	7
Miscellaneous ν_μ Events	13
NC π^0	62
NC $\Delta \to N\gamma$	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^0_L Decay	23
ν_e from π Decay	3
Total Background	358 ±35(syst)
0.26% $\nu_\mu \to \nu_e$	163

If LSND correct

The Box Opening: What we found

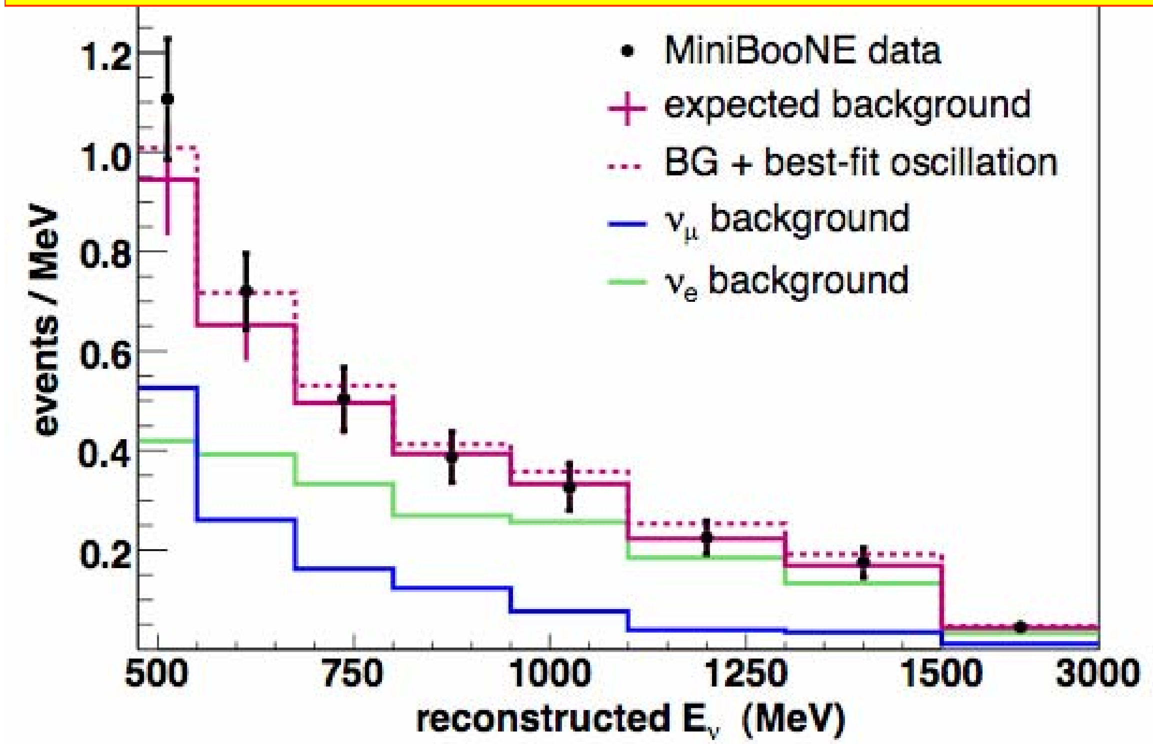
Open the box and look into E_ν^{QE} :Return the fit parameters.

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 σ



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

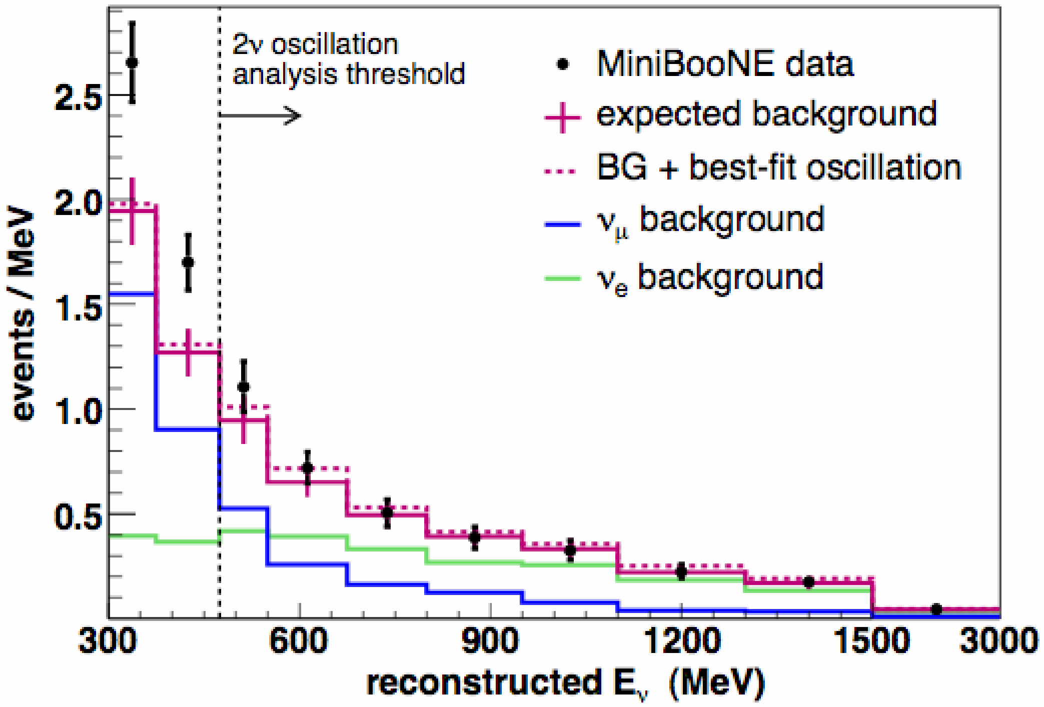
Probability of Null Fit: 93%
Probability of Best Fit: 99%

