MiniBooNE

Primi risultati per la ricerca di oscillazioni nella regione permessa da LSND

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Outline

Motivation

Neutrino Beam and Detector

Closed electron neutrino box era (2002 – March 2007):

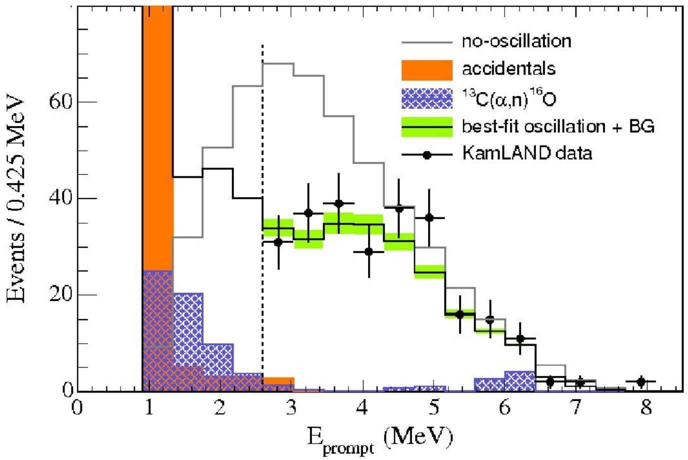
- Tuning experiment's simulations, event reconstruction, and PID
- Constraining electron neutrino backgrounds with data
- Systematic uncertainties and cross-checks

Open electron neutrino box era (March 2007 - present):

- Electron neutrino candidate events
- Result on muon-to-electron neutrino oscillations

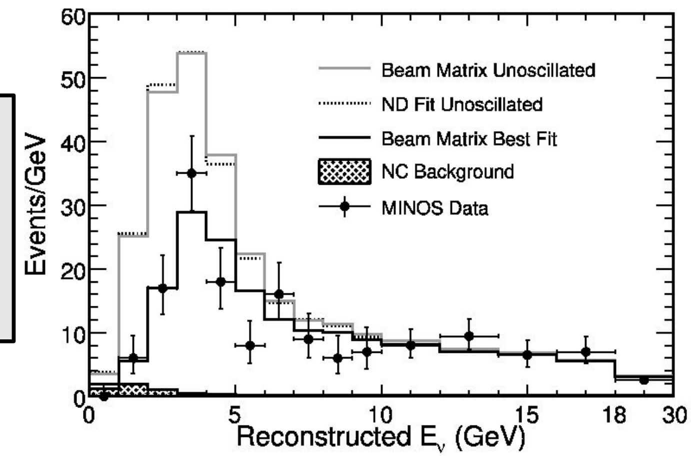
Conclusions and the next steps

Neutrino Oscillation Signatures



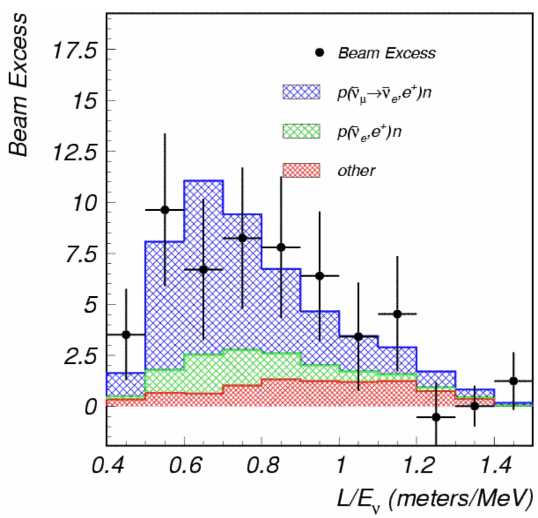
Solar Neutrino Oscillations

- Deficit of nues observed from the Sun
Homestake, SAGE, GALLEX/GNO, Super-K, SNO
- Confirmed by KamLAND (reactor nuebars)



Atmospheric Neutrino Oscillations

- Zenith angle-dependent deficit of atmospheric numus
Kamioka, Super-K, Soudan, MACRO
- Confirmed by K2K and MINOS (accelerator numus)

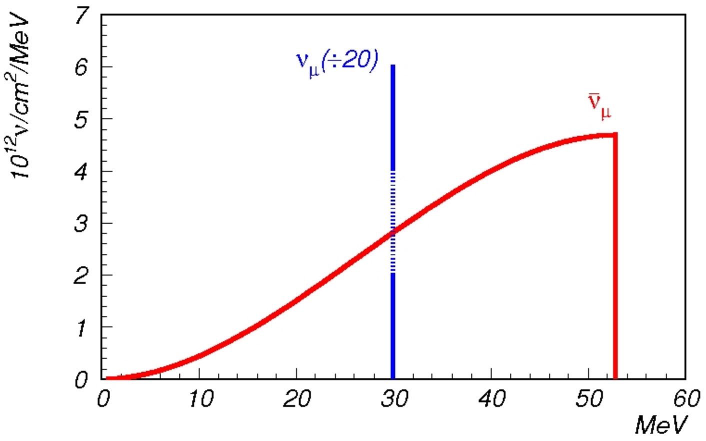


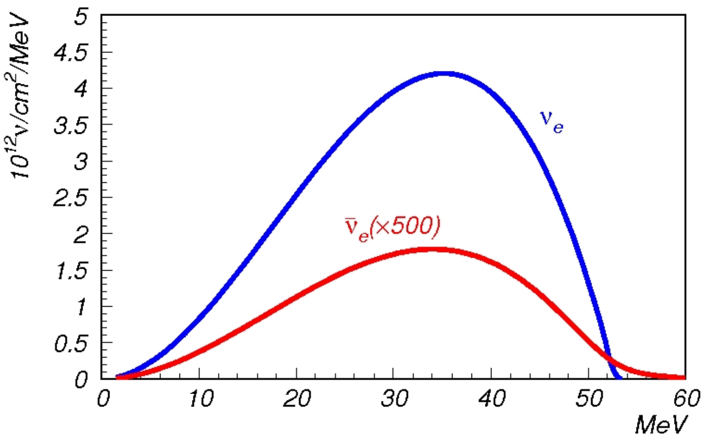
LSND Neutrino Oscillations

- Excess of nuebars in numubar beam produced from muon decay-at-rest
- Unconfirmed by other experiments, but not excluded

The LSND Experiment

- *The neutrino source:*
  - $\bar{\nu}_\mu$ from: $\pi^+ \to \mu^+ \nu_\mu, \;\; \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
  - $E_\nu = 20-53$ MeV, $L_\nu = 25-35$ m
  - Almost no $\bar{\nu}_e$ at source

