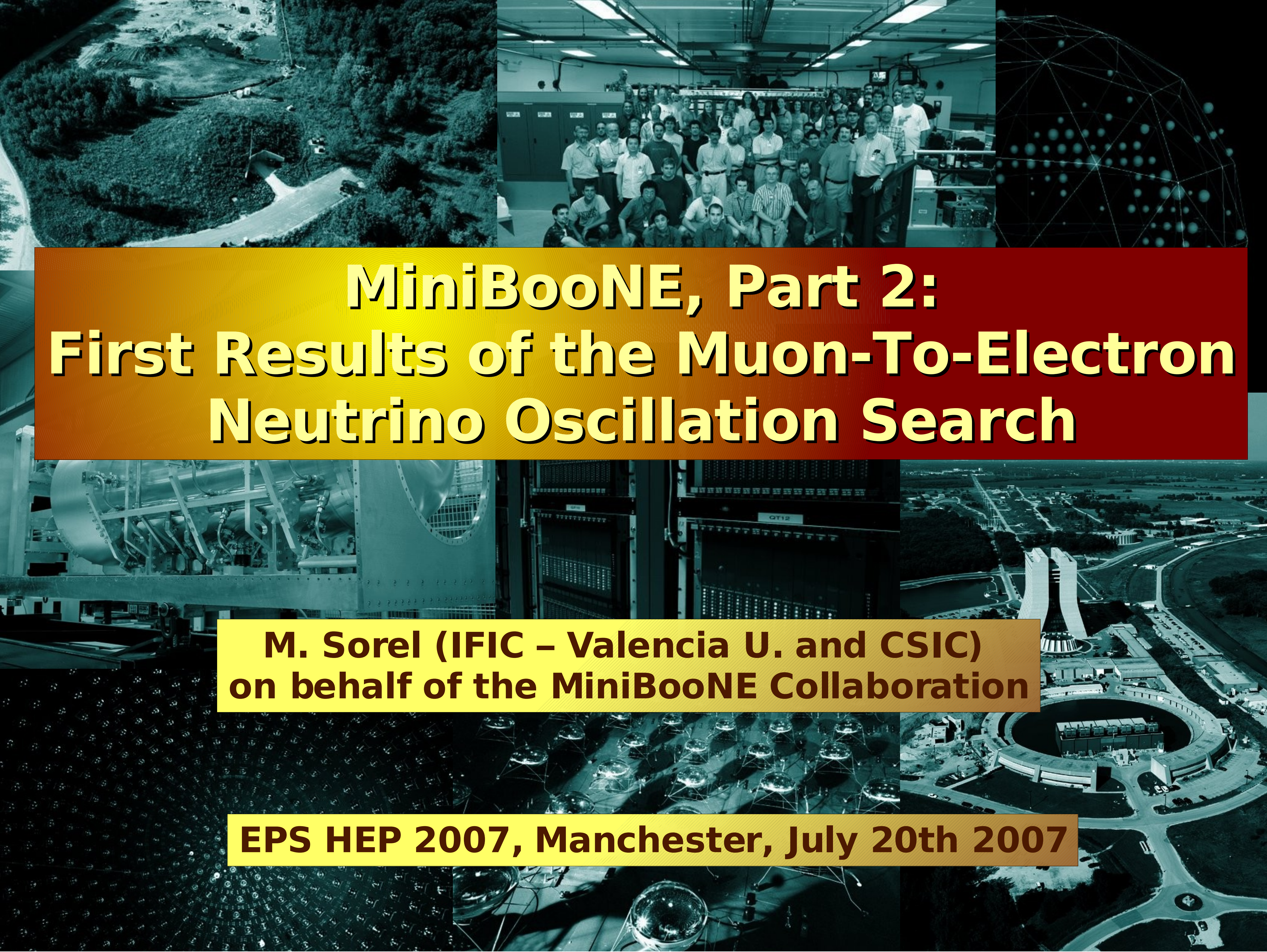


MiniBooNE, Part 2:
First Results of the Muon-To-Electron Neutrino Oscillation Search

M. Sorel (IFIC – Valencia U. and CSIC)
on behalf of the MiniBooNE Collaboration

EPS HEP 2007, Manchester, July 20th 2007

MiniBooNE Electron 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

- Energy range for expected oscillation signal events: $300 < E_\nu < 1500$ *MeV*

- Two largely independent analyses were performed, differing in reconstruction, particle identification, and oscillation fit procedure details:

  - Track-based (TB) analysis
  - Boosted decision tree (BDT) analysis

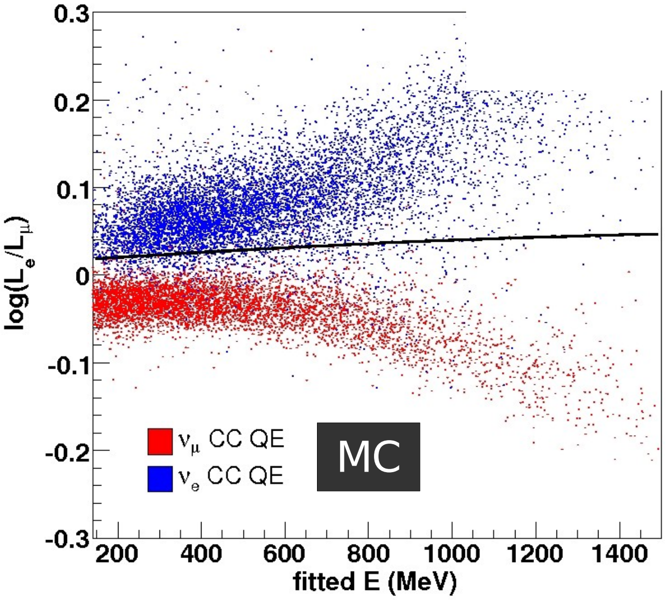
- Will mostly discuss TB, chosen as the primary analysis because of slightly better muon-to-electron neutrino appearance sensitivity

- This was a blind analysis. The closed box was opened on March 26, 2007. Results released to the public on April 11, 2007.

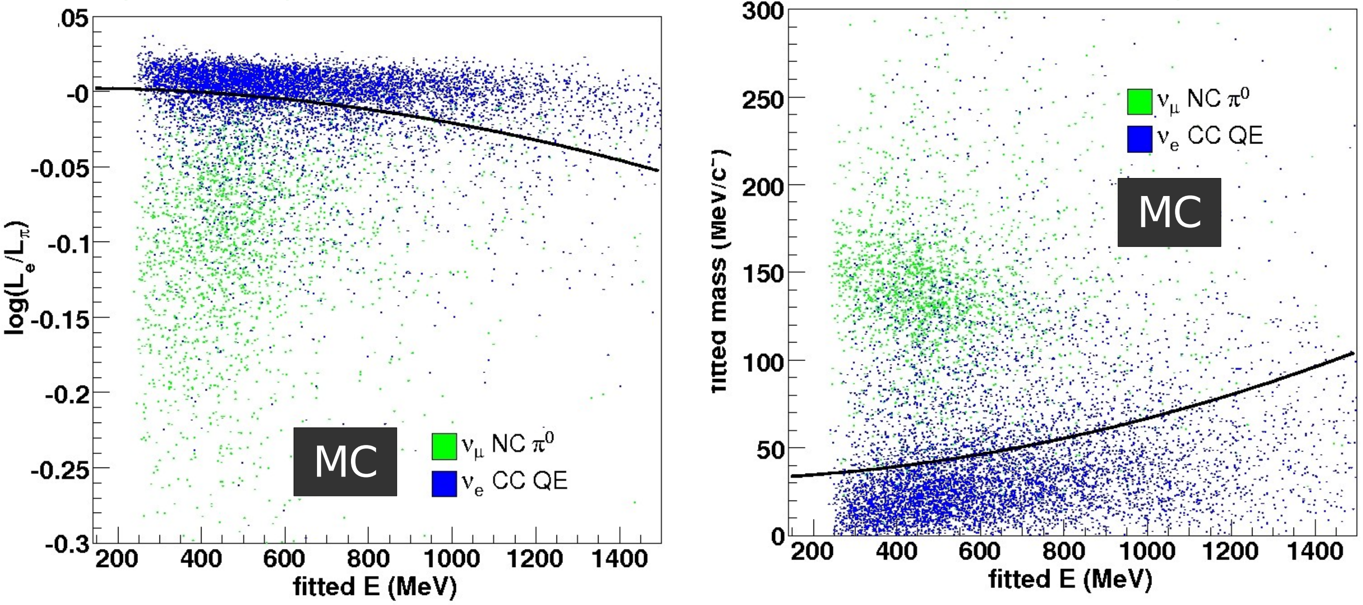
Selecting ν_e CCQE Candidate Events

- Goal: reject final state muons and π^0's, and enhance CCQE fraction in ν_e sample
- Each event reconstructed under four hypotheses, returning L_μ, L_e, L_π, $m_{\gamma\gamma}$:
  - *muon 1-ring*
  - *electron 1-ring*
  - *2-ring with fixed invariant mass $m_{\gamma\gamma} = m_\pi$*
  - *unconstrained 2-ring*
- Cut on likelihood fit ratios and 2-ring mass value
- Cut values chosen to optimize oscillation sensitivity

Rejecting muons:



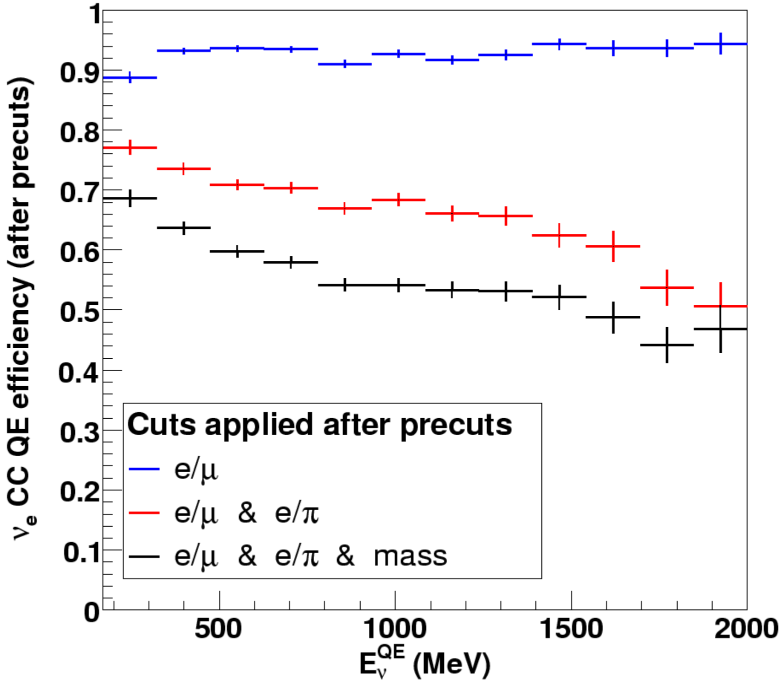
Rejecting NC π^0 events, main mis-ID background:

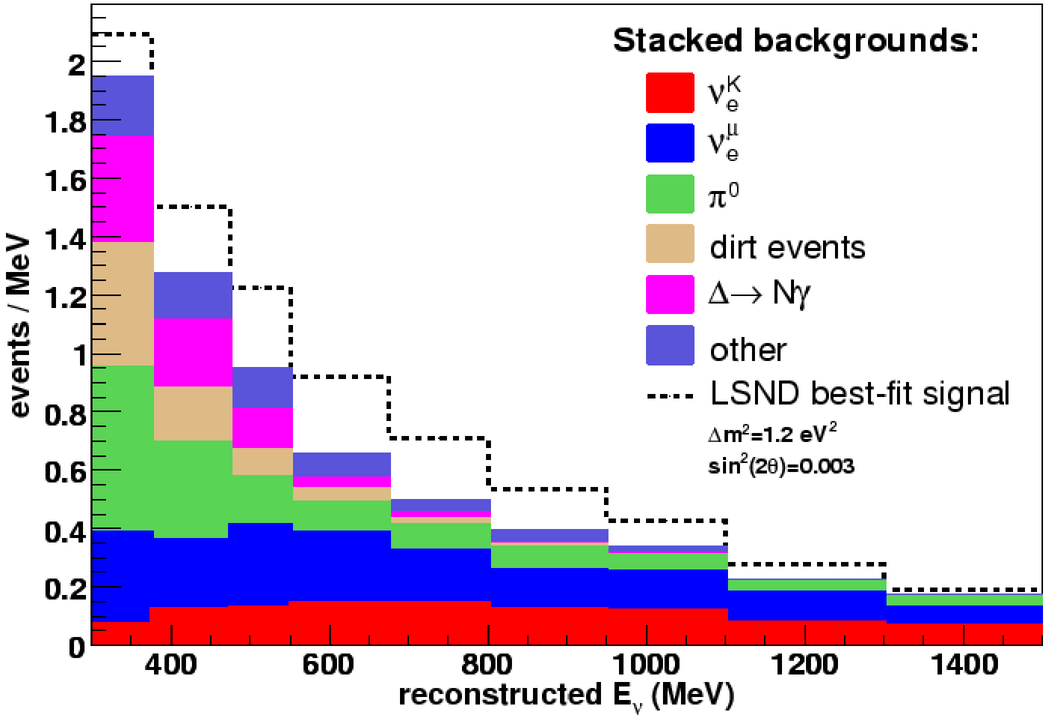


Signal Efficiency and Background Composition

- Signal efficiency:

Single subevent,hit-level,
fiducial volume, energy threshold cuts
+ $\mathrm{Log}(L_e/L_\mu)$
+ $\mathrm{Log}(L_e/L_\pi)$
+ invariant mass cuts





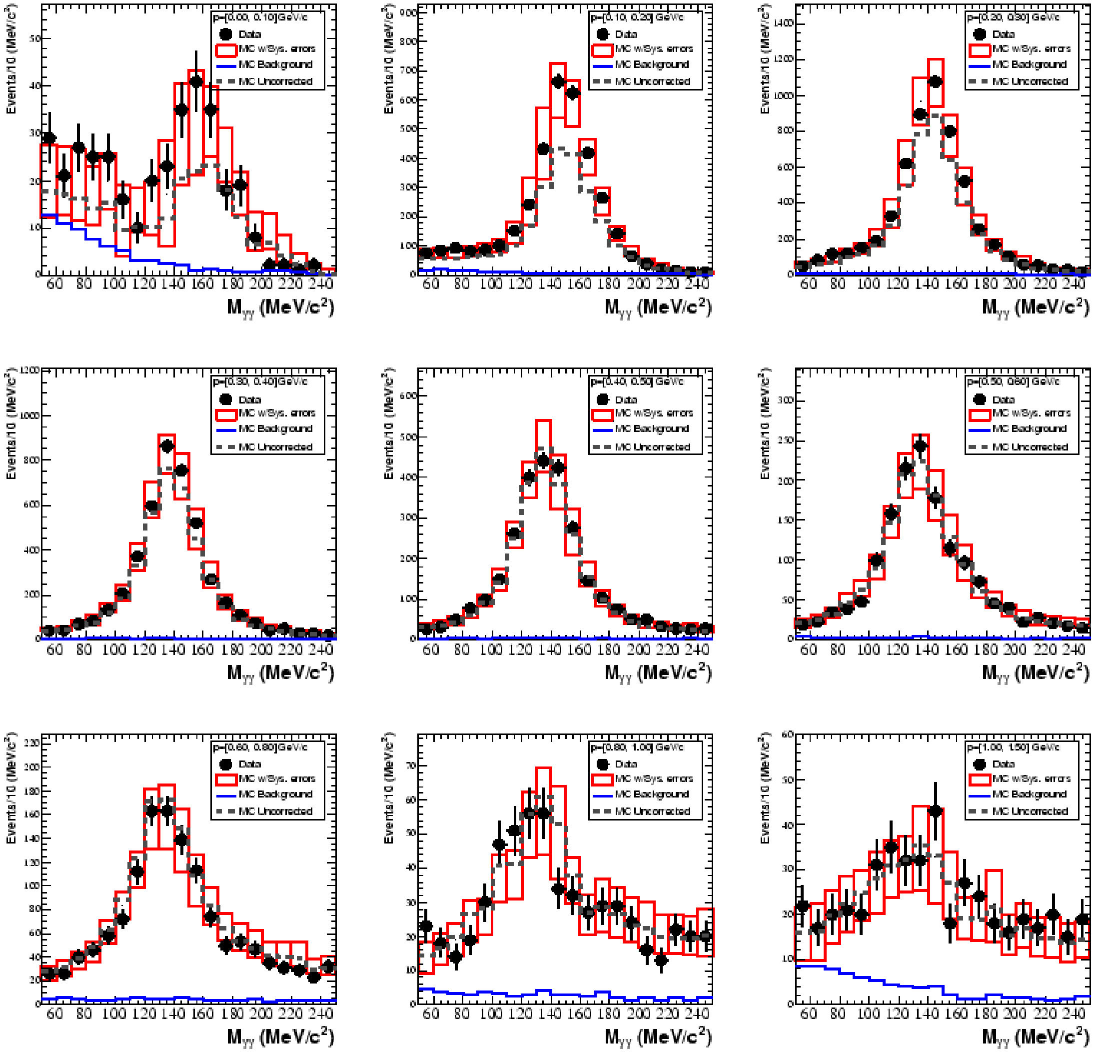
- All major backgrounds for the ν_e appearance search can be constrained / checked from MiniBooNE measurements

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

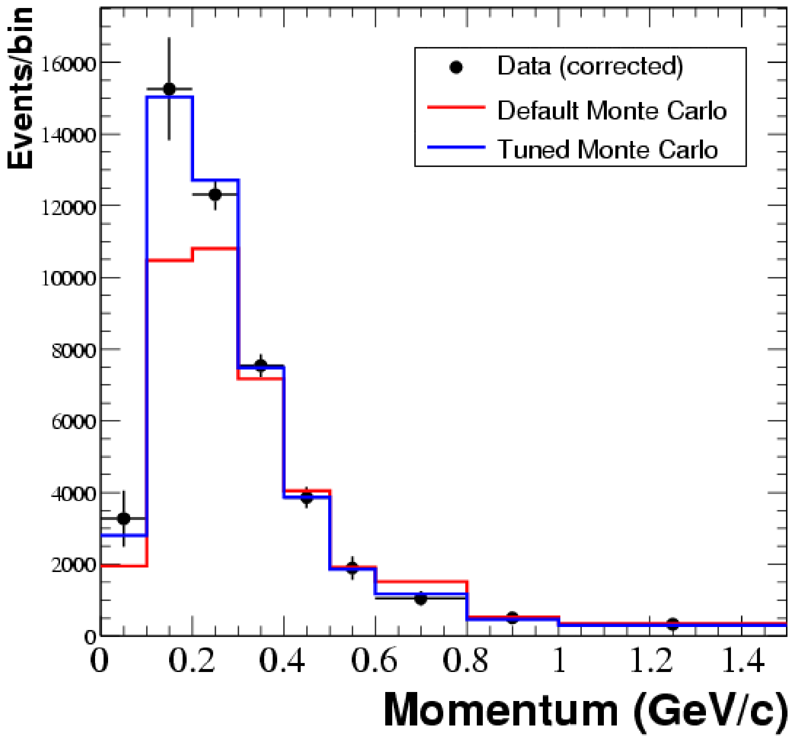
MiniBooNE Constraints on mis-ID Backgrounds

NC π^0 background where one photon is not seen:

1. Select >90% pure sample of NC π^0



2. Correct MC π^0 production versus π^0 momentum

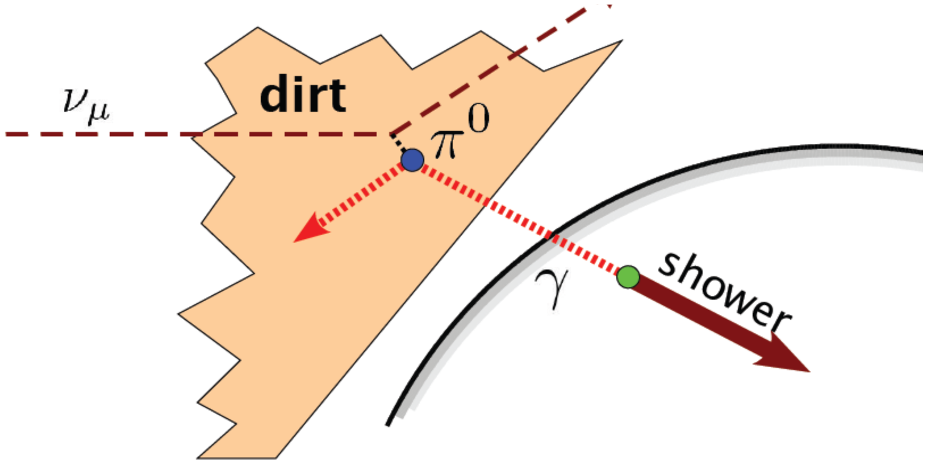


3. Correct MC π^0 mis-ID rate

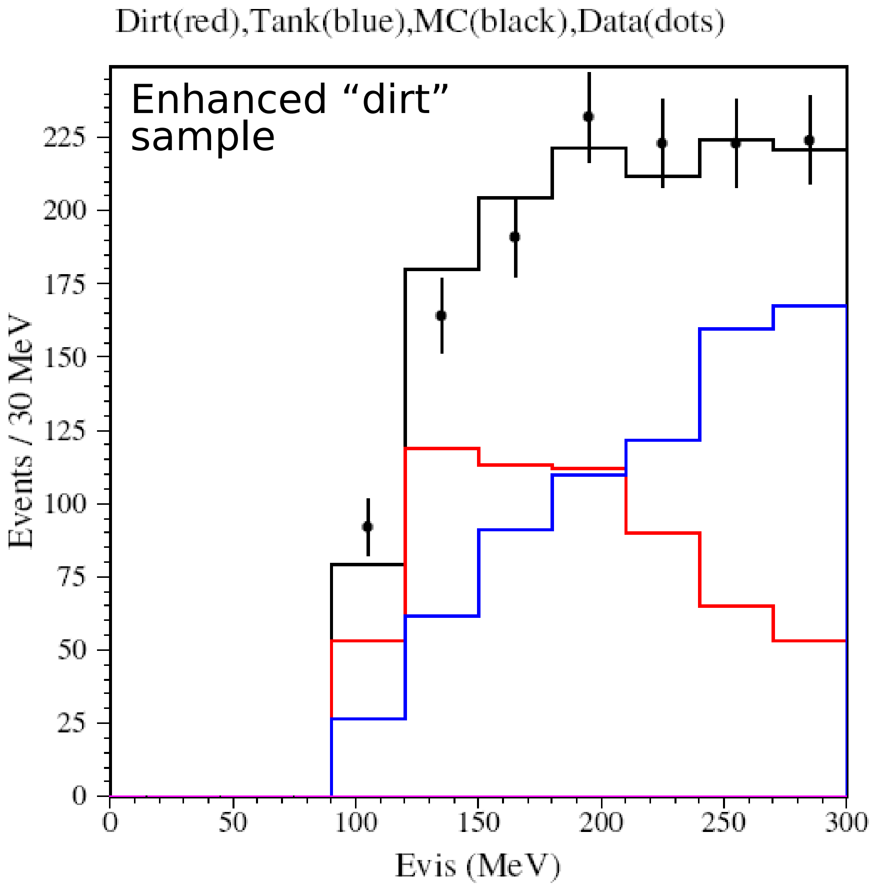
MiniBooNE Constraints on mis-ID Backgrounds

External backgrounds:

- Neutrino beam interacts with material outside detector
- Creates 100-300 MeV photons that come into the tank unvetoed
- Produces e-like events



- Measure rate with enhanced “dirt” “dirt” sample: high radius, inward-going events
- **Data/MC rate = 0.99 ± 0.15**