Full Energy Range

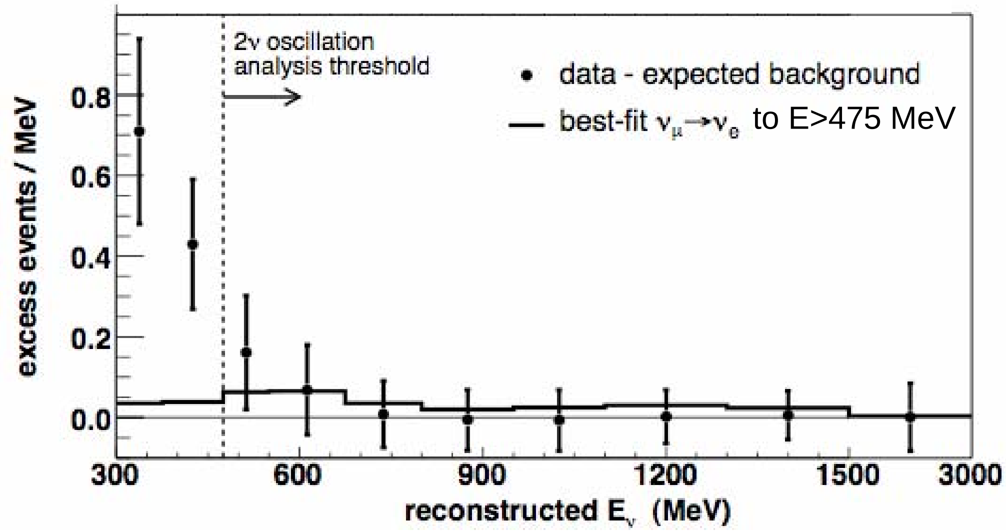
Report the full range:
300< E_ν^{QE} <3000 MeV