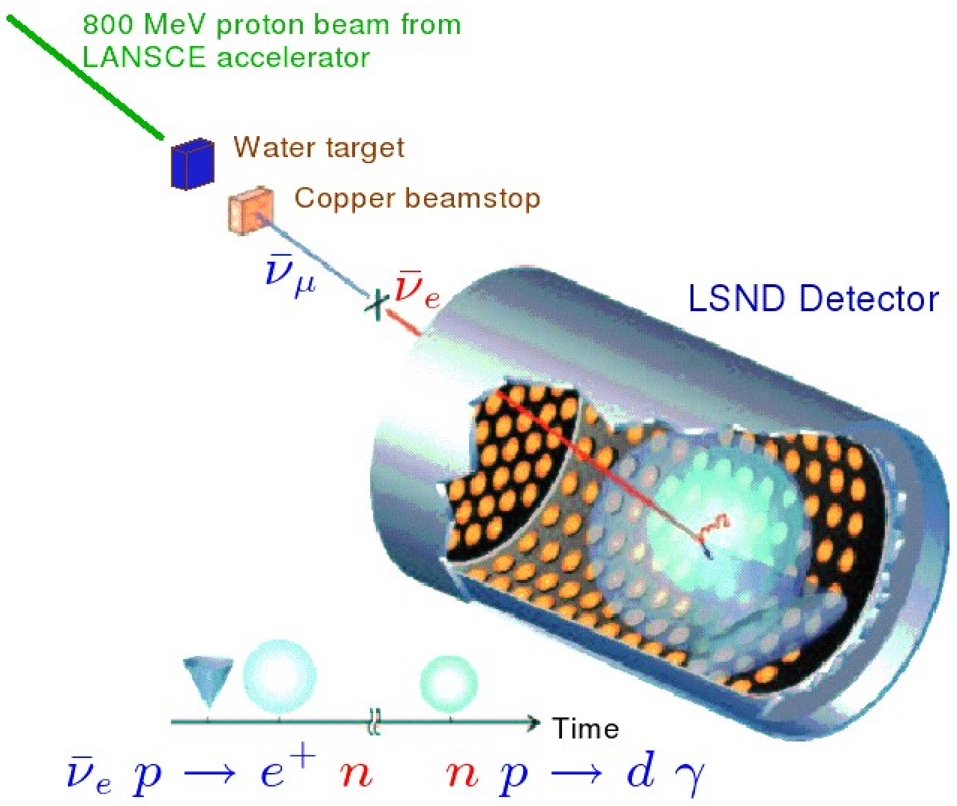




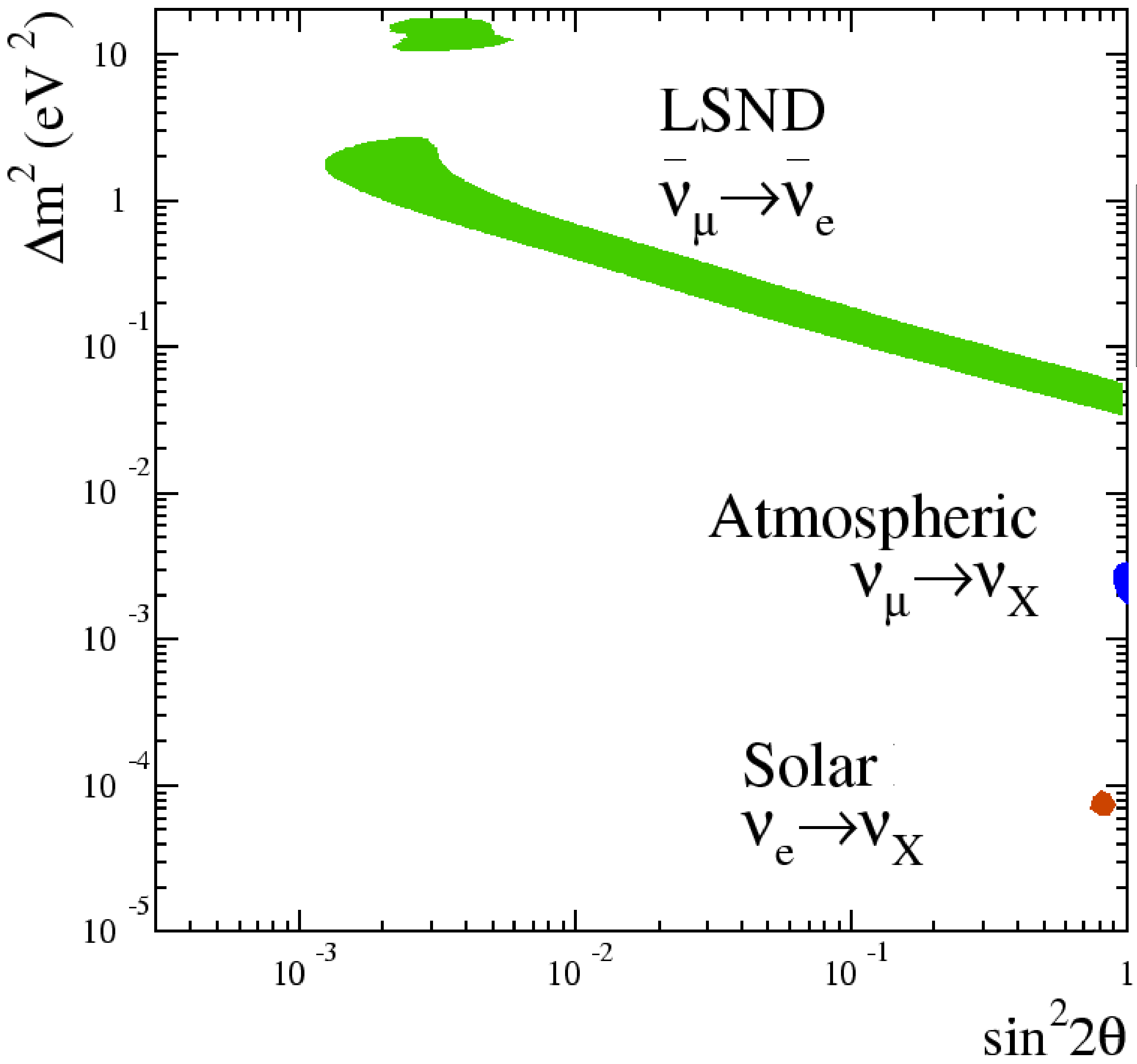
- *The neutrino detector:*

For $\bar{\nu}_e p \to e^+ n$ interactions, detects:

- Cherenkov/scintillation light from e^+
- Scintillation light from n capture



The LSND Oscillation Result



$\overline{\nu}_e$ candidate excess:
$(87.9 \pm 22.4 \pm 6.0) \rightarrow 3.8\sigma$

If interpreted as oscillations:
$\langle P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \rangle = (0.264 \pm 0.067 \pm 0.045)\%$

Mass and mixing parameters:
$\Delta m^2 \sim 0.1 - 10\ eV^2$, small mixing
Large $(\sin^2 2\theta, \Delta m^2)$ degeneracy

$\Delta m^2_{\mathrm{LSND}} \gg \Delta m^2_{\mathrm{atm}} + \Delta m^2_{\mathrm{sol}}$ and
$\Delta m^2_{\mathrm{LSND}} \sim 1\ \mathrm{eV}^2$:
Cannot be explained within the standard neutrino physics and cosmology paradigms

MiniBooNE Goal and Design Strategy

- **Primary goal:**

confirm or refute the oscillation interpretation of the LSND anomaly in an unambiguous and independent way

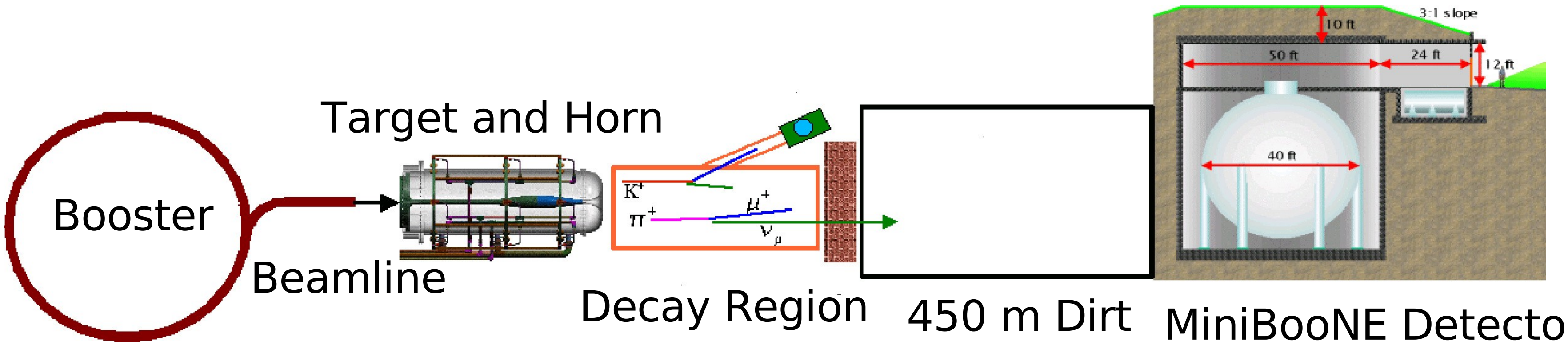
- **Design strategy to accomplish this goal:**
  - High statistics sample of electron neutrino candidate events
  - Keep L/E as LSND, with order-of-magnitude longer baseline (~500 m) and higher neutrino energy (~800 MeV)

    -> different oscillation signature, backgrounds, systematics

MiniBooNE Collaboration

U. of Alabama
Bucknell U.
U. of Cincinnati
U. of Colorado
Columbia U.
Embry Riddle Aeronautical U.
Fermi National Accelerator Lab.
Indiana U.
Los Alamos National Lab.
Louisiana State U.
U. of Michigan
Princeton U.
Saint Mary's U. of Minnesota
Virginia Polytechnic Inst. & State U.
Western Illinois U.
Yale U.

Neutrino Beam



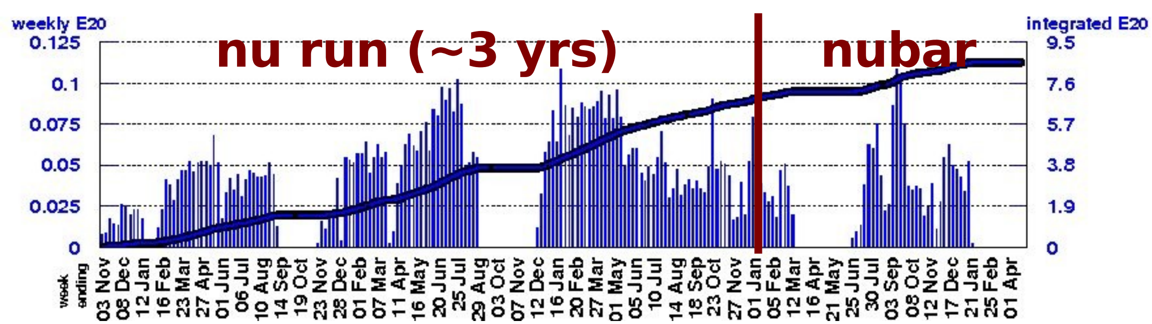
Primary Beam (protons) → **Secondary Beam** (mesons) → **Neutrino Beam**

Primary Beam: 8 GeV protons from Booster, $8 \cdot 10^{-6}$ duty factor

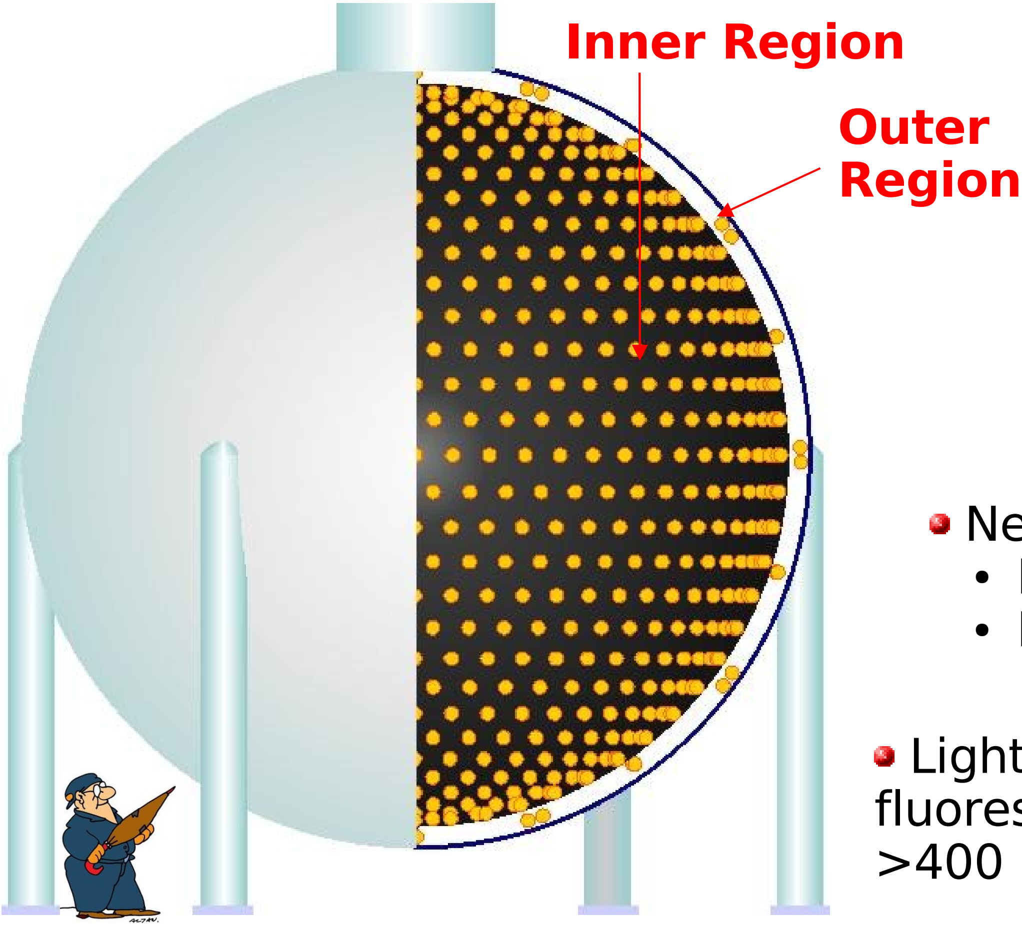
Secondary Beam: mesons are produced from protons striking Be target, and focused by horn. Switchable horn polarity allows for nu and nubar beams

Neutrino Beam: neutrinos from meson decay in 50m pipe, pass through 450m of dirt (and oscillate?) to reach MiniBooNE detector

Number of accumulated protons on target: $8.5 \cdot 10^{20}$
Used in current neutrino oscillation analysis: $5.6 \cdot 10^{20}$