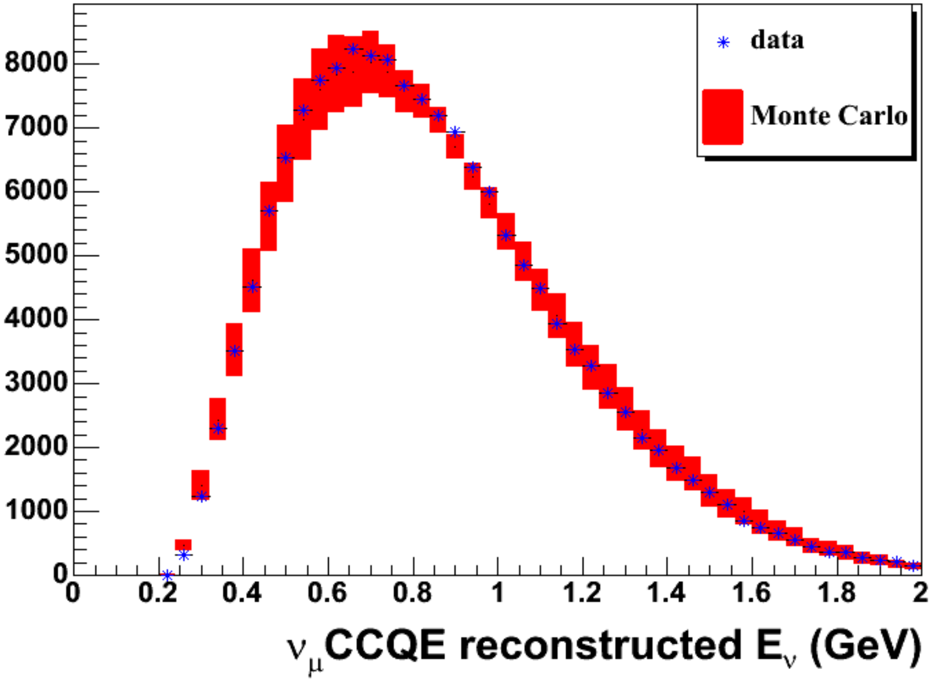


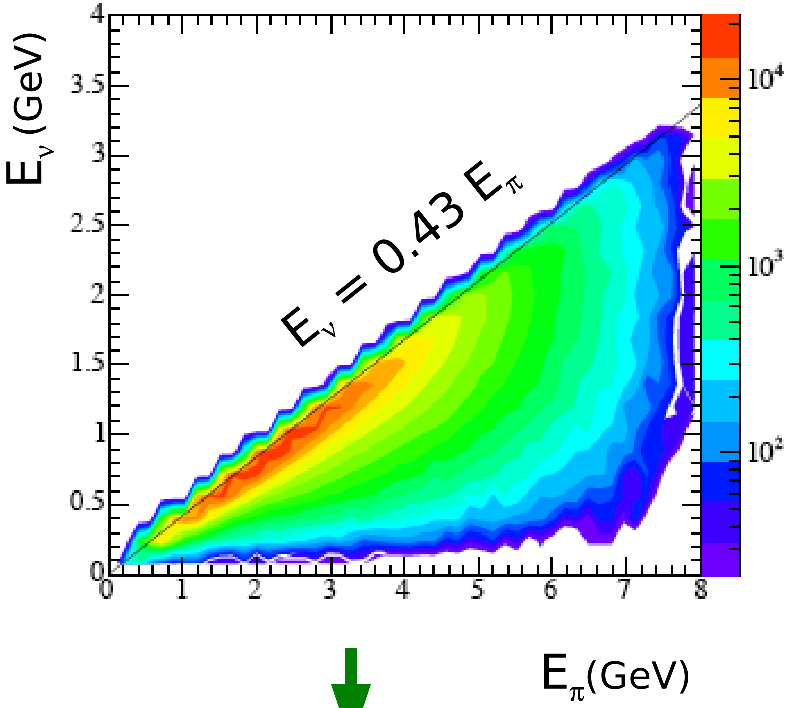
MiniBooNE Constraints on Intrinsic Backgrounds

Muon decay ν_e intrinsic background:

1. Measure ν_μ flux with ~80% pure ν_μ CCQE sample:

2. Kinematics allows to infer parent π^+ flux and momentum distribution from observed ν_μ events:





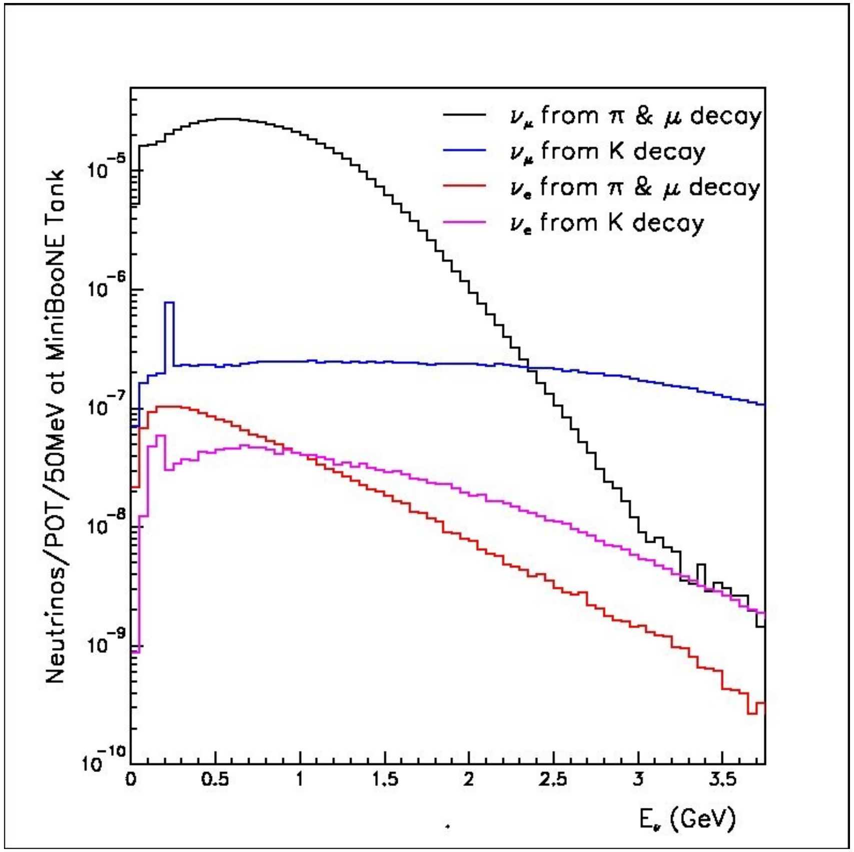
3. Once the pion flux is known, the $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ decay chain is well constrained

- Use same ν_μ CCQE sample to determine normalization of predicted signal

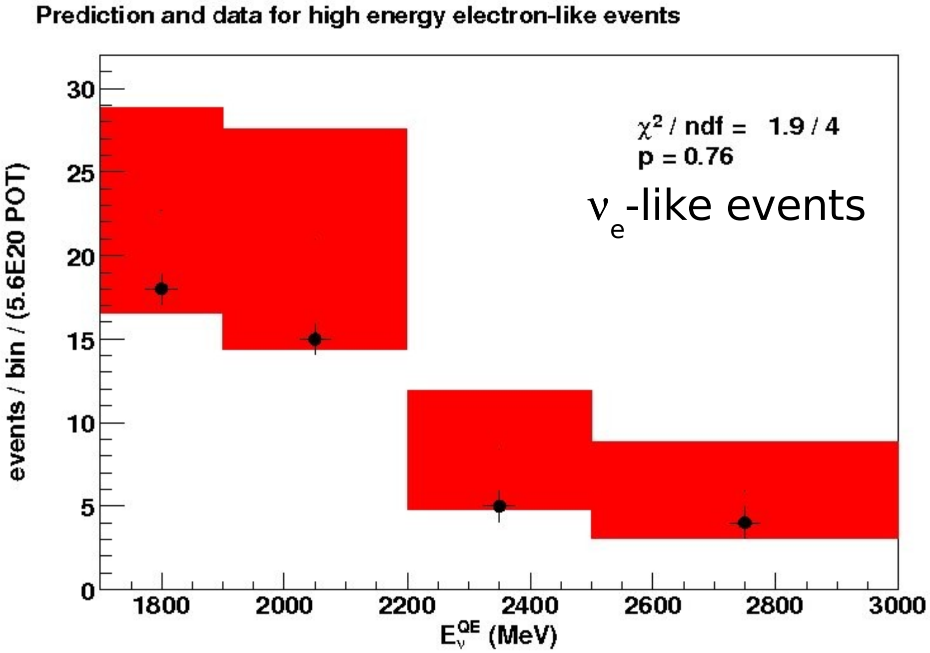
MiniBooNE Constraints on Intrinsic Backgrounds

Kaon decay ν_e intrinsic background:

- At high energies, both ν_μ and ν_e-like events are largely due to Kaon decay



- Measure Kaon-induced flux at high energies, where no oscillation events are expected



ν_e-like events

- Use MC to extrapolate to lower energies

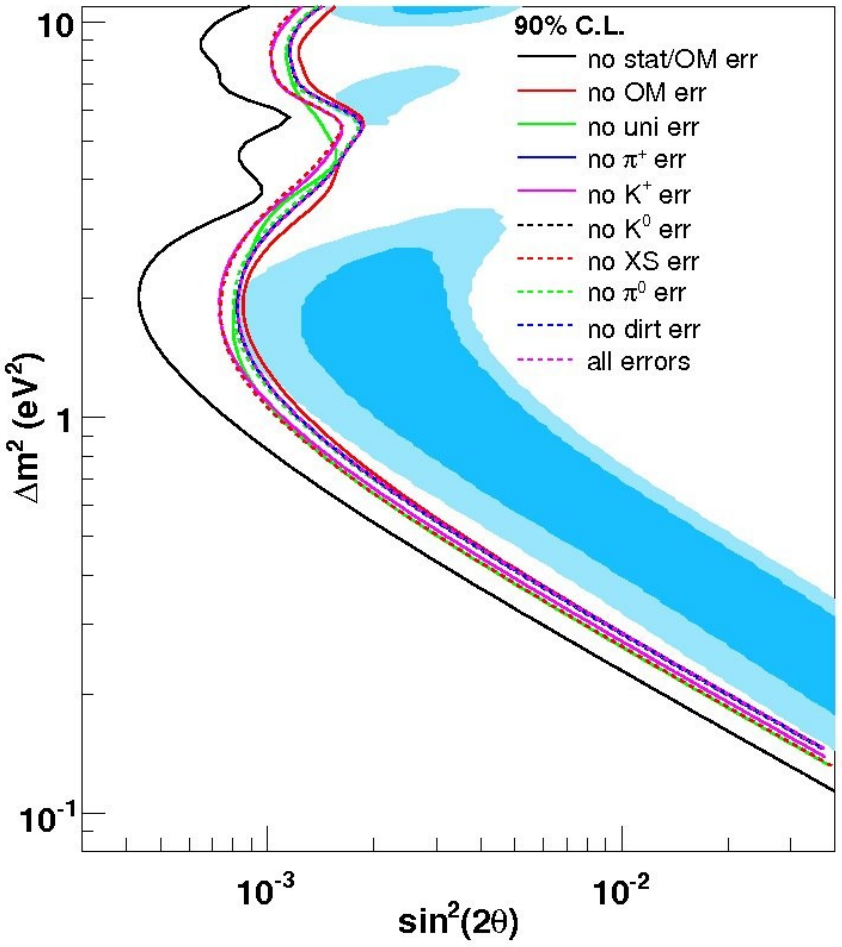
Systematic Uncertainties and Oscillation Sensitivity

- Systematic uncertainties in predicting electron candidate events come from the modeling of the beam, neutrino interactions, detector (see B. Roe's talk)

- 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 TB analysis:
  - Statistical uncertainty affects sensitivity most
  - Dominant systematics: neutrino cross-section (11 sources), K^+-induced neutrino flux, and final state interactions
  - Detector optical model (OM) systematic uncertainties: smaller impact