96 ± 17 ± 20 events above background, for 300< E_ν^{QE} <475MeV

Deviation: 3.7 σ

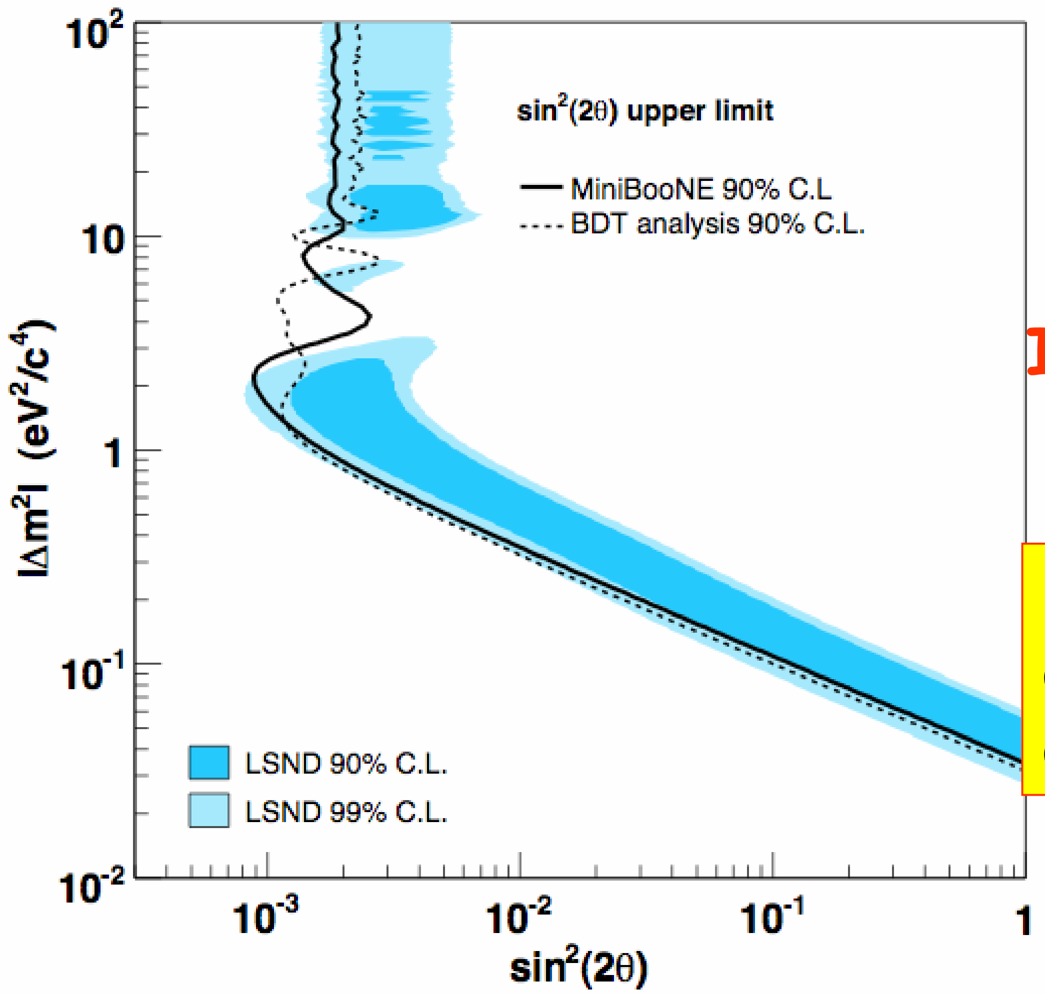


Background-subtracted:



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

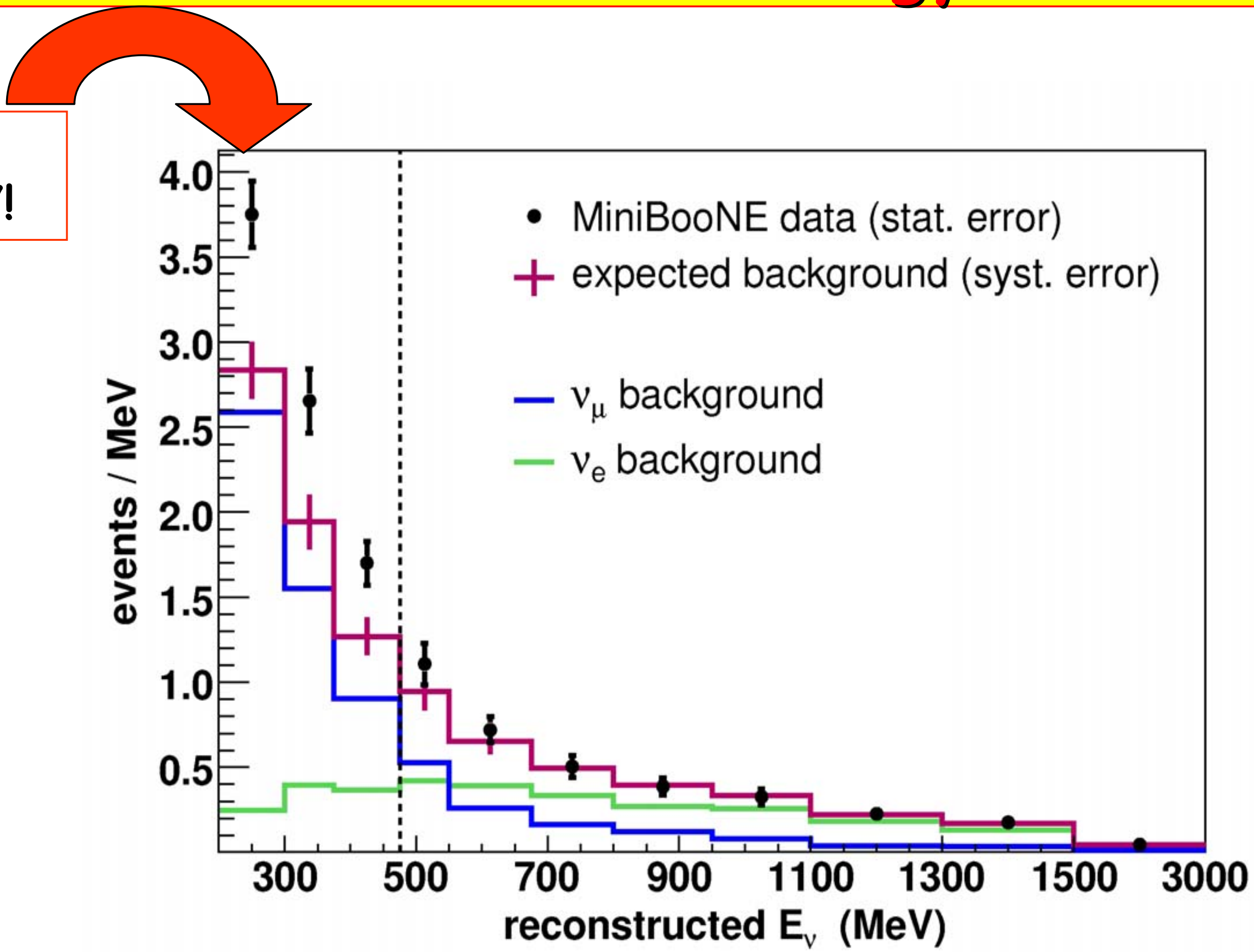
Details:

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_ν^{QE} = 200 MeV!



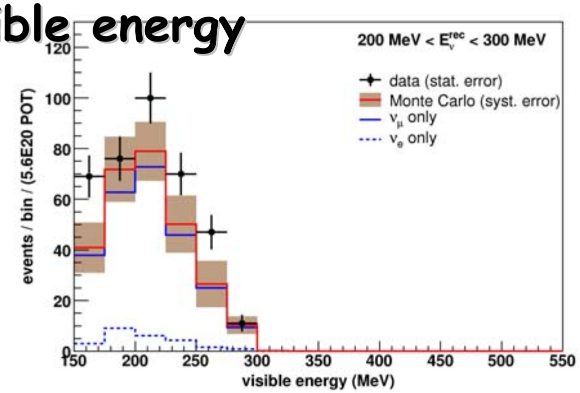
Reconstructed E_ν^{QE}: from E_{lepton} ("visible energy") and lepton angle wrt neutrino direction

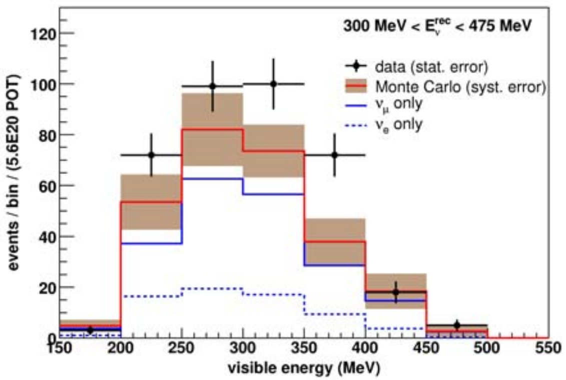
$$E_\nu^{QE} = \frac{1}{2} \frac{2M_p E_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)} cos\theta_\ell}$$

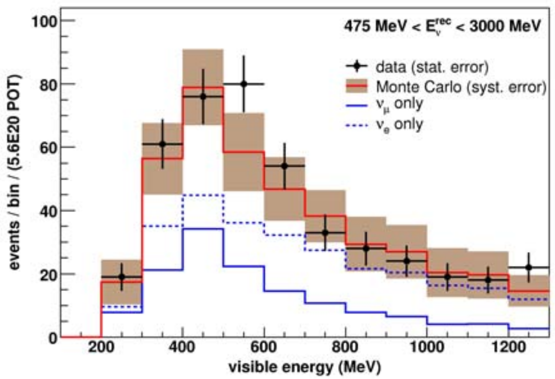
Visible energy and angle in E_ν^{QE} bins