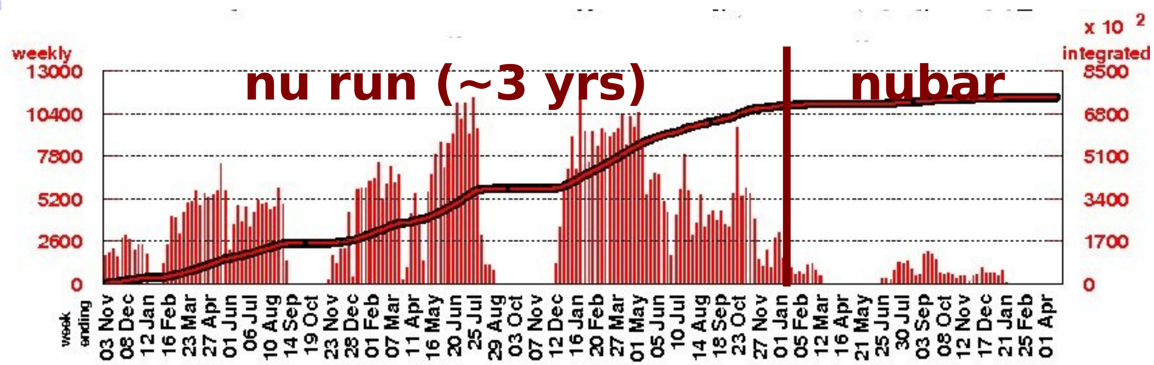


Neutrino Detector



- 12 m in diameter sphere filled with 800 t of undoped mineral oil
- Light tight inner region with 1280, 20 cm diam., PMTs (10% coverage)
- 240 PMTs in veto region (>99.9% veto efficiency)
- Neutrino interactions in oil produce:
  - Prompt, ring-distributed, Cerenkov light
  - Delayed, isotropic, scintillation light
- Light transmission affected by: fluorescence, scattering, absorption (>20m for >400 nm light)

Number of accumulated neutrino interactions: $7.4 \cdot 10^5$



MiniBooNE Appearance Search

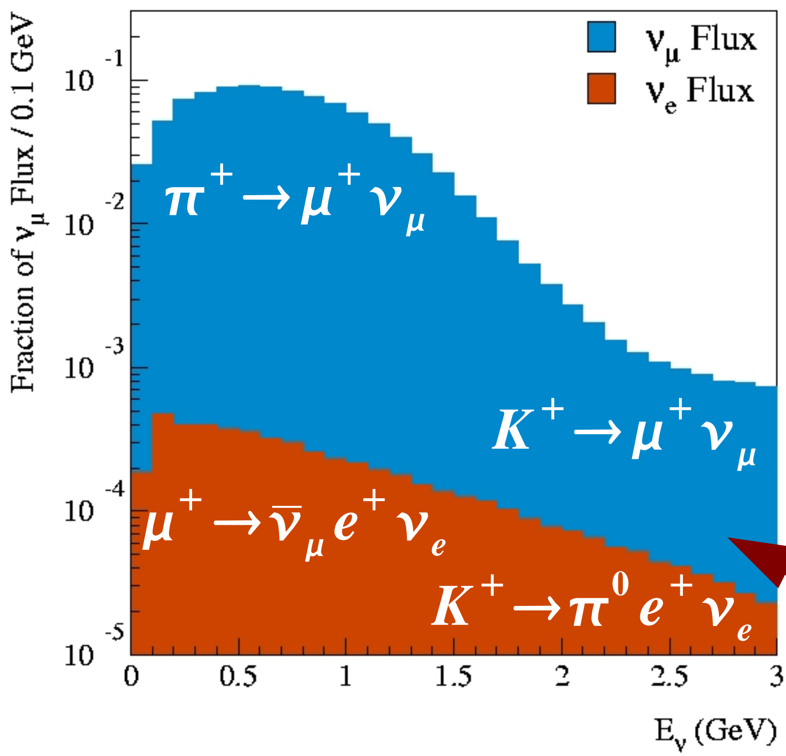
- MiniBooNE initial results:
  - A generic search for an electron neutrino excess (or deficit) in a muon neutrino beam
  - An analysis of the data within a two neutrino, muon-to-electron appearance-only neutrino oscillation context, to test this interpretation of the LSND anomaly
- Two independent analyses were performed:
  - Track-based analysis (TBA): less sensitive to systematic uncertainties
  - Boosted decision tree (BDT) analysis: better oscillation signal-to-background ratio expectation
- Will discuss almost exclusively TBA, chosen as the primary analysis because of slightly better muon-to-electron neutrino appearance sensitivity
- This was a blind analysis. The closed box was opened on March 26, 2007. Results released to the public on April 11, 2007 (yesterday).

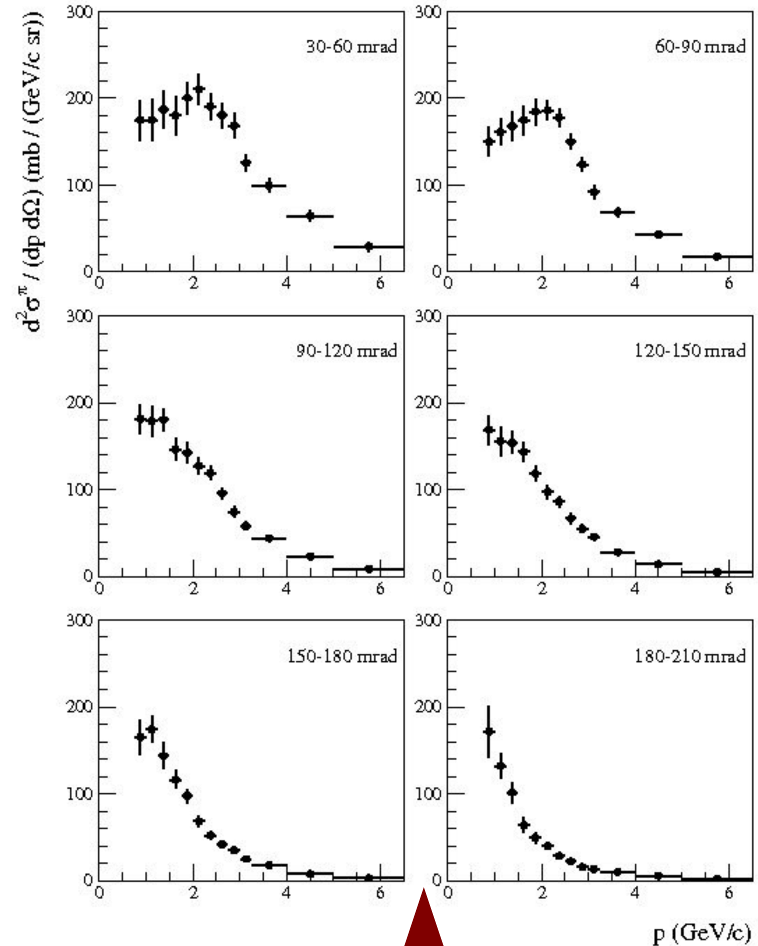
Neutrino Fluxes

GEANT4 beamline description, simulating:

- Primary protons, geometry, materials and horn field
- Interactions, focusing, meson and muon decays

- Pion/kaon production data on beryllium is the most important external physics input to the simulation
-> parametrized according to relevant hadron production data sets



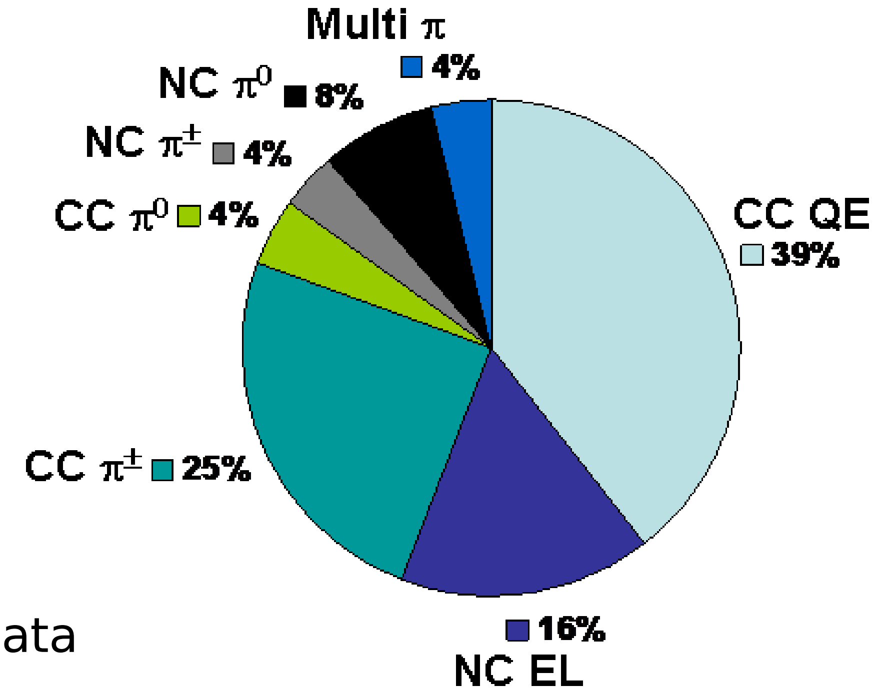


HARP data on:
p(8.9 GeV/c) + Be $\to \pi^+$ + X
(hep-ex/0702024)

ν_μ and ν_e flux predictions. $\nu_e/\nu_\mu \sim 0.5$ %

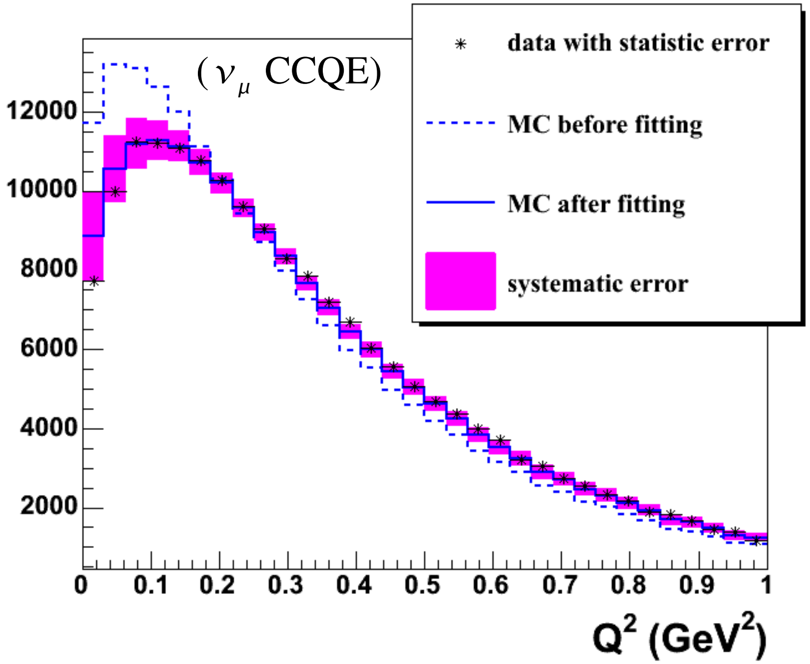
Neutrino Interactions

- **NUANCEv3 cross-section generator**, simulating all relevant neutrino processes, including detailed treatment of Carbon nuclear effects (D. Casper, hep-ph/0208030)