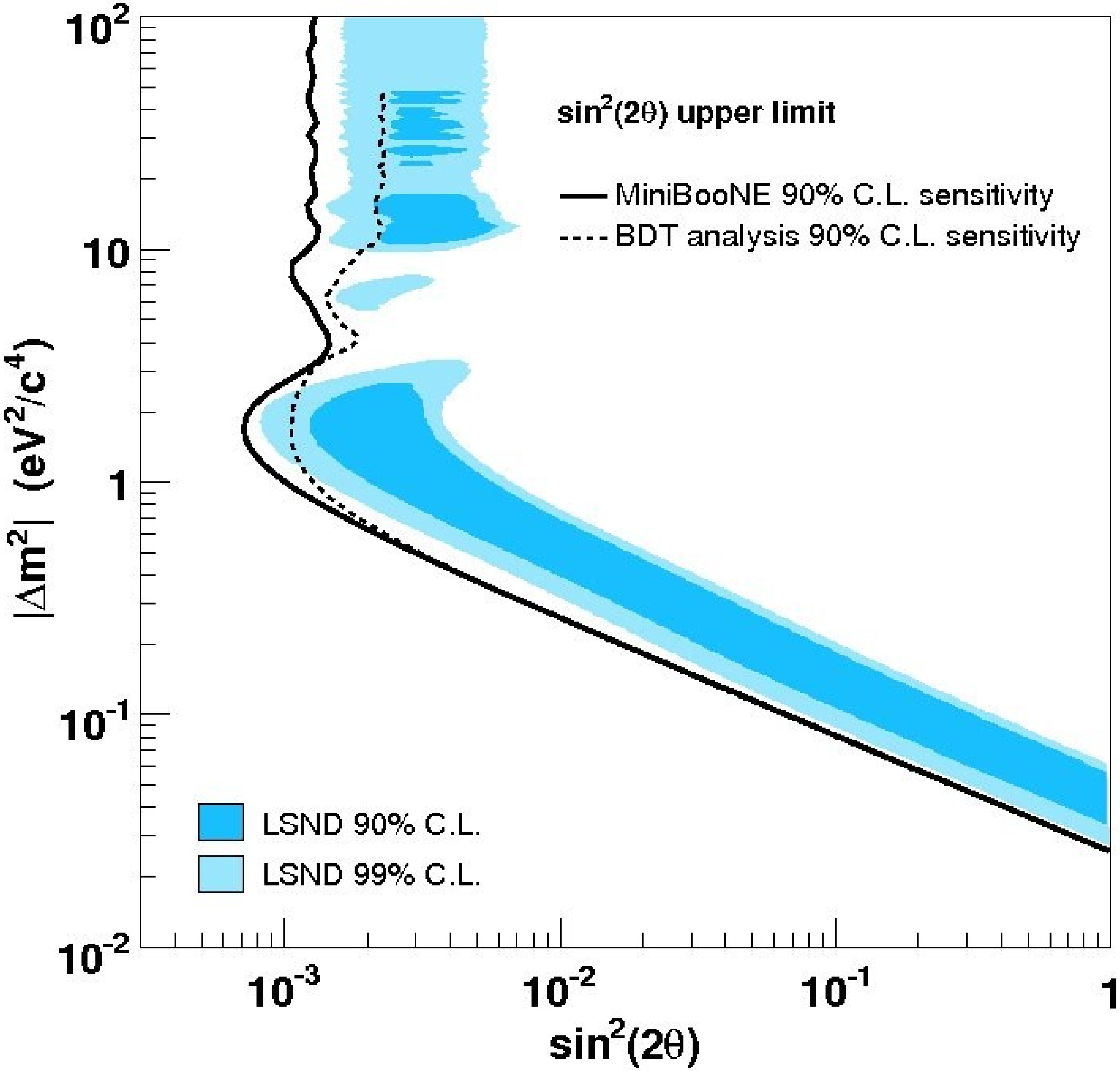


- Complementary (BDT) analysis affected by a different stat./syst. uncertainty mix

Neutrino Oscillation Sensitivity

- MiniBooNE has good sensitivity reach to test the oscillation parameter region allowed by LSND

- Two MiniBooNE analyses with comparable oscillation sensitivity

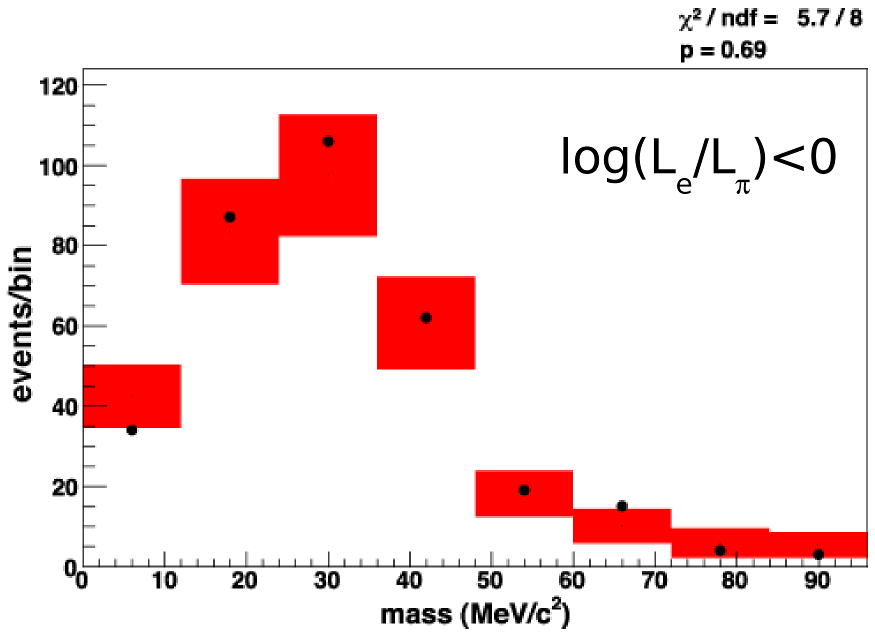


Cross-Checks

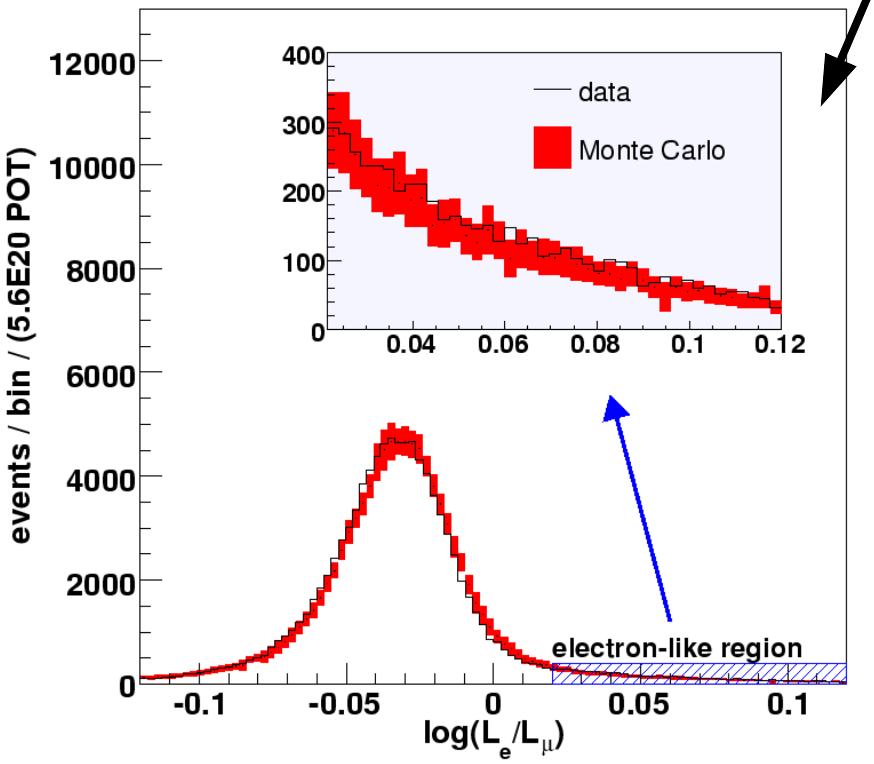
- Checked simulation, reconstruction, PID, uncertainty predictions on a variety of open data samples and distributions

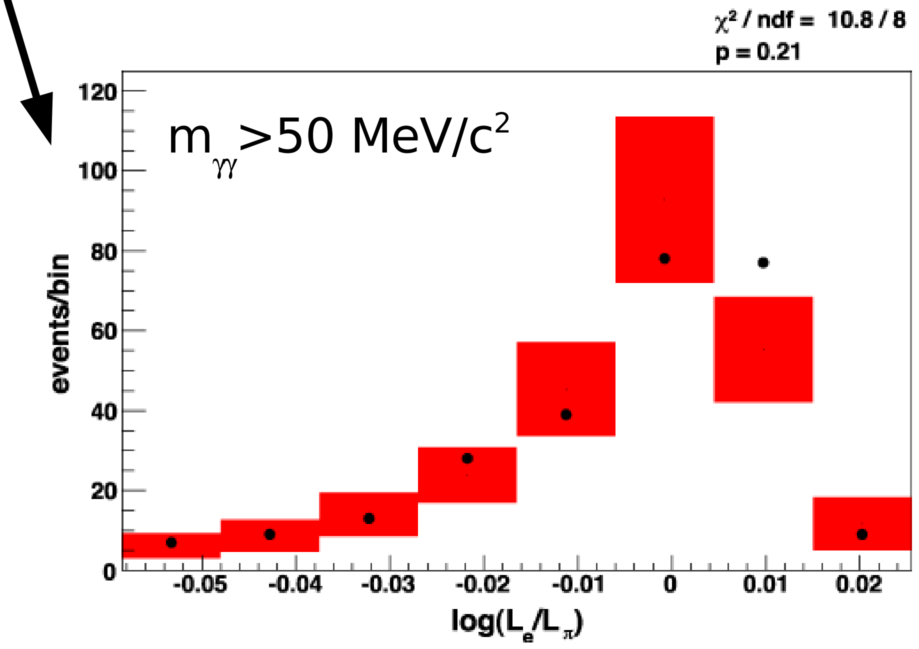
- Some examples for ν_e selection quantities

- Good agreement found everywhere
-> proceed to step-wise box opening



ν_μ **CC QE events**





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 were determined before full information on electron candidate events and oscillation fit results was disclosed

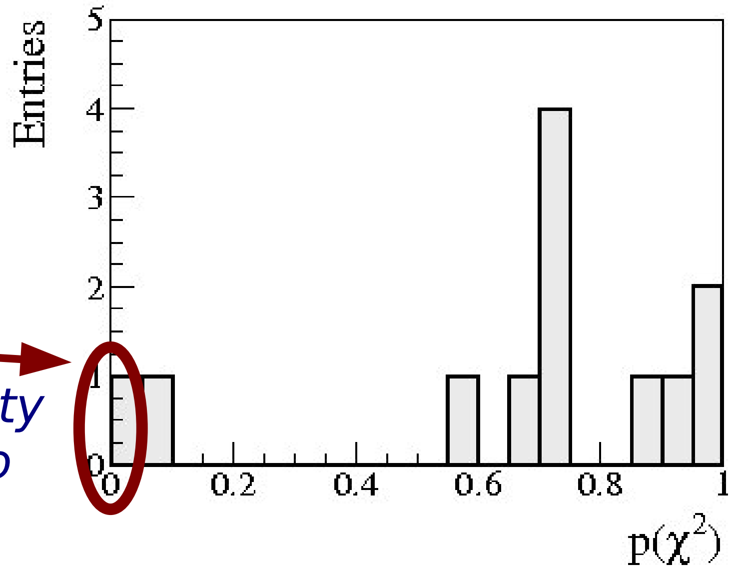
Box Opening Step 1: First Try

- 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 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

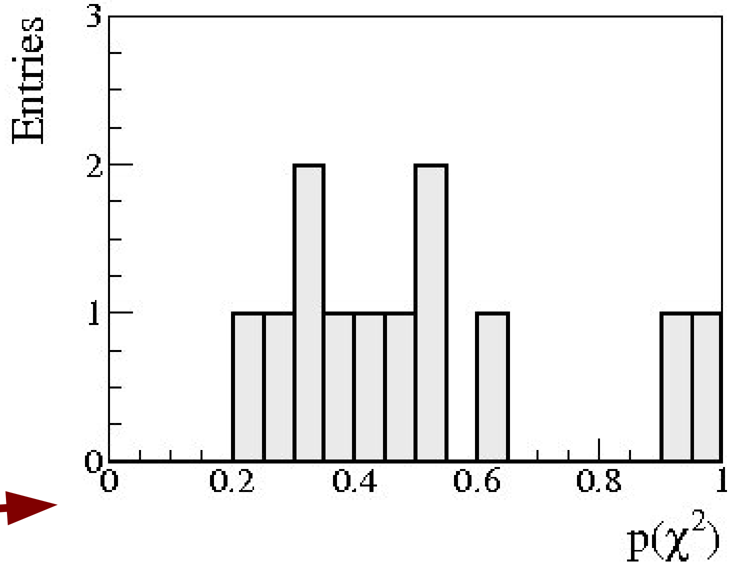
-> we decided to look for oscillations (and diagnostic χ^2) in the reduced (475 < E_ν < 3000 MeV) range, and report events over full (300 < E_ν < 3000 MeV) one

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

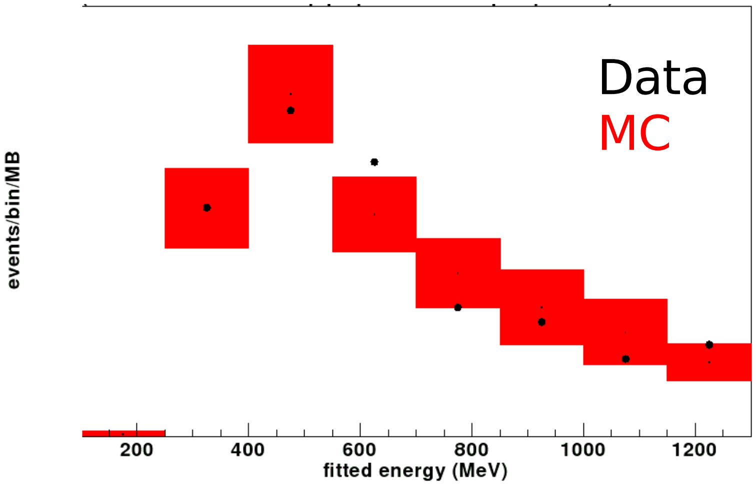
- **Step 1:** χ^2 probability for data/MC comparisons on 12 diagnostic variables:

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 that same day...*

The Box Opening

FNAL, March 26th, 2007

Oscillation Search Results

Counting experiment (475-1250 MeV):

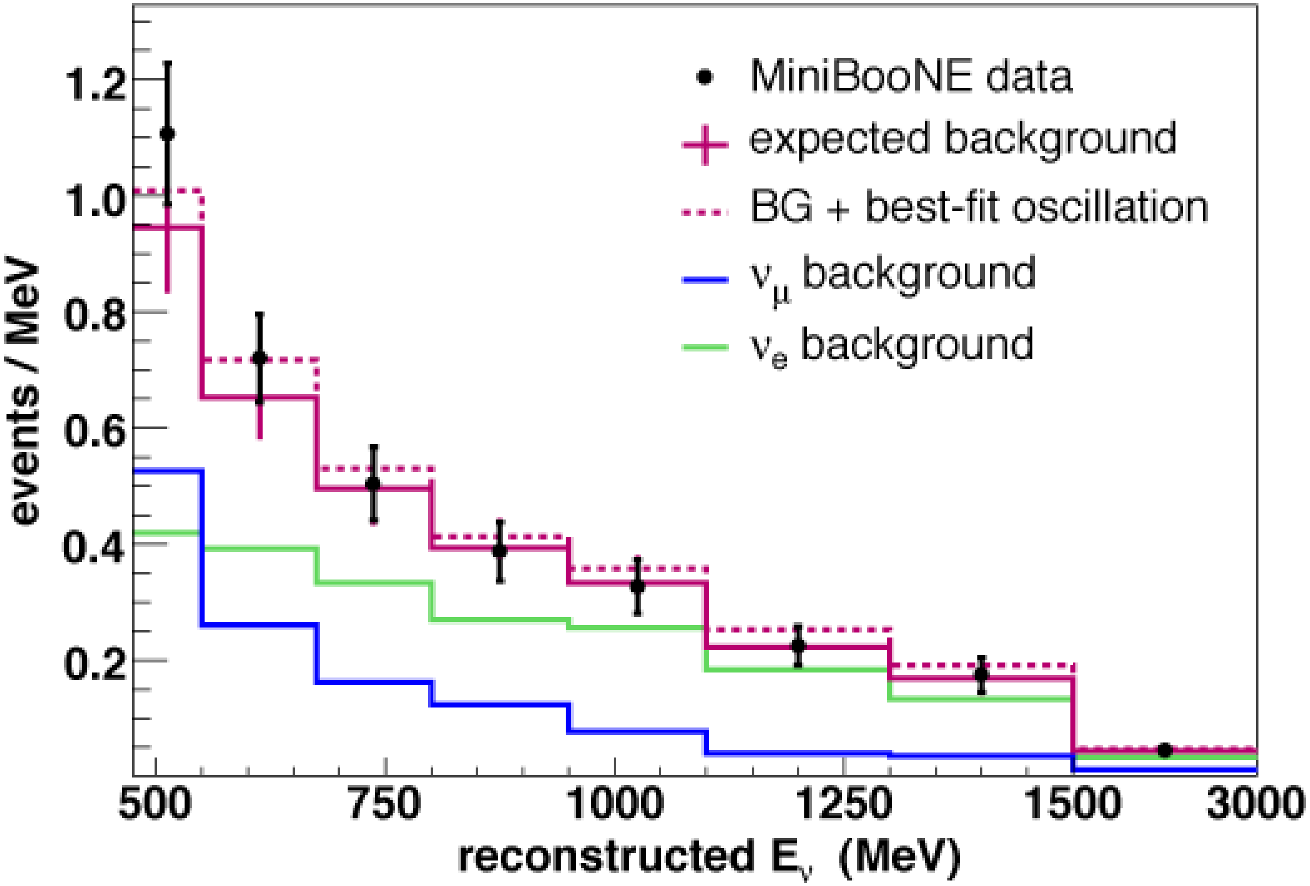
- Observe **380 events,** predict **358±19±35 events**
- **0.55 σ** excess over no-oscillations background

No evidence for oscillations

Energy Distribution and Oscillation Best-Fit (475-3000 MeV):

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

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

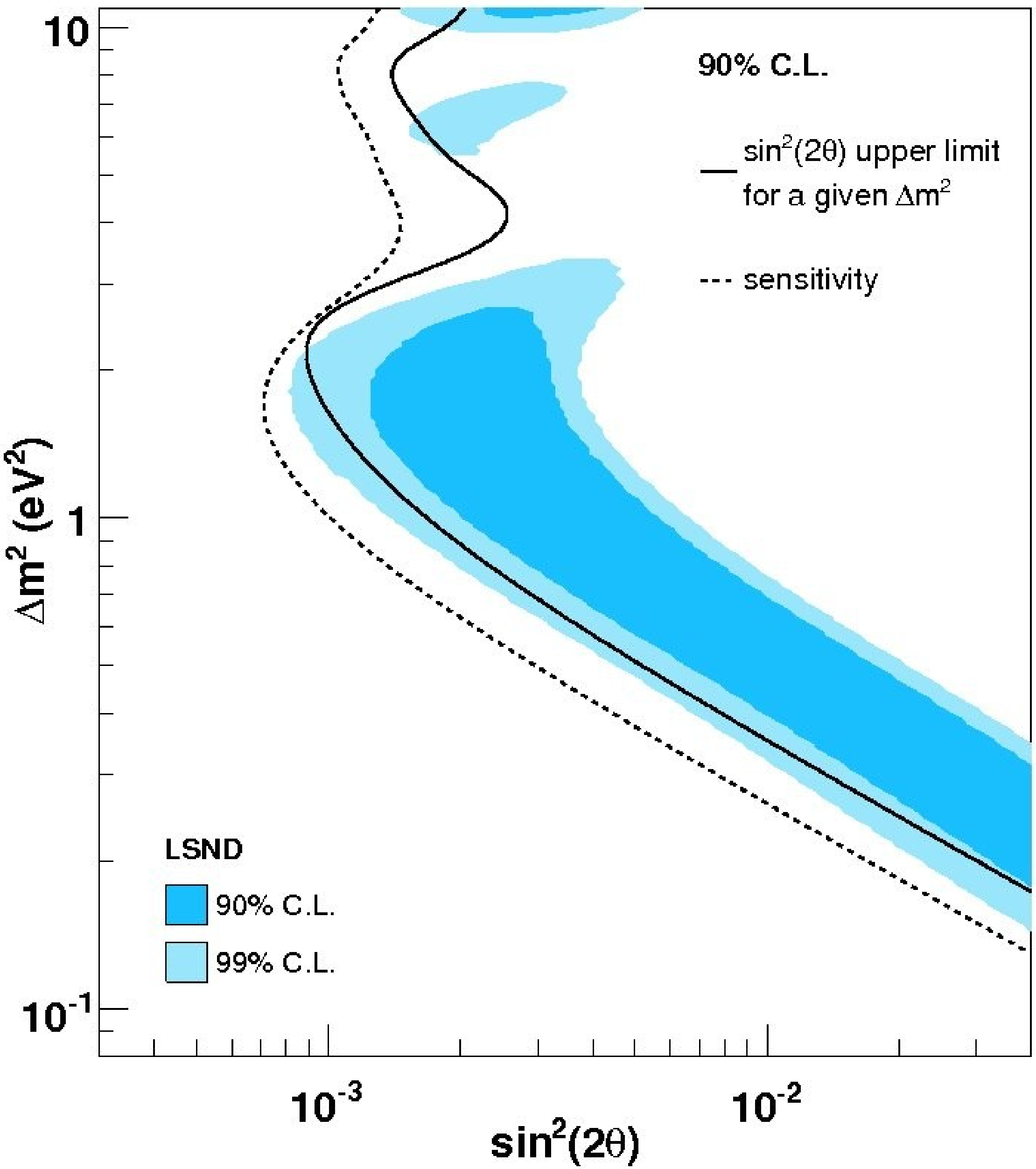


Oscillation Parameters Exclusion

- No overlap in 90% CL allowed LSND and MiniBooNE regions

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

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



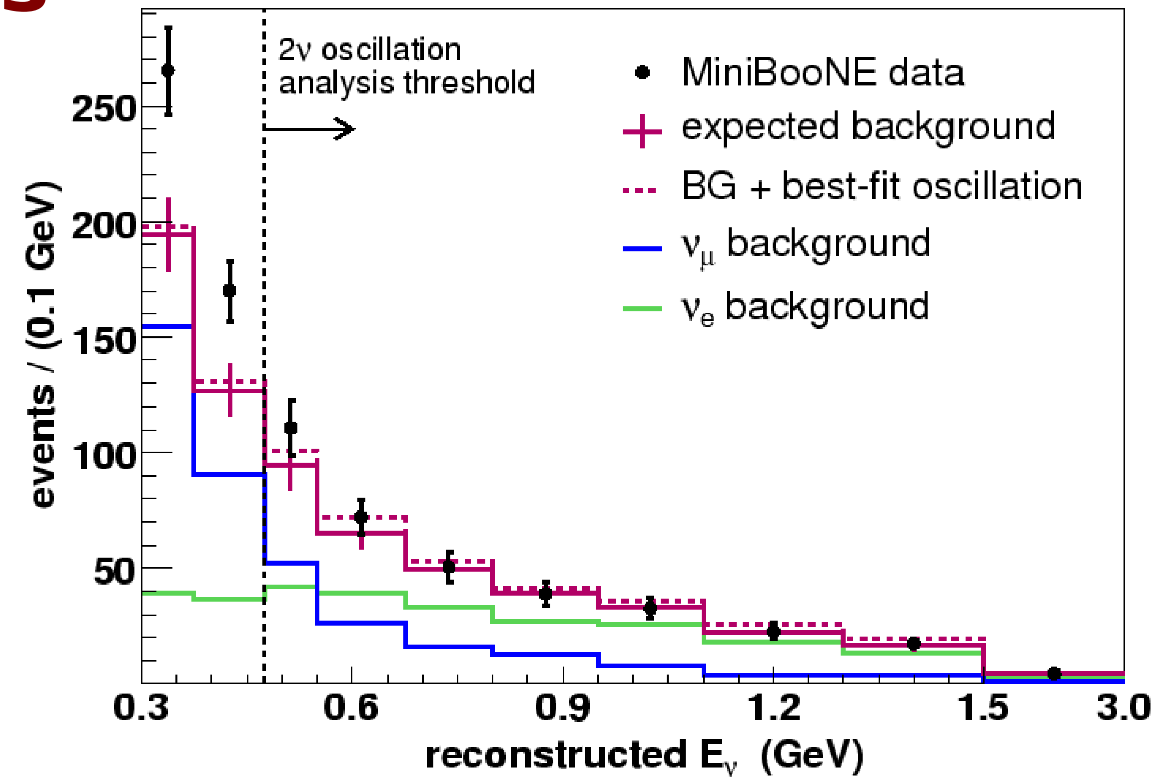
Low-Energy Excess

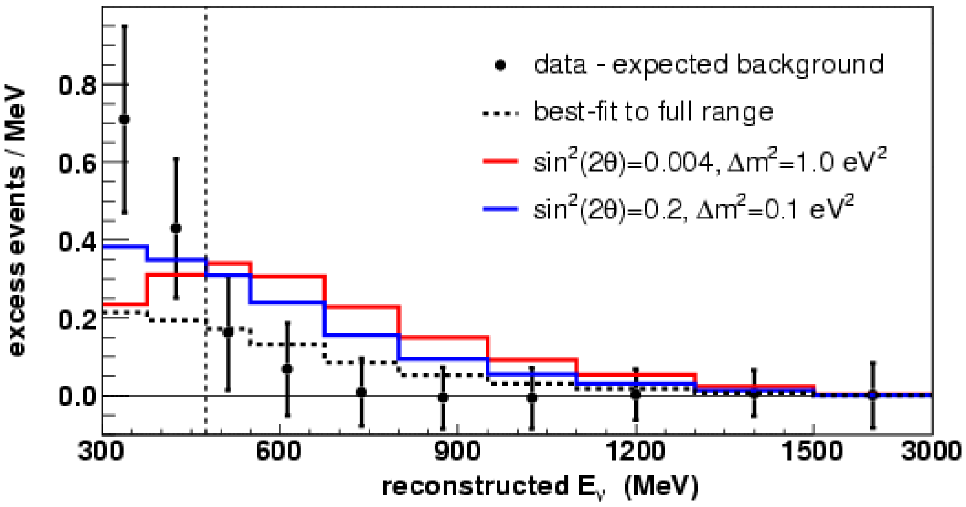
- Electron candidate events over the full ($300 < E_\nu < 3000$ MeV) energy range

- The low-energy data does not match expectations:

3.7σ excess in ($300 < E_\nu < 475$ MeV)

- This discrepancy is *not* understood





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

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

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

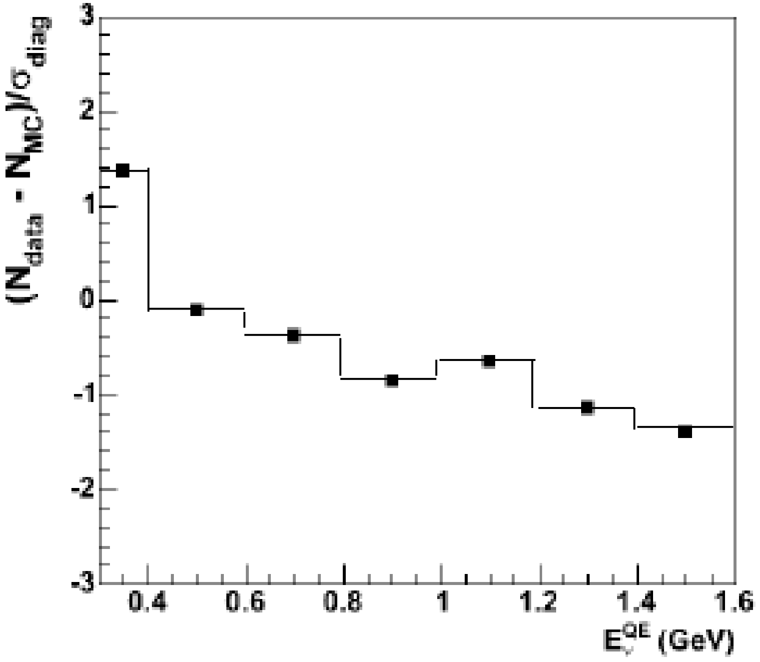
What about independent analysis (BDT)?