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

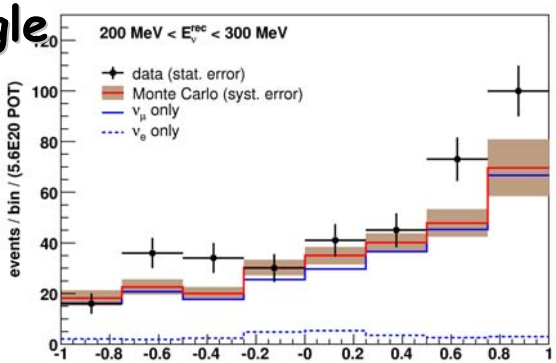
Visible energy



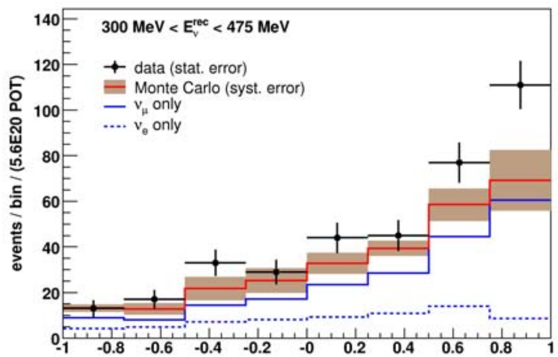




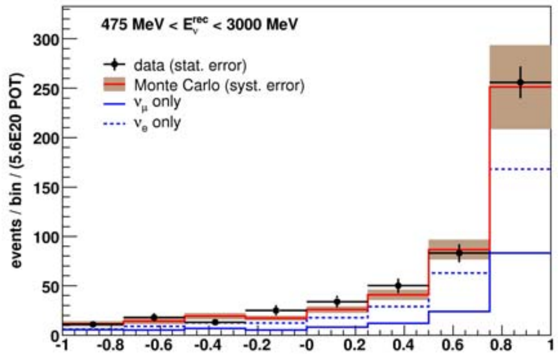
Angle



$\cos\theta$



$\cos\theta$



$\cos\theta$

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

Summary of estimated backgrounds vs data

E_ν^{QE} [MeV]	200-300	300-475	475-1250
total background	284±25	274±21	358±35
ν_e intrinsic	26	67	229
ν_μ induced	258	207	129
NC π^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 ν_μ-induced, in particular:
  - NC π^0
  - NC $\Delta \rightarrow N\gamma$
  - Dirt

-High Energy: no significant excess with ν_e bkgd dominant

Currently re-checking these processes.

In addition, new processes being considered:

- ν_μ-induced NC π^0 with photonuclear absorption of π^0 photon

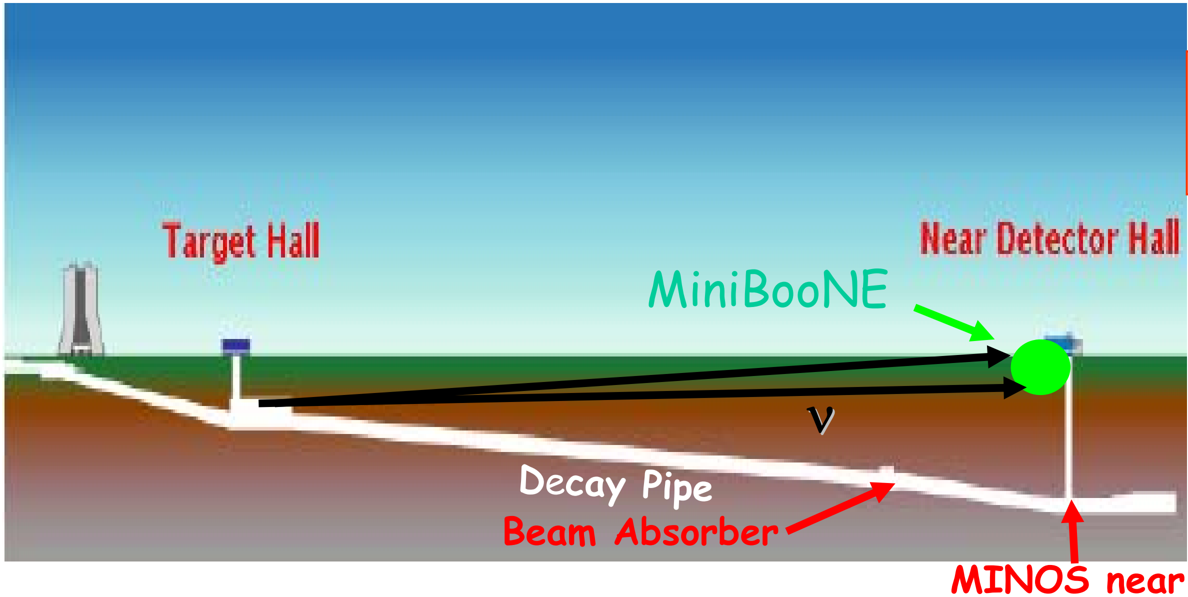
- new ν_μ-induced NC photon production (eg: hep-ex:0708.1281v2)