- **External constraints used in NUANCEv3:**
  - Free nucleon cross-sections from neutrino data
  - Nuclear model from electron data
  - Final state interactions from π/p scattering data

- **MiniBooNE's modifications to NUANCEv3 (based on MB neutrino data):**
  - nucleon axial form factor for QE scattering
  - Pauli blocking model
  - coherent pion cross-sections
  - final state interactions
  - angular correlations in resonance decay
  - nuclear de-excitation photon emission



Detector Response

Tabletop measurements & laser calibration

↓

First calibration with michels

↓

Calibration of scintillation light with NC events

↓

Final calibration with michels

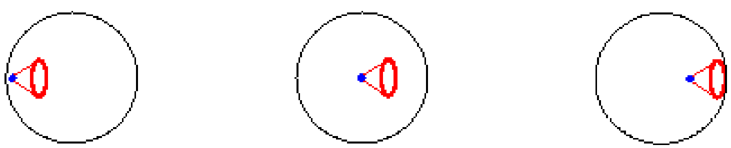
↓

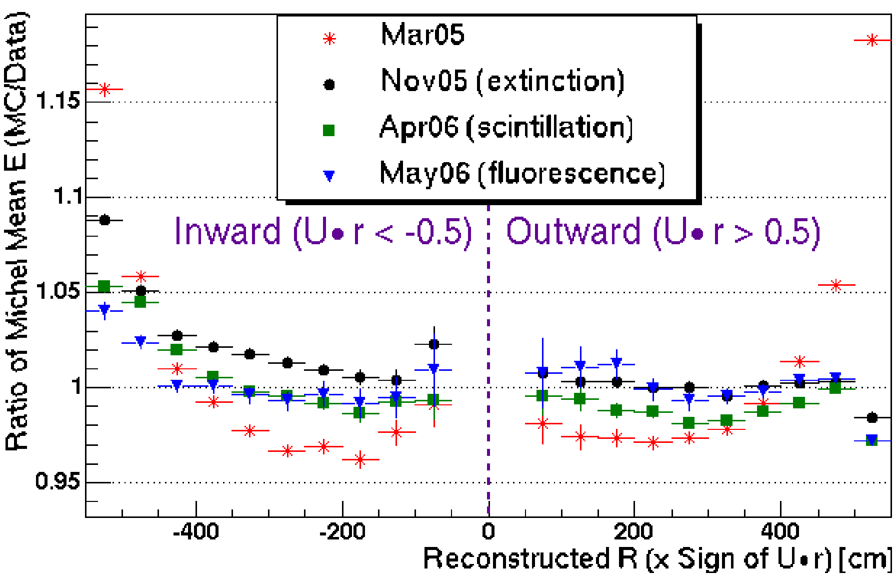
Validation with cosmic muons, ν_μ events, and NuMI ν_e events

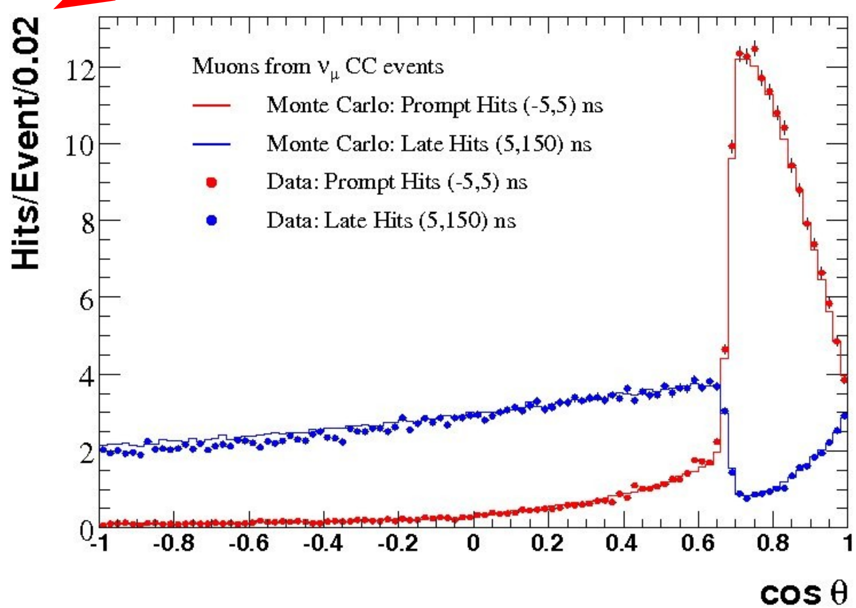
GEANT3 description, with detailed simulation of:

Light production and transmission:
- Cherenkov, scintillation, fluorescence
- tank reflections, Raman/Rayleigh scattering, absorption

PMT charge/time response:
- single PE charge distribution and charge linearity
- time distribution







Reconstruction and Particle Identification

Reconstruction:

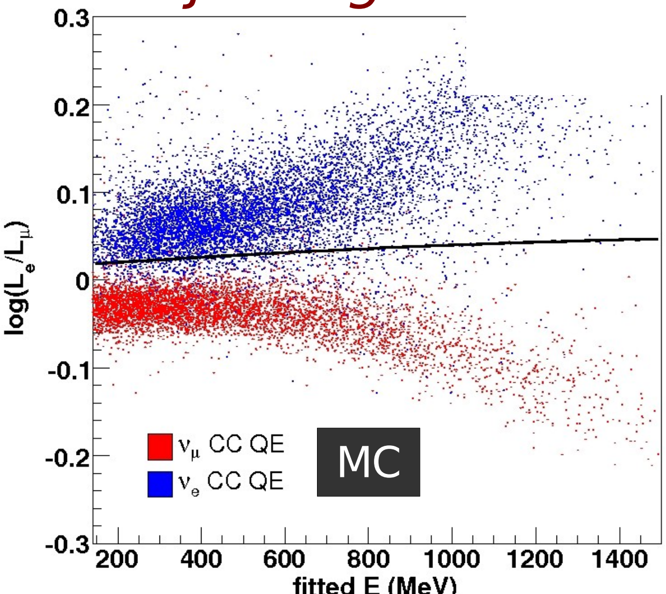
- Detailed model of extended-track light production and propagation

• 22 cm resolution for ν_e event vertex
• 2.8 deg for electron track direction
• 11% for electron track energy
• 20 MeV for invariant mass resolution in NC π^0 events

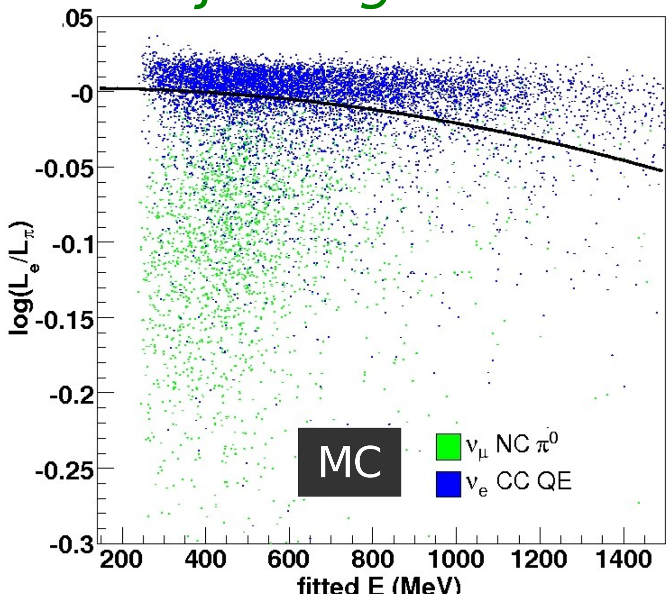
Particle Identification:

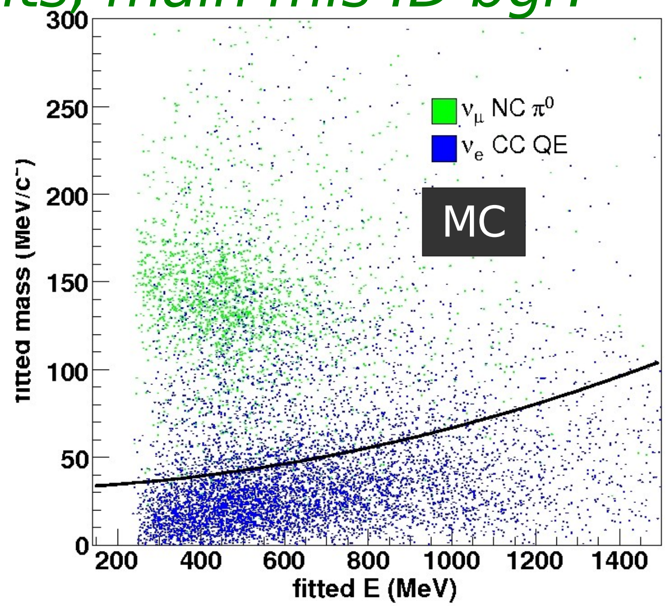
- To reject muons and π^0's, and enhance CCQE fraction in ν_e sample
- Each event reconstructed under muon 1-ring, electron 1-ring, fixed-mass 2-ring, and unconstrained 2-ring hypotheses
- Cut on likelihood fit ratios and 2-ring mass value

Rejecting muons:



Rejecting NC π^0 events, main mis-ID bgr:





Cut values chosen to optimize $\nu_\mu \rightarrow \nu_e$ sensitivity

Signal Efficiency and Background Composition

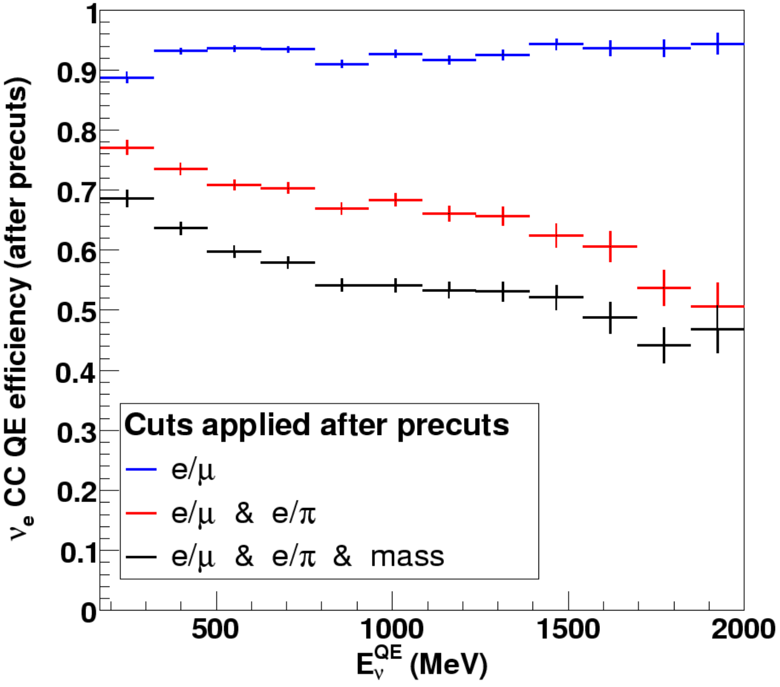
- Signal efficiency:

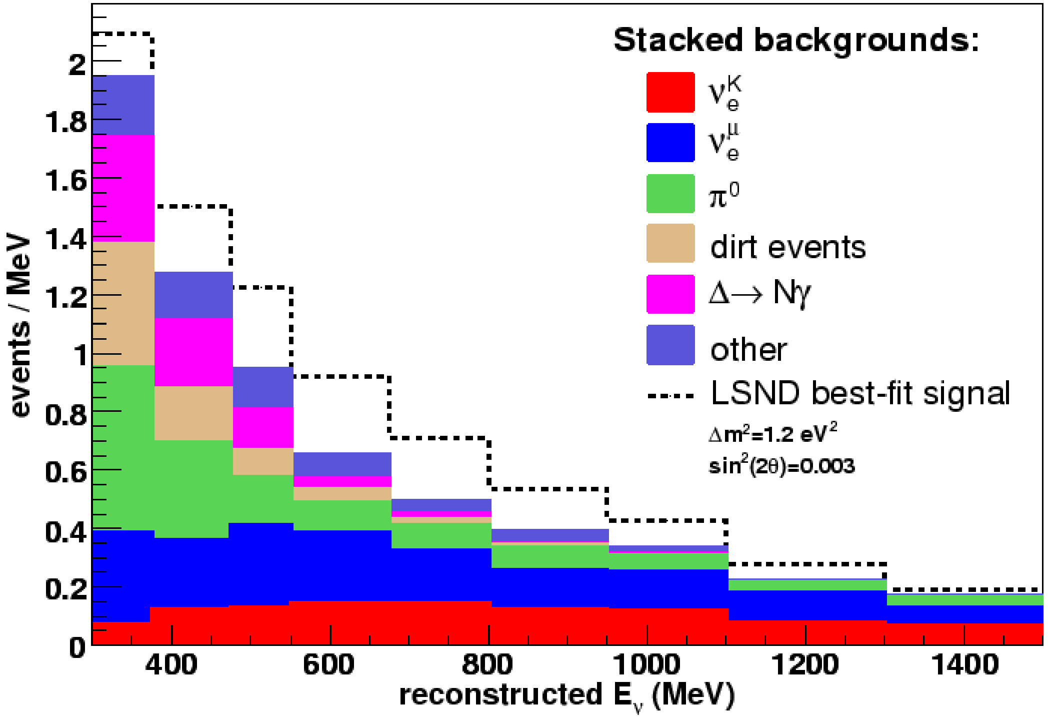
Hit-level, fiducial volume, energy threshold cuts

+ $\log(L_e/L_\mu)$

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

+ invariant mass cuts





- Background events in signal region can be constrained or checked with other samples:

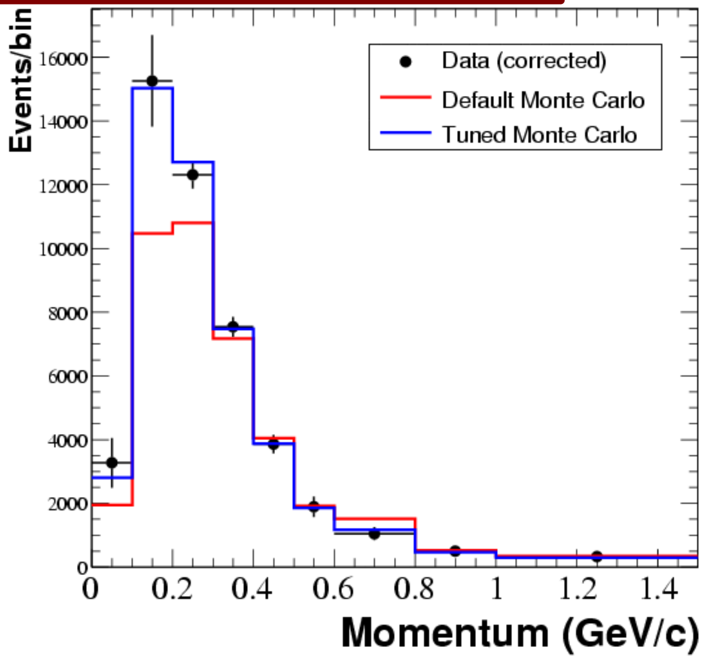
high energy events
ν_μ CC QE
π^0
high radius events
π^0
ν_μ CC QE
ν_μ CC QE

MiniBooNE Constraints on mis-ID Backgrounds

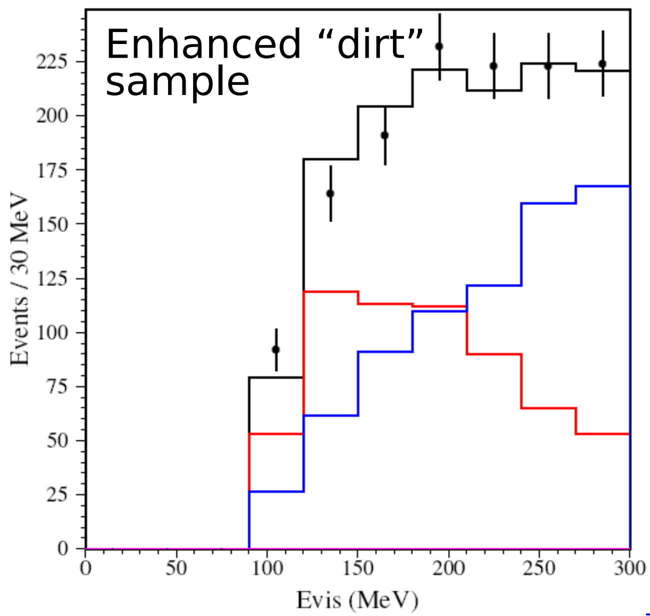
All of the major backgrounds for the ν_e appearance search can be constrained directly from MiniBooNE measurements

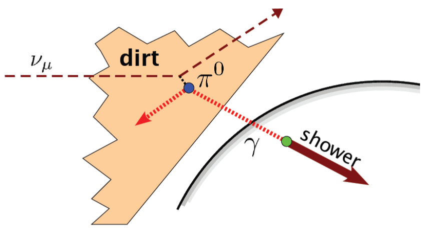
NC π^0 background (one photon not seen)

- Select >90% pure sample of NC π^0 events
- Correct MC π^0 production rate .vs. π^0 momentum
- Correct MC π^0 mis-ID rate
- Ability to isolate resonant/coherent π^0 contributions allows to correct also $\Delta \rightarrow N\gamma$ background



Dirt(red),Tank(blue),MC(black),Data(dots)





External backgrounds

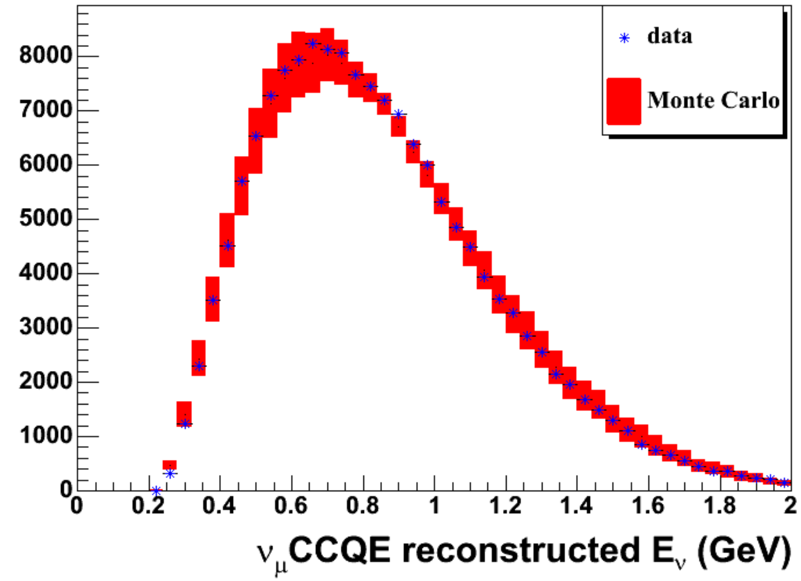
- Neutrino beam interacts with material outside detector creating 100-300 MeV photons that come into the tank unvetoed, producing e-like events
- "Dirt" background rate data/MC = 0.99 ± 0.15

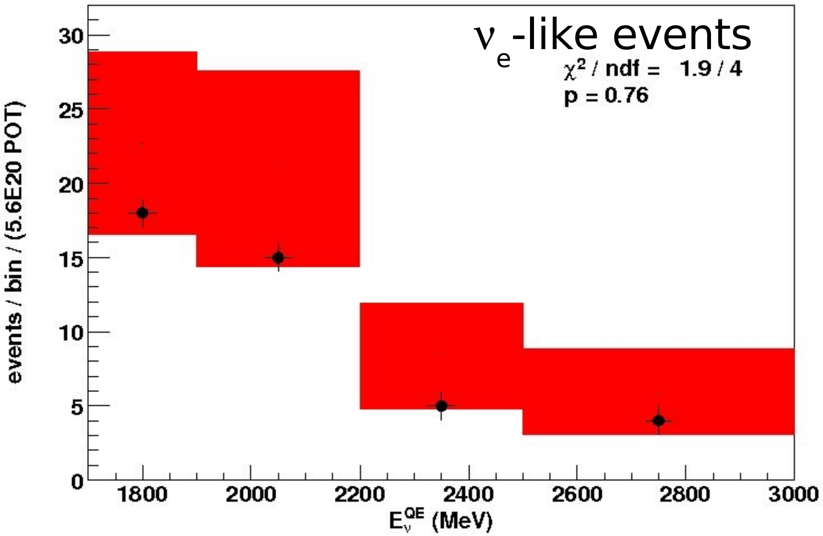
MiniBooNE Constraints on Intrinsic Backgrounds

All of the major backgrounds for the ν_e appearance search can be constrained directly from MiniBooNE measurements