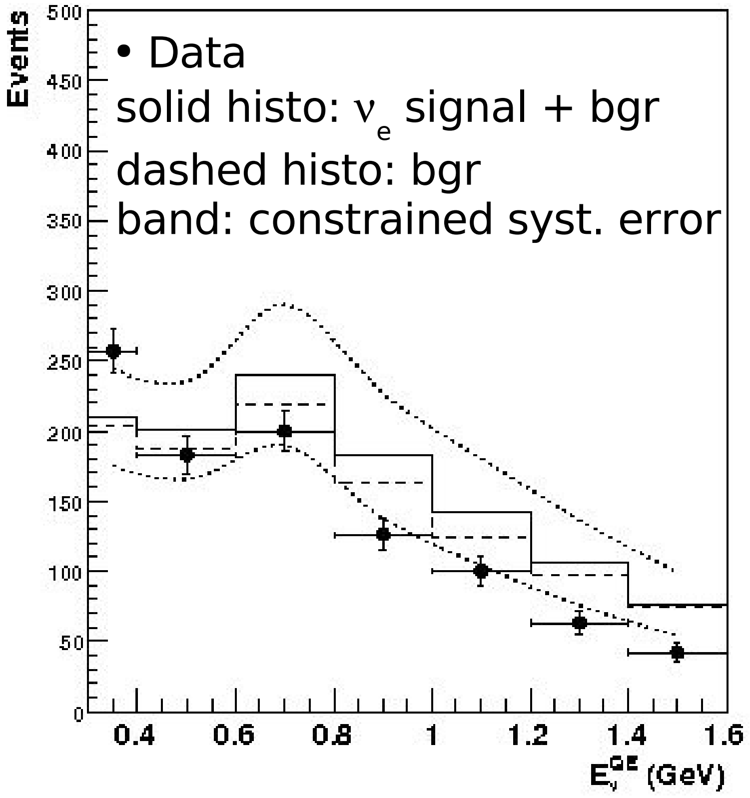
Oscillation Search Results (BDT)

Counting experiment (300-1600 MeV):

- Observe **971 events**
- Predict **1070±33±225 events**
- **-0.38 σ** excess over background

No evidence for oscillations





- Data

solid histo: ν_e signal + bgr

dashed histo: bgr

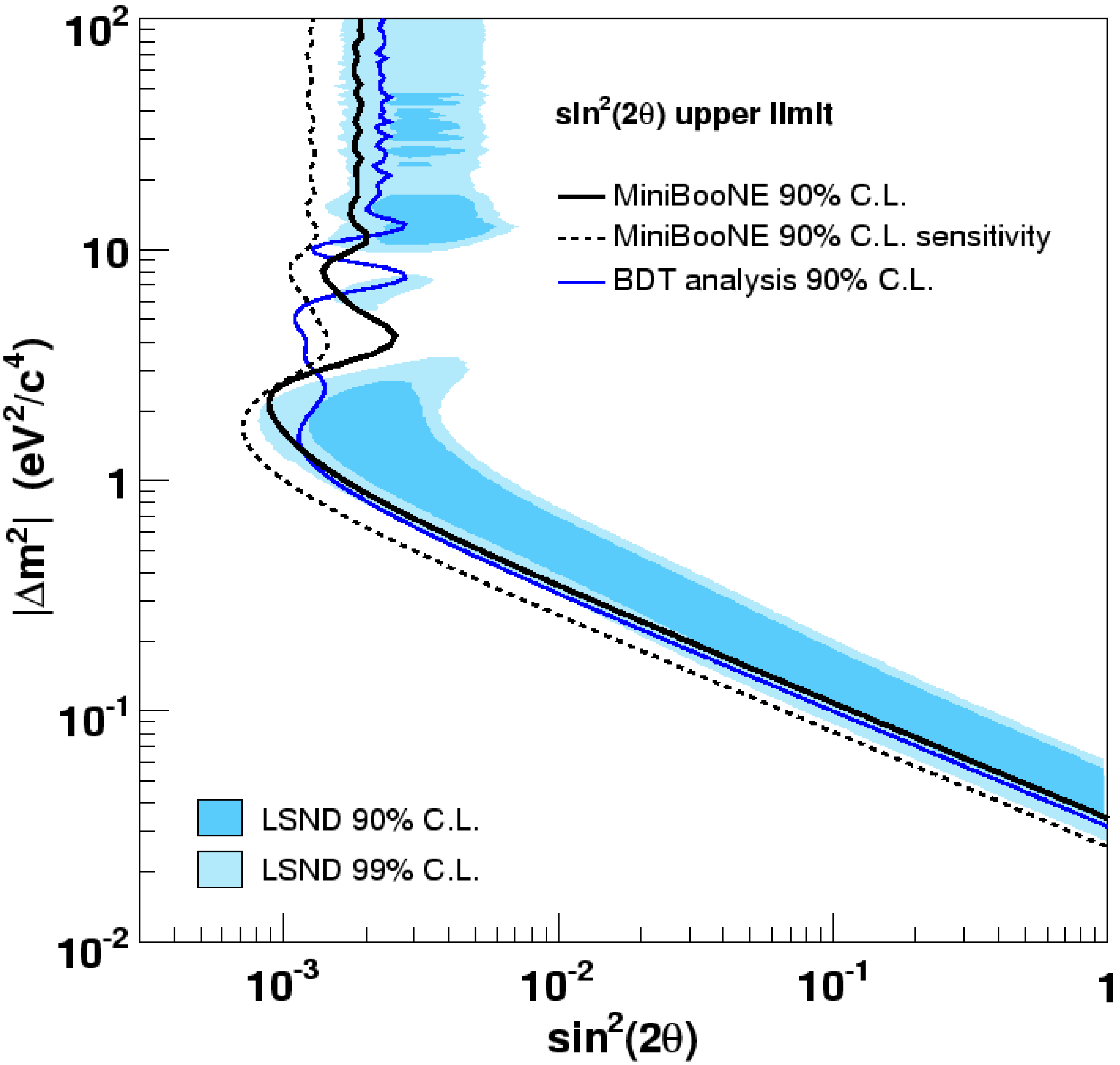
band: constrained syst. error

Energy-dependent Oscillation Best-Fit (200-3000 MeV ν_e-like and ν_μ):

- $\sin^2 2\theta = 1.2\times10^{-3}$
- $\Delta m^2 = 7.5\ \mathrm{eV}^2/c^4$
- $\chi^2_{null} - \chi^2_{best} = 0.71$

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

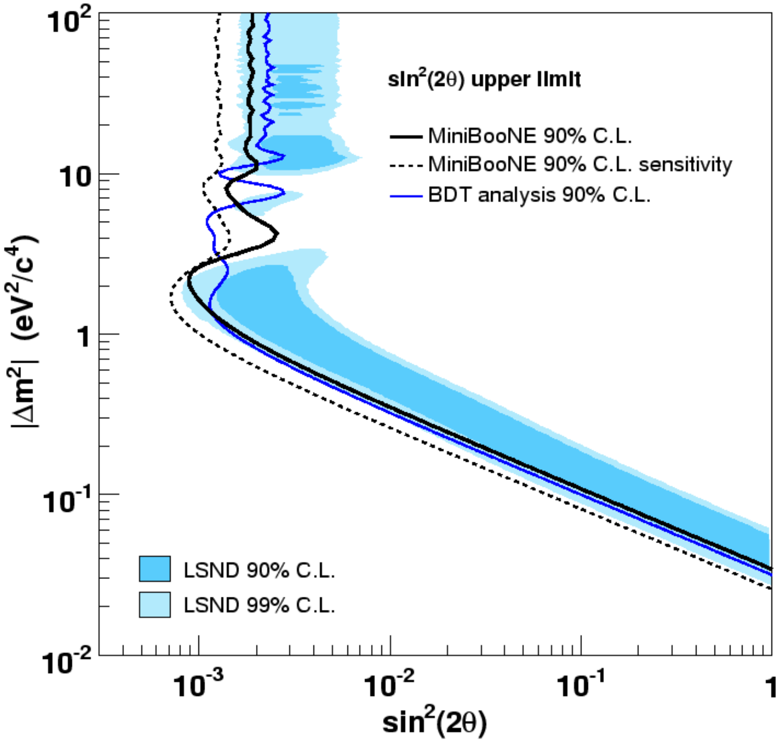
Oscillation Parameters Exclusion (BDT)



- *Very similar oscillation fit results obtained with two analyses*

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 oscillation analysis range:*
  - currently not understood and under investigation

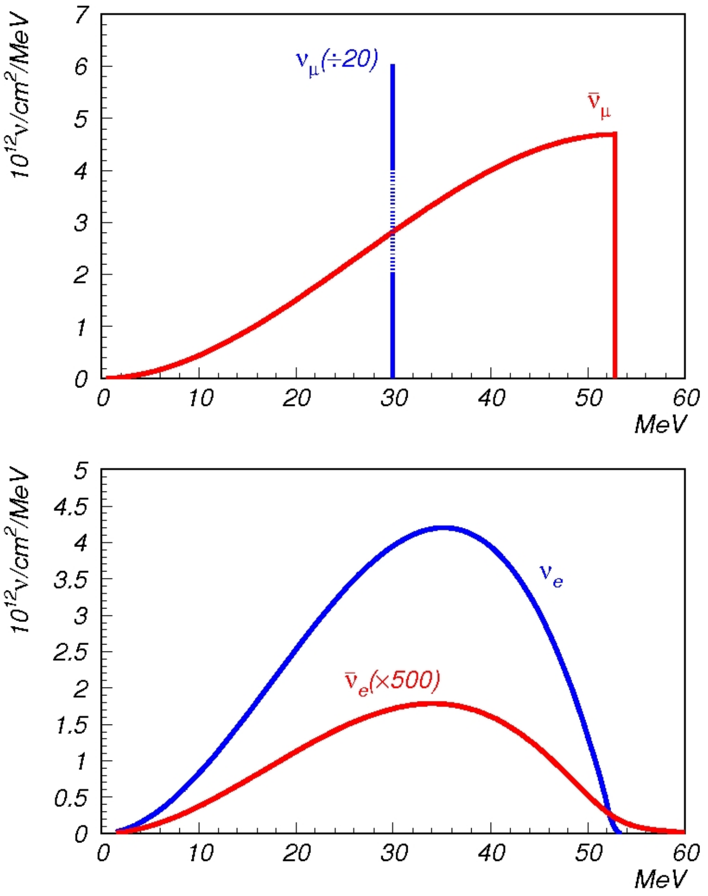
- *More sensitive/generic analyses of electron candidate events being developed, results from antineutrino data sample will follow after that*