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

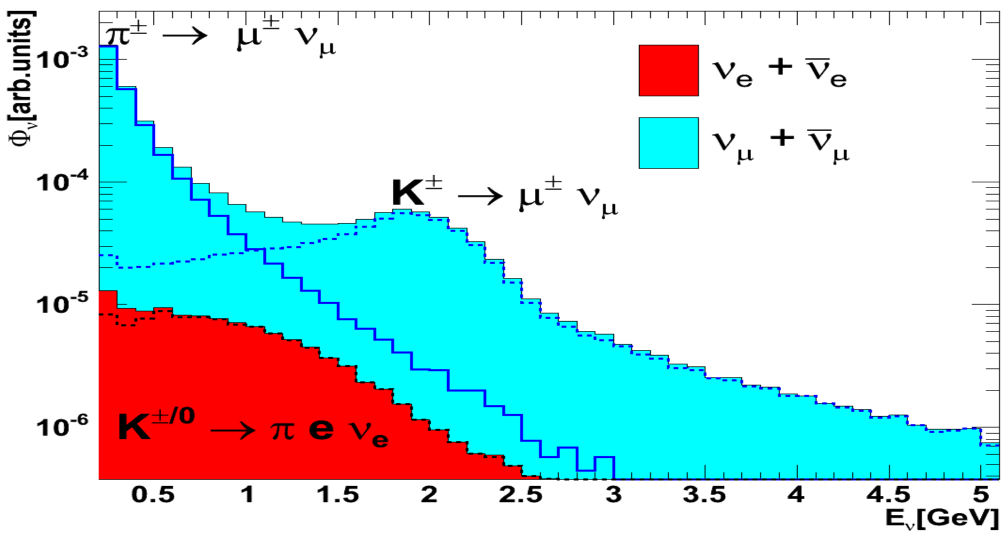
Analysis of the events from NuMI beam

NuMI events (for MINOS) detected in MiniBooNE detector!