Muon decay ν_e intrinsic background

- Measure ν_μ flux with ~80% pure ν_μ CCQE sample
- Kinematics allows to infer parent π^+ flux and momentum distribution from observed ν_μ events
- Once the pion flux is known, the $\pi^+ \to \mu^+ \to \nu_e$ decay chain is well constrained
- Use same sample to determine normalization of predicted signal





Kaon decay ν_e intrinsic background

- At high energies, both ν_μ and ν_e-like events are largely due to Kaon decay
- Kaon-induced flux measured at high energies, where no oscillation events are expected, and extrapolated to lower energies

Systematic Uncertainties and Oscillation Sensitivity

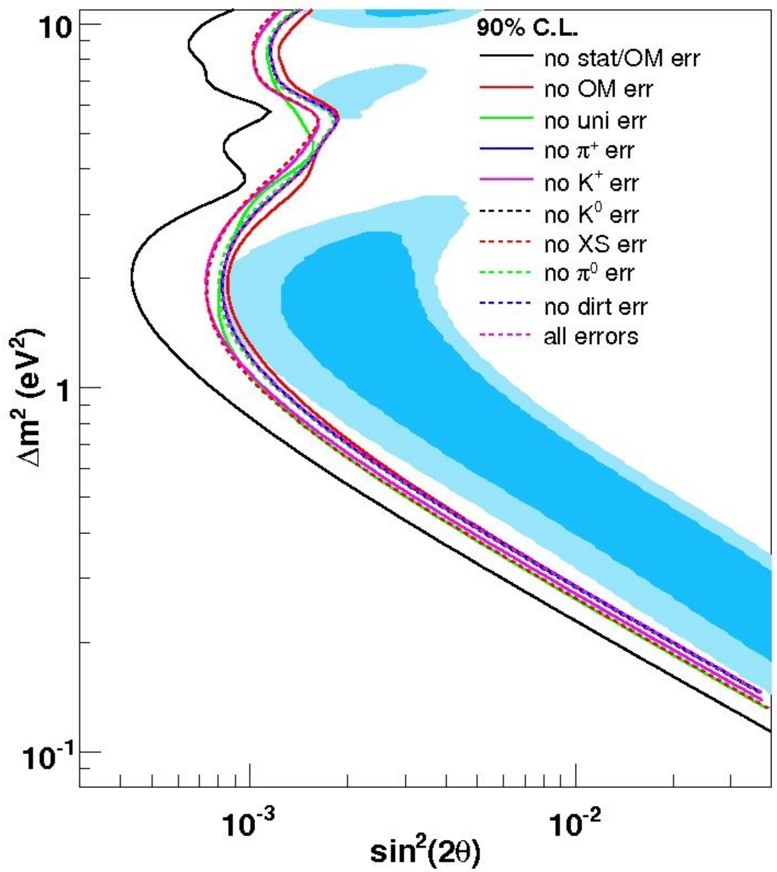
• Systematic uncertainties in predicting electron candidate events come from the modeling of the beam, neutrino interactions, detector

• Start from “first principles” uncertainties from simulation models and measurements external to MiniBooNE. Obtain better uncertainty estimates from MiniBooNE calibration and neutrino data fits

• For primary TBA analysis:

- statistical uncertainty affects sensitivity most
- neutrino cross-section (11 sources), K^+-induced neutrino flux, and final state interactions are most important systematic uncertainties
- detector optical model (OM) systematic uncertainties (~40 parameters varied) have little impact

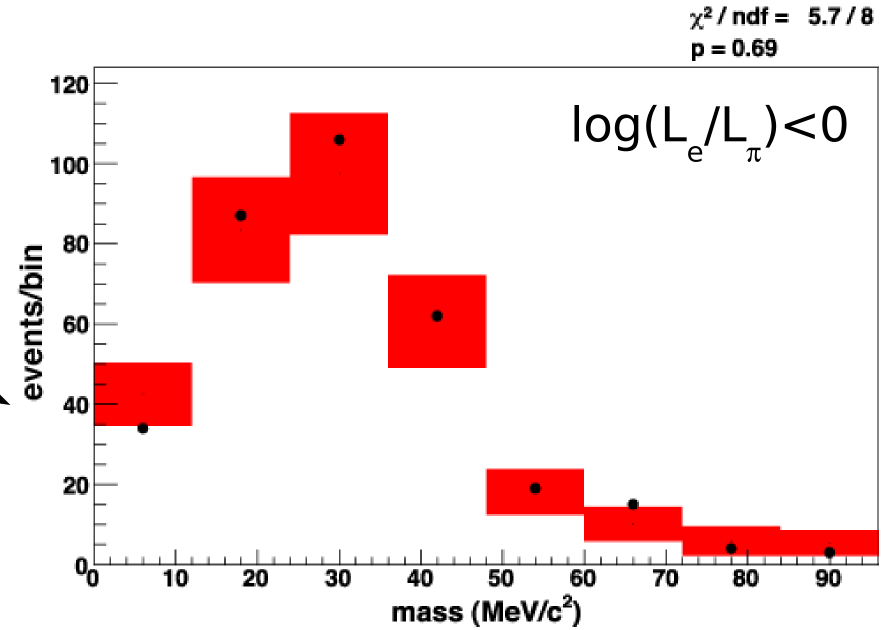
• Complementary (BDT) analysis affected by a different stat./syst. uncertainty mix

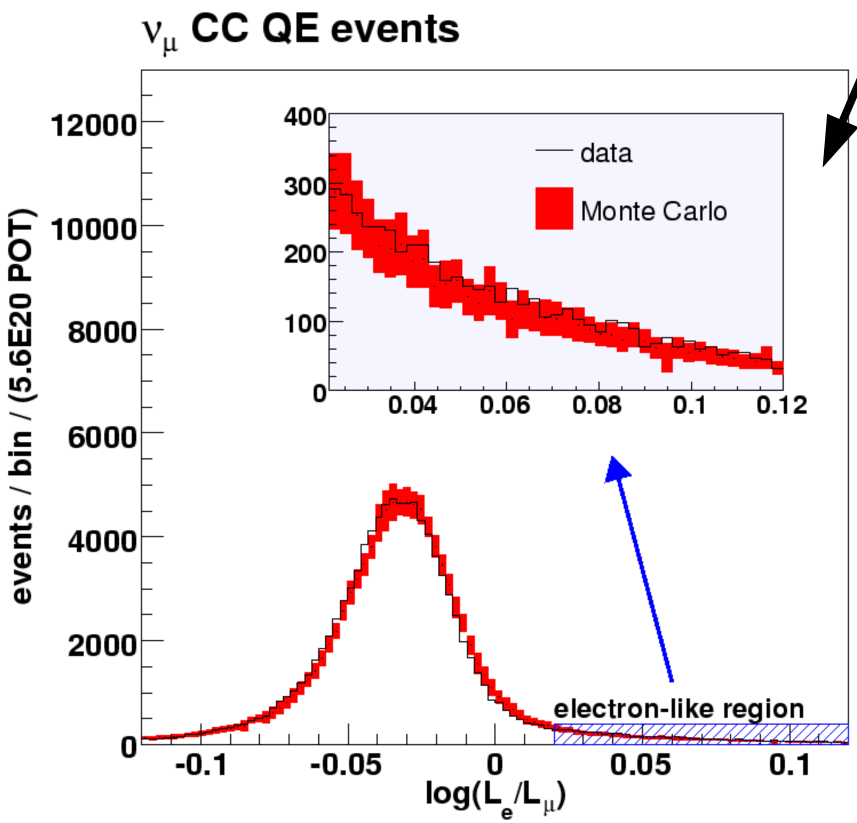


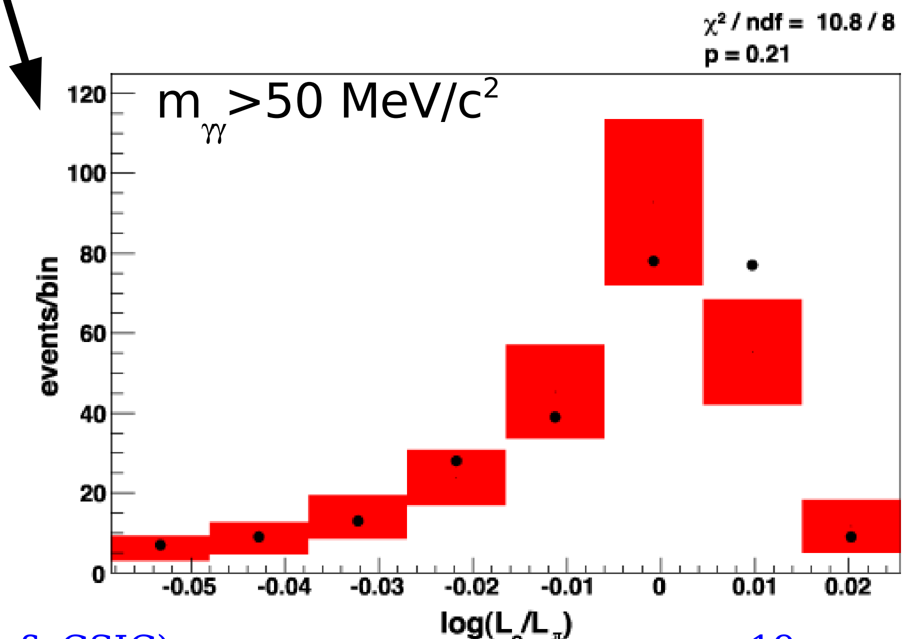
Cross-Checks

- Checked simulation, reconstruction, PID, uncertainty predictions on a variety of open data samples and distributions
- Some examples for ν_e selection quantities
- Good agreement found everywhere

-> proceed to step-wise box opening







Electron Neutrino Box Opening Procedure

Step 1: perform fit of E_ν distribution of electron candidate events in the $300 < E_\nu < 3000$ MeV energy range to oscillation hypothesis, where best-fit oscillation signal added to background prediction is unknown. Disclose χ^2 values from data/MC comparisons of several diagnostic variables

Step 2: disclose histograms for data/MC comparisons of same diagnostic variables

Step 3: disclose χ^2 value for E_ν data/MC comparison over oscillation fit range, still retaining blindness to oscillation signal component

Step 4: disclose full information on electron candidate events and oscillation fit results