Backups

The LSND Experiment

- *The neutrino source:*

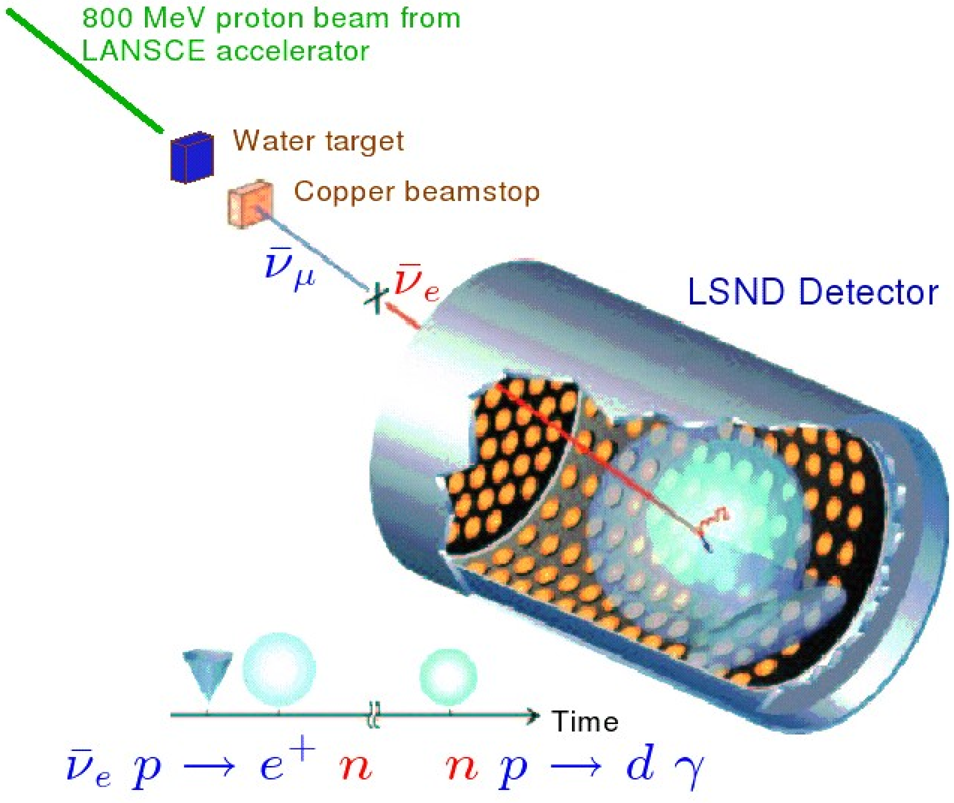
- $\bar{\nu}_\mu$ from: $\pi^+ \rightarrow \mu^+ \nu_\mu,\ \ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
- $E_\nu = 20-53$ MeV, $L_\nu = 25-35$ m
- Almost no $\bar{\nu}_e$ at source



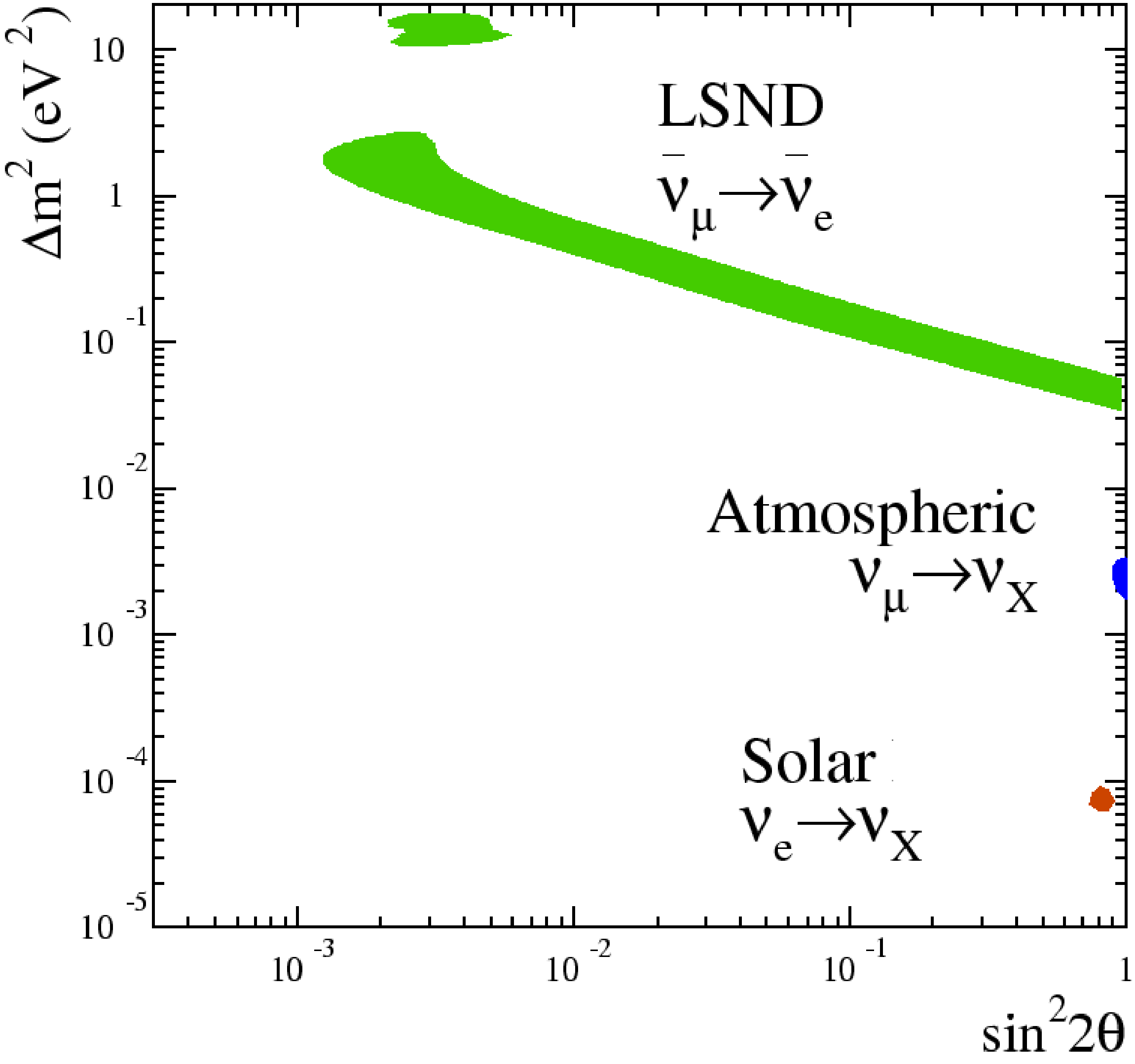
- *The neutrino detector:*

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

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



The LSND Oscillation Result



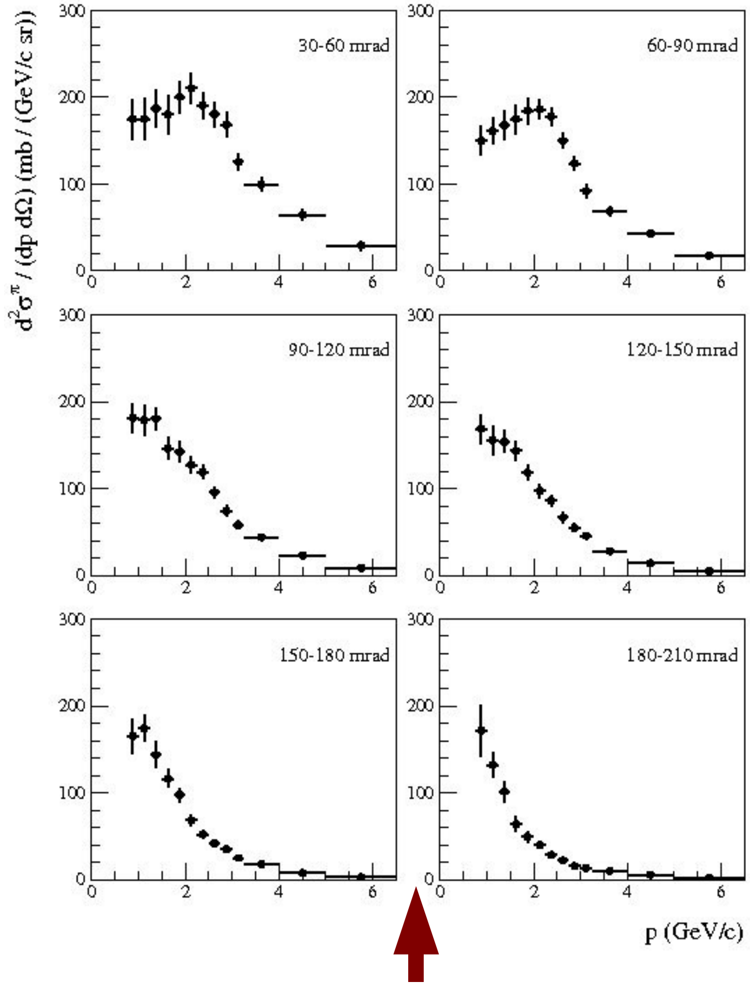
$\bar{\nu}_e$ candidate excess:
$(87.9 \pm 22.4 \pm 6.0) \rightarrow 3.8\sigma$

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

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

Modeling Neutrino Fluxes

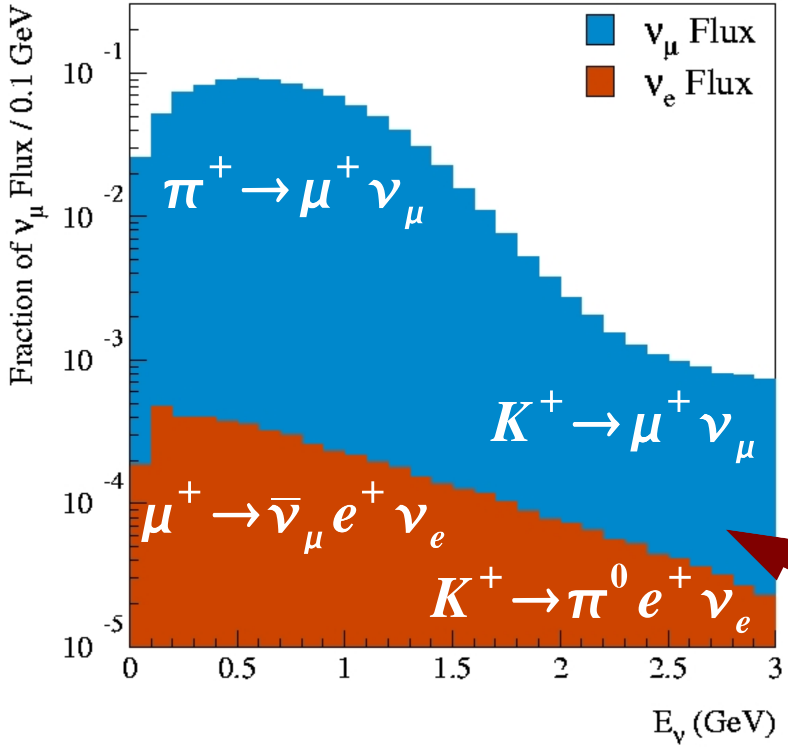


GEANT4 beamline description, simulating:

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

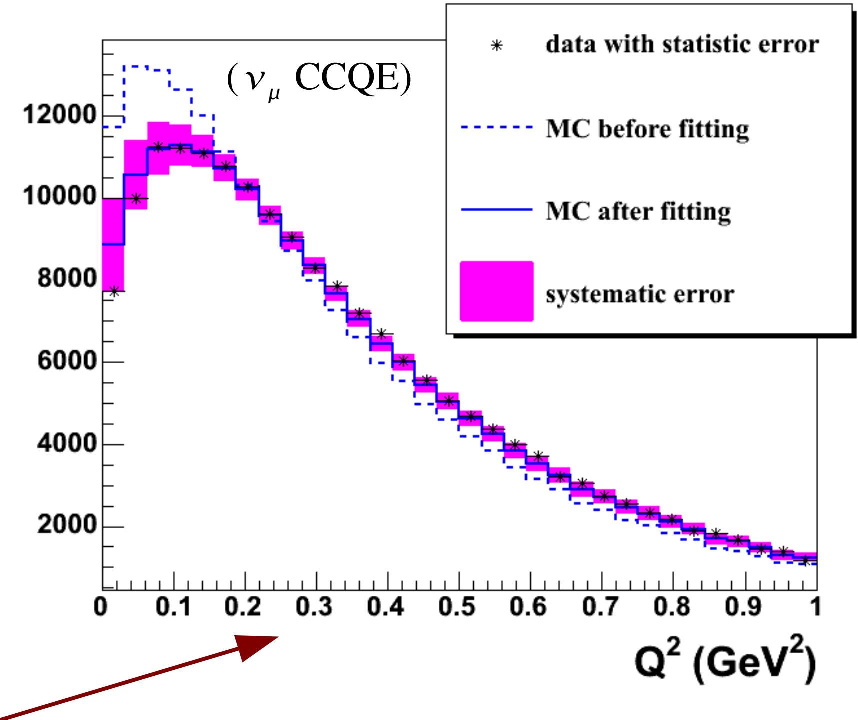
- Pion/kaon production data on beryllium is the most important external physics input to the simulation *-> parametrized according to relevant hadron production data sets*