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

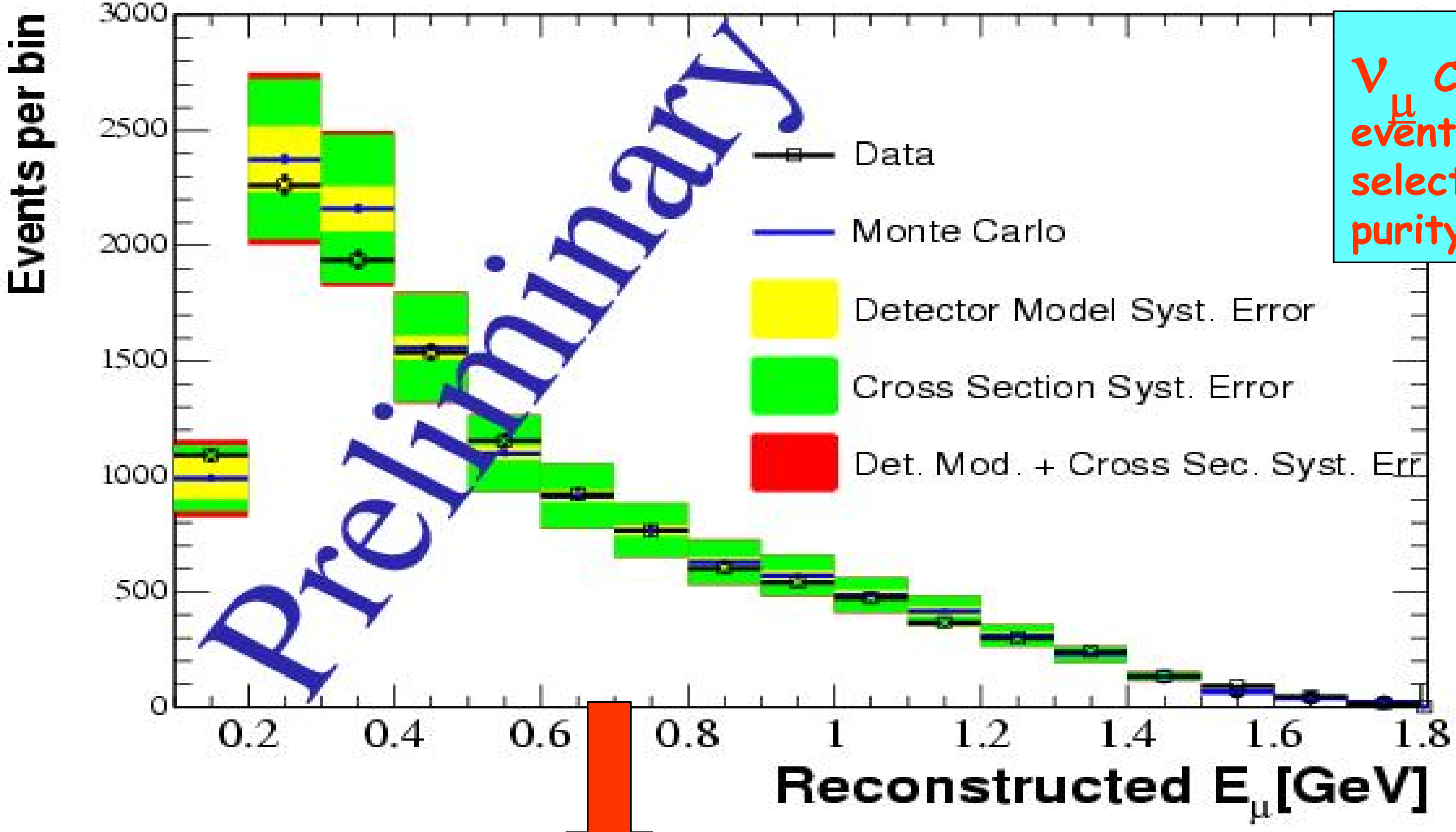


NuMI ν Flux at MiniBooNE



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

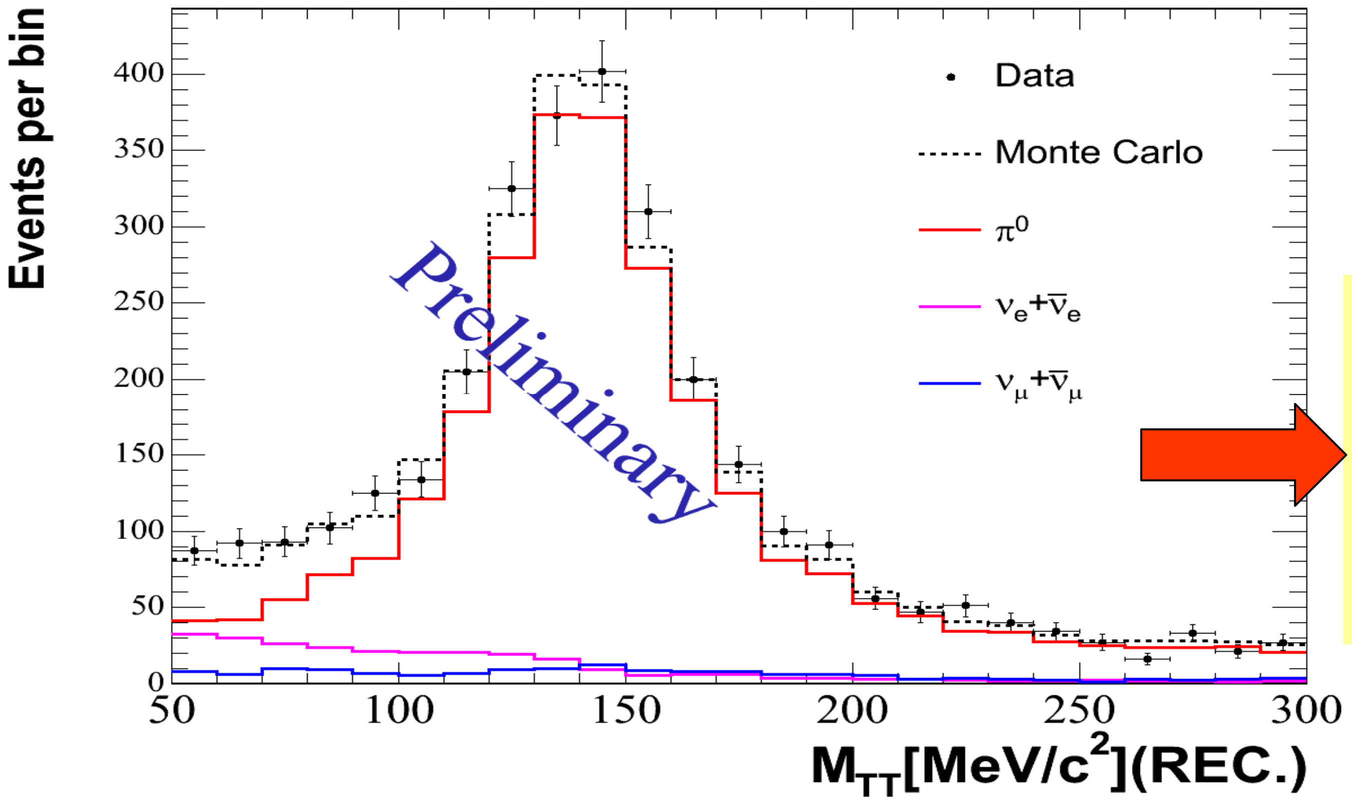
Analysis of the CCQE events from NuMI beam



ν_μ CCQE events selection: purity 70% .

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

Analysis of π^0 events from NuMI beam



π^0 events selection: purity 87% .

Step II: Understanding of the bkgds to ν_e search: Good data/MC agreement with π^0 events!