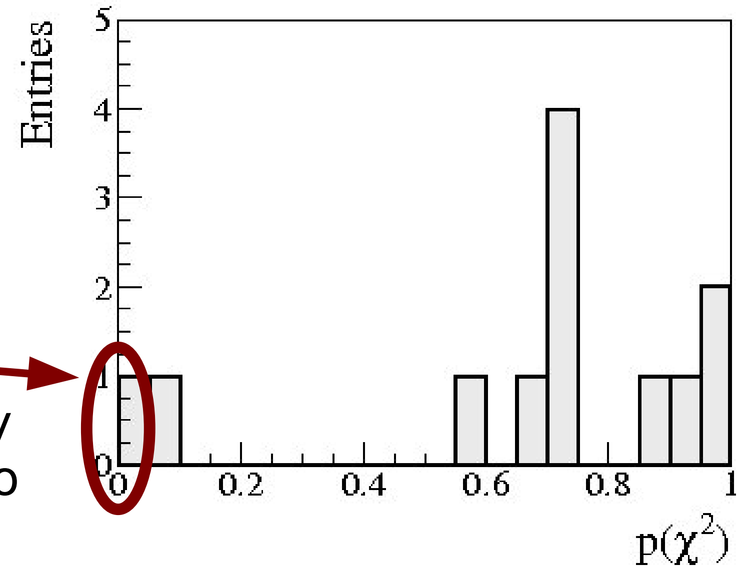
- Progress in a step-wise fashion, with ability to iterate if necessary
- All event selection and oscillation fit procedures are determined before full information on electron candidate events and oscillation fit results is disclosed

Box Opening Step 1: First Try

• χ^2 probability for data/MC comparisons on 12 diagnostic variables:

event/track position, direction, visible energy, and PID quantities

• Comparisons looked good except event visible energy: p($\chi^2 > \chi^2$(obs)) = 1%



• Indicates poor data/MC agreement beyond ability of 2-neutrino, appearance-only oscillation model to handle

• Triggered further investigations of low-energy background estimates and associated uncertainties, using “sideband” samples
-> we found no evidence of a problem

• However, knowing that:

- backgrounds predicted to rise at low energy
- studies focused suspicions in low-energy region
- choice has negligible impact on oscillation sensitivity

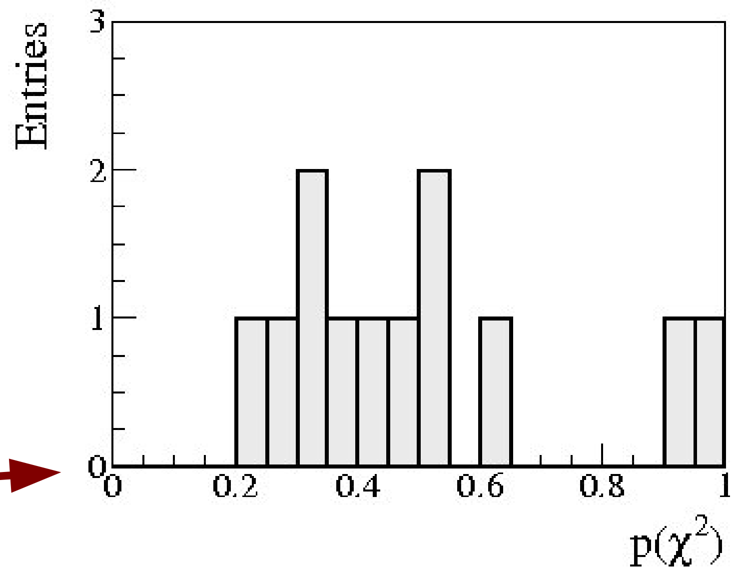
-> we decided to look for oscillations (and diagnostic χ^2) in the reduced (475 < E_ν < 3000 MeV) range, and report events over full (300 < E_ν < 3000 MeV) one

Box Opening Steps 1 (Again), 2, and 3

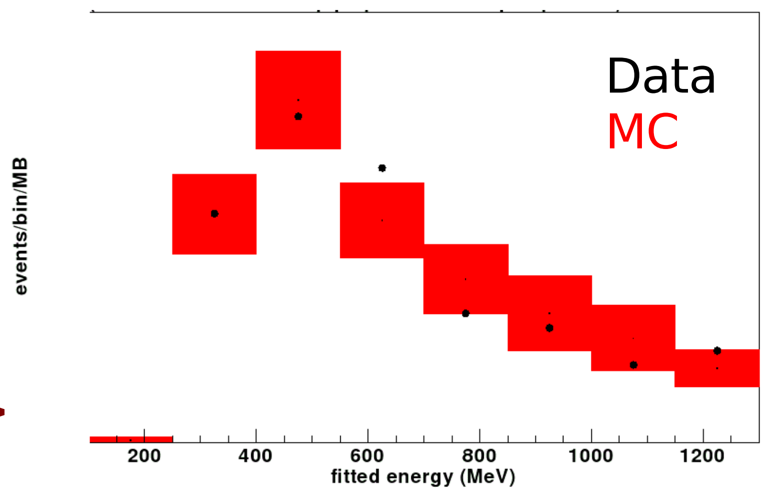
- **Step 1:** χ^2 probability for data/MC comparisons on 12 diagnostic variables:

event/track position, direction, visible energy, and PID quantities

- Comparisons look good



- **Step 2:** disclose histograms for data/MC comparisons of same diagnostic variables
- Example: event visible energy data/MC distributions (28% χ^2 probability)

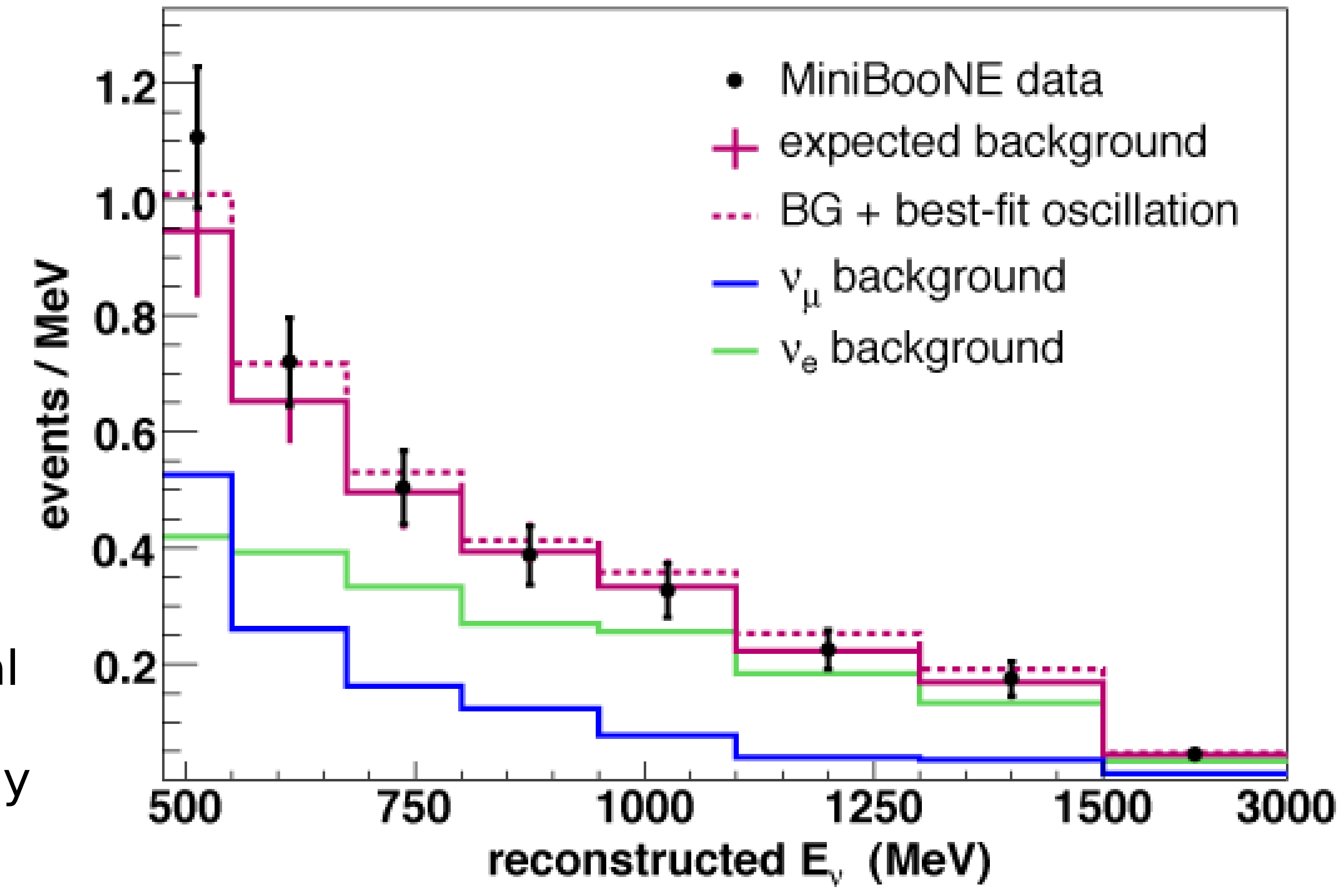


- **Step 3:** disclose χ^2 value for E_ν data/MC comparison over ($475 < E_\nu < 3000$ MeV) oscillation fit range, still retaining blindness to oscillation signal component
- Oscillation best-fit χ^2 probability: 99% (χ^2/dof = 0.9/6)
- Proceed to full box opening...

Full Box Opening and Oscillation Best-Fit Results

Energy-dependent Oscillation Best-Fit (475-3000 MeV):

- $\sin^2 2\theta = 1.1\text{x}10^{-3}$
- $\Delta m^2 = 4.1\ eV^2/c^4$
- $\chi^2_{null} - \chi^2_{best} = 0.94$



- Data error bars are statistical
- Predictions error bars from diagonal elements of syst.-only covariance matrix

Counting experiment (475-1250 MeV):