Step III: Analysis of ν_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

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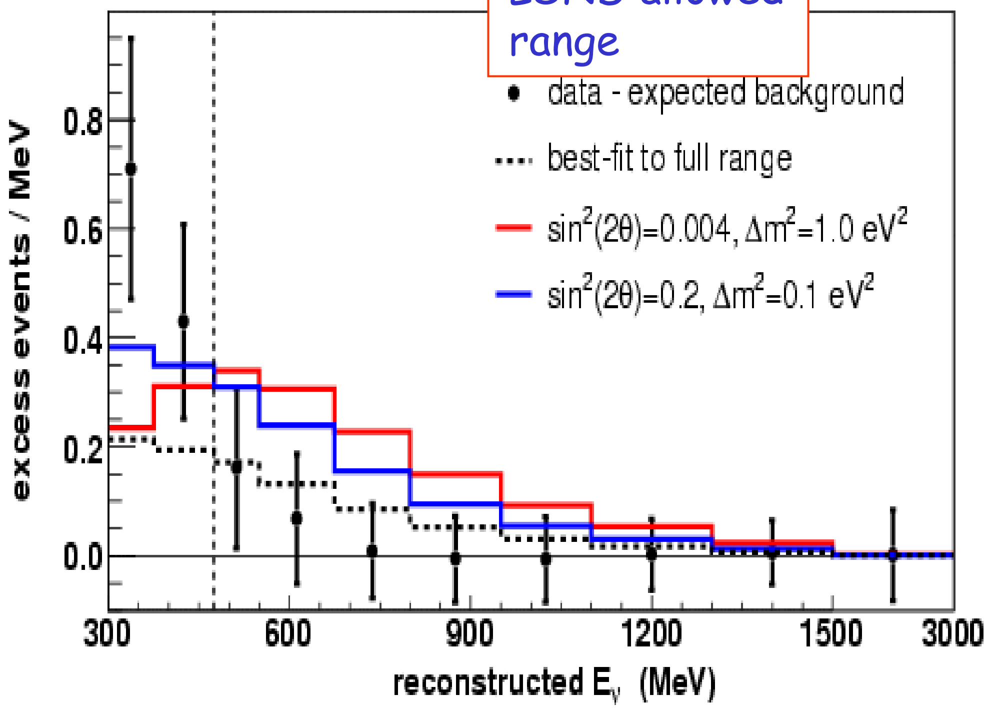
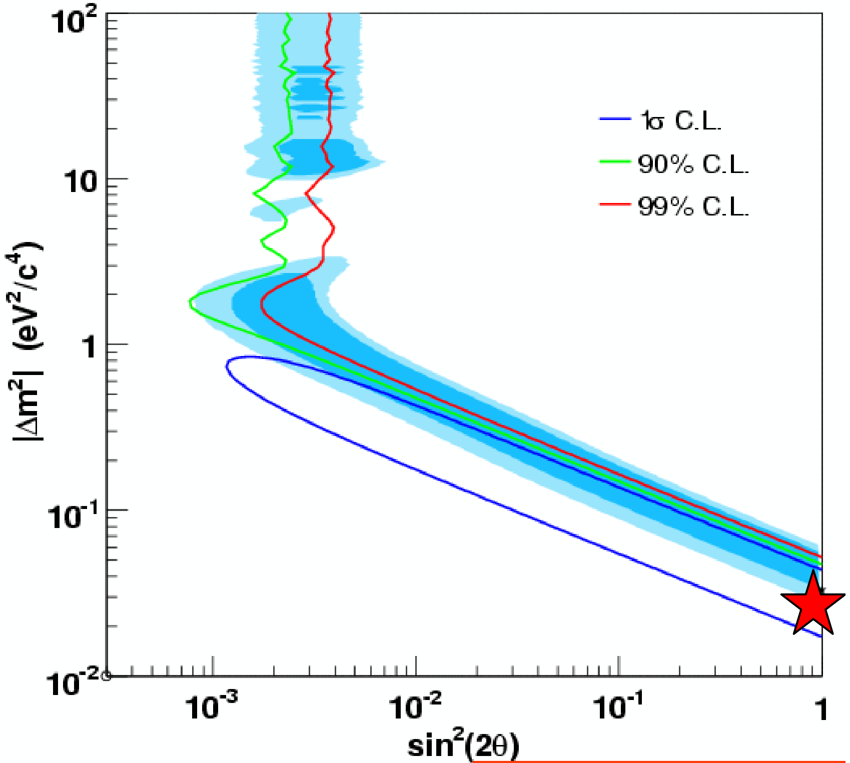
Indiana University
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

Backups

Full Energy Range Fit 300< E_ν^{QE}< 3 GeV

Examples in LSND allowed range





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

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

Testing e-π^0 separation using the data

What is applied:

Event pre-selection

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

$\log(L_e/L_\pi)<0$ (π^0-like)

mass>50