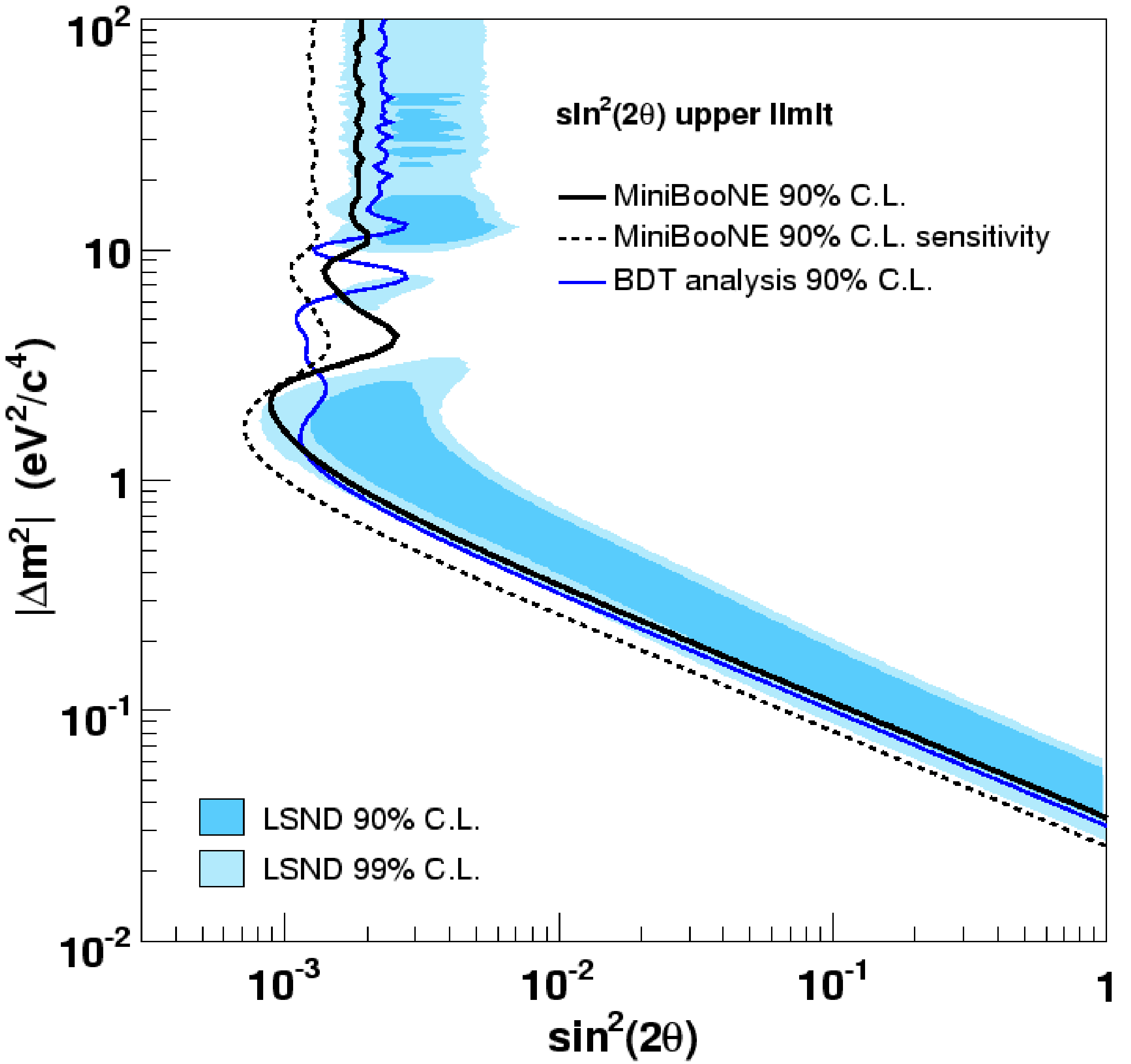
- Observe **380 events,** predict **358±19±35 events**
- **0.55 σ** excess over background

Oscillation Parameters Exclusion

- MiniBooNE **excludes** two neutrino appearance-only oscillations as the explanation of the LSND anomaly at **~98% CL**

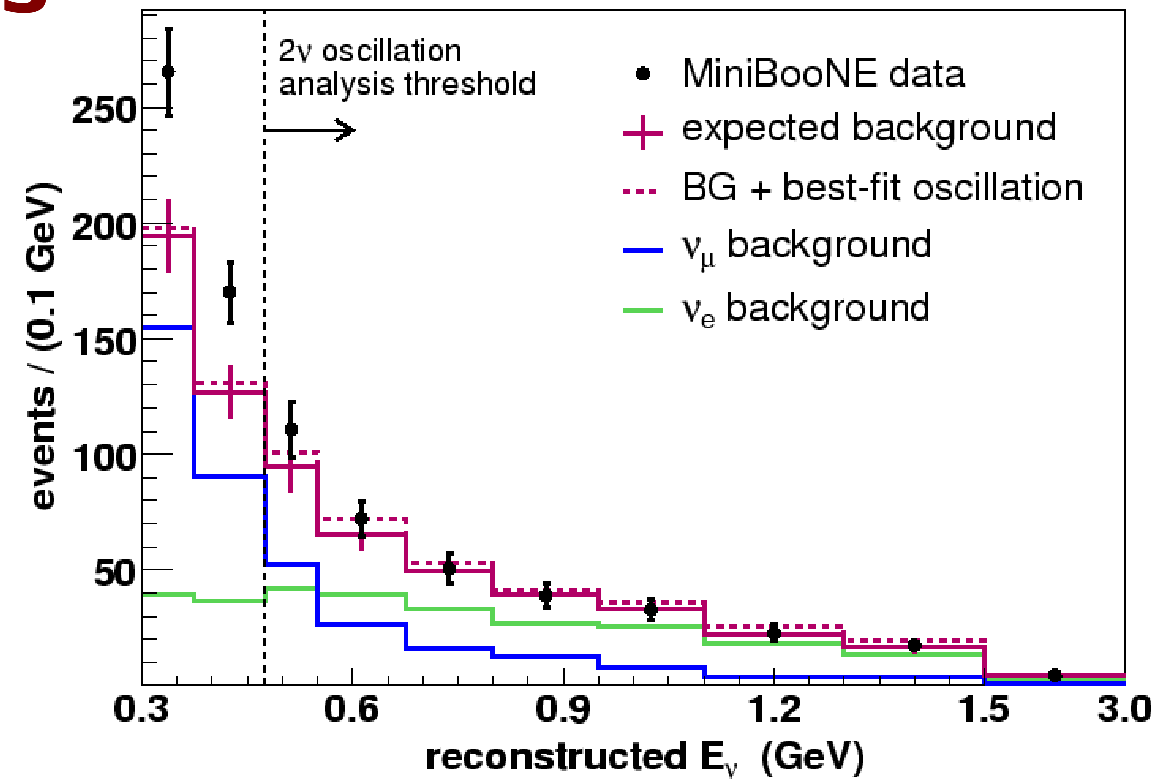
- Very similar oscillation fit result obtained with independent boosted decision tree (BDT) analysis

- Any interpetation of the LSND anomaly that would produce a significant excess for E_ν>475 MeV at MiniBooNE is also ruled out



Low-Energy Excess

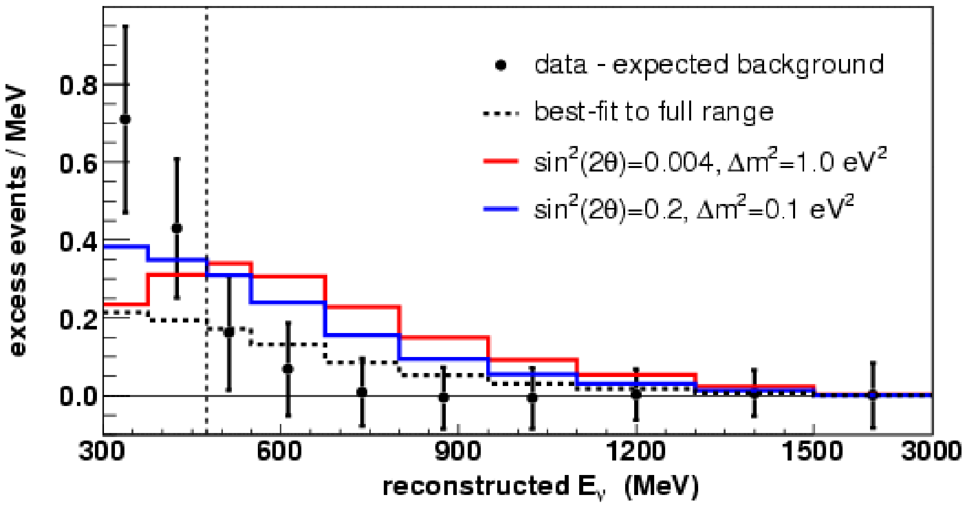
- Electron candidate events over the full (300 < E_ν < 3000 MeV) energy range



- The low-energy data does not match expectations:

3.7σ excess in (300 < E_ν < 475 MeV)

- This discrepancy is *not* understood



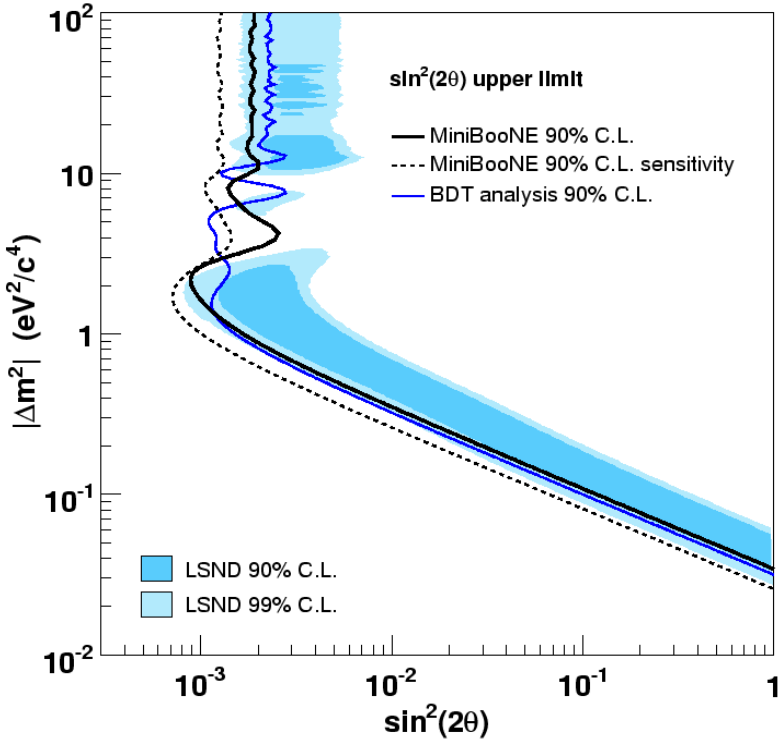
- Low-energy excess is *not* consistent with two neutrino appearance oscillations

- Fit to the (300 < E_ν < 3000 MeV) energy range gives a 18% χ^2 probability

- Need to do more analysis and gather more facts before making any conclusions

Conclusions

The LSND anomaly remains ... an anomaly:



- MiniBooNE finds excellent agreement between data and the no-oscillation prediction in the oscillation analysis region

- MiniBooNE excludes at ~98% confidence level the interpretation of the LSND anomaly put forward by the LSND collaboration to interpret its own result:

two neutrino, muon-to-electron neutrino appearance-only oscillations

MiniBooNE finds a discrepancy at energies below the oscillation analysis range:

- currently not understood and under investigation

MiniBooNE's Next Steps

- A paper on this oscillation analysis posted in the archives
- Papers to follow in the near future, supporting this oscillation analysis:
  - Measurement of ν_μ charged-current, quasi-elastic interactions
  - Measurement of neutral-current π^0 production
- Further oscillation analyses of neutrino data sample will follow:
  - combine merits of two present analyses
  - address more general models explaining the LSND anomaly
- Results from MiniBooNE's ongoing antineutrino running