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



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

Modeling Neutrino Interactions

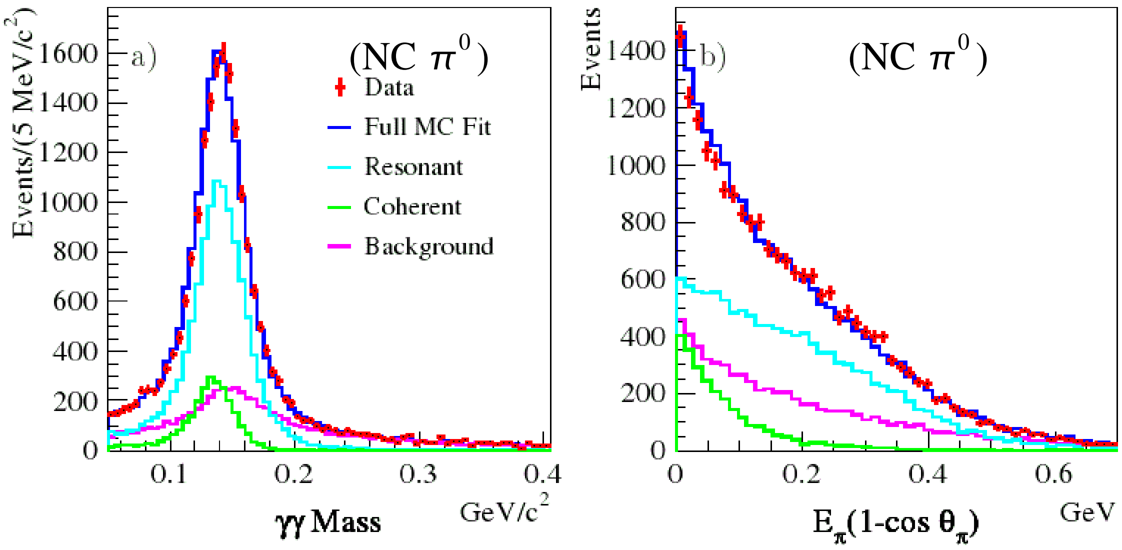


- **NUANCEv3 cross-section generator**

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

- **NUANCE inputs:**
  - Free nucleon cross-sections from neutrino data
  - Nuclear model from electron data
  - Final state interactions from π/p scattering data

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

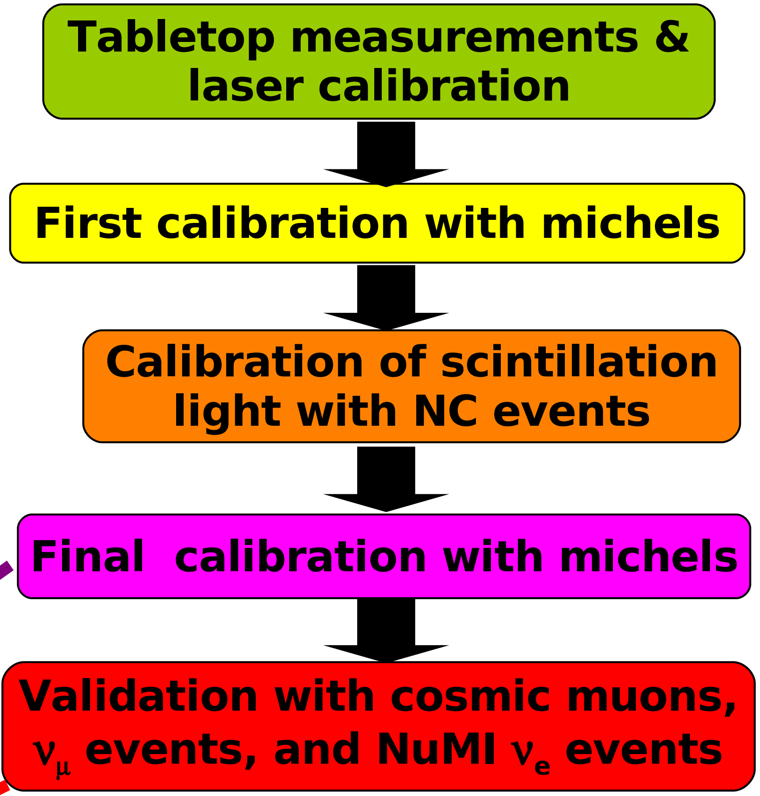


Modeling Detector Response

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



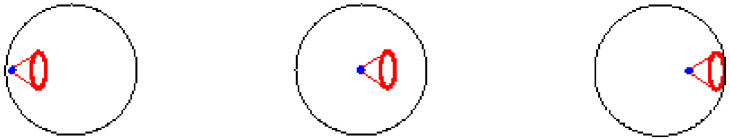
Tabletop measurements & laser calibration

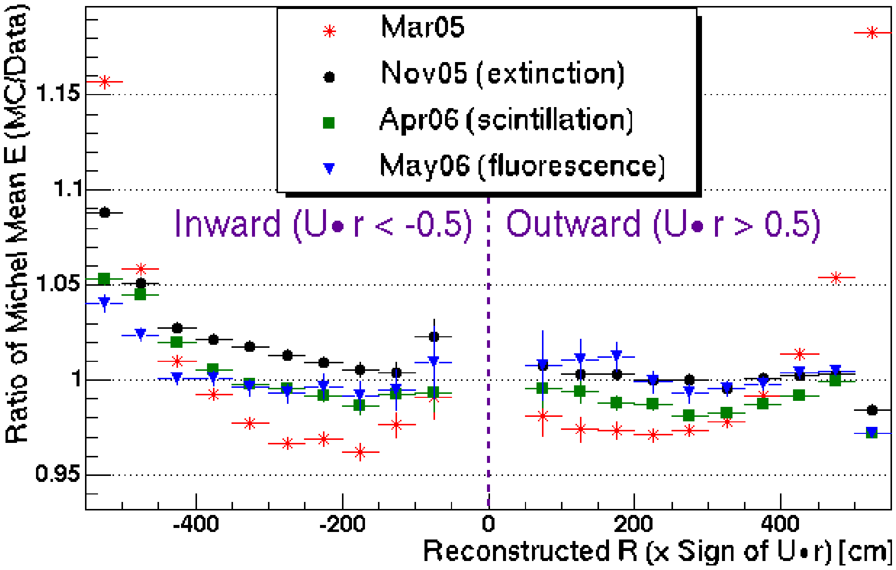
First calibration with michels

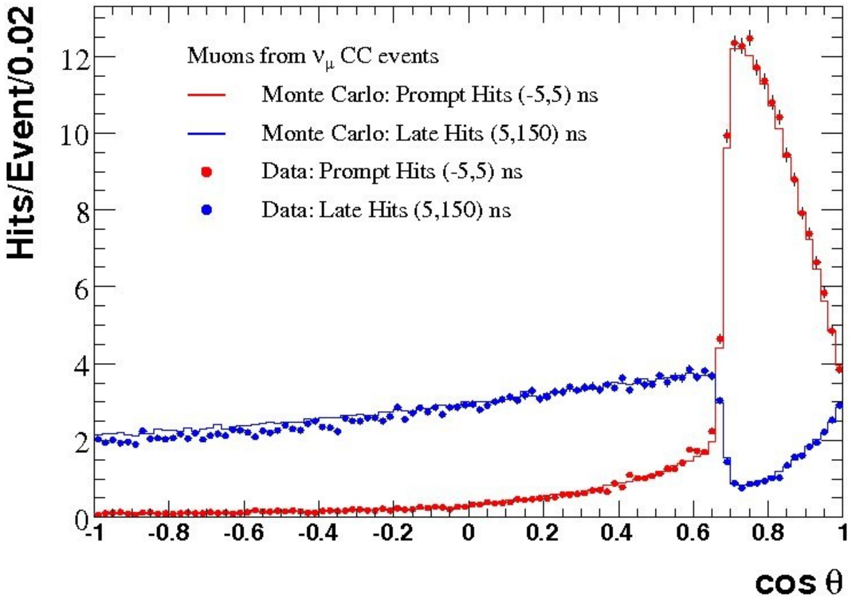
Calibration of scintillation light with NC events

Final calibration with michels

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







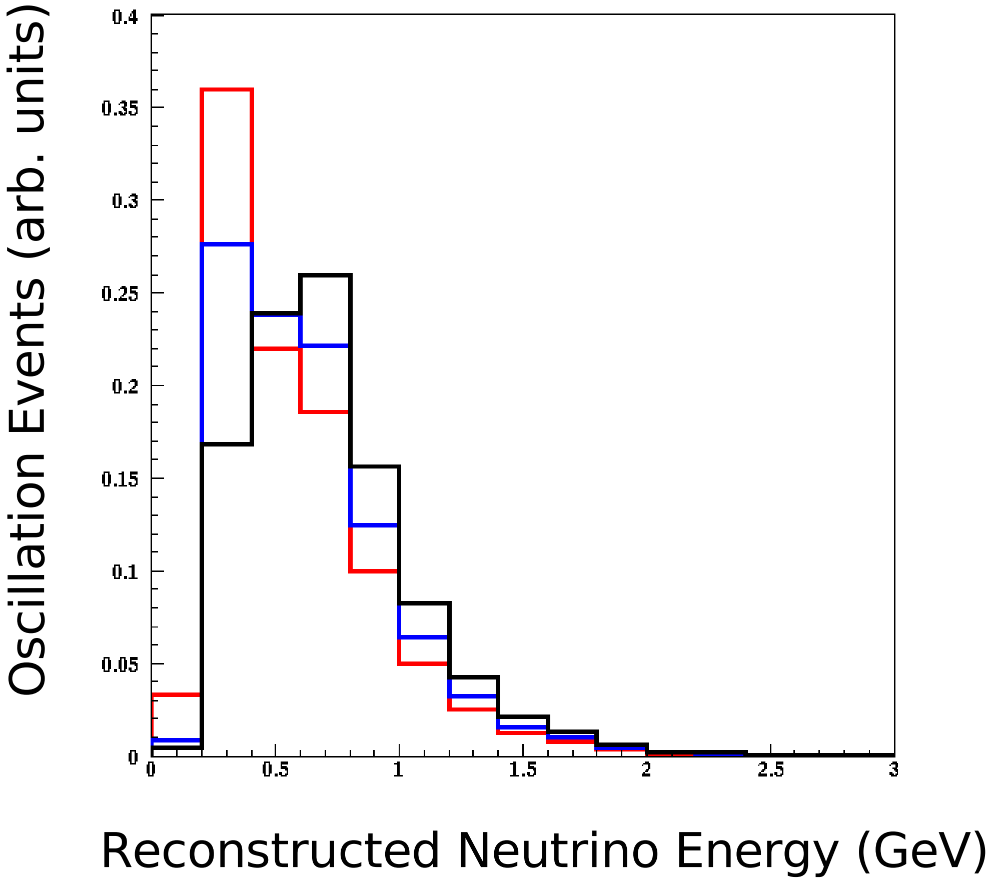
Signal Energy Region in Appearance Search

- Energy range for expected signal events is approximately:

$300 < E_\nu < 1500$ MeV

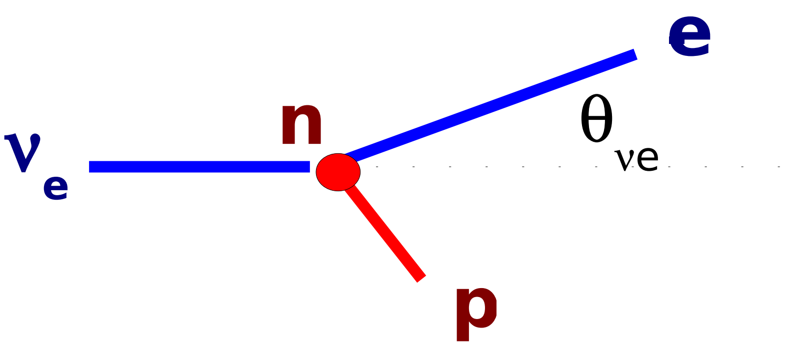
- MiniBooNE signal examples:

  $\Delta m^2 = 0.4$ eV^2
  $\Delta m^2 = 0.7$ eV^2
  $\Delta m^2 = 1.0$ eV^2



- In this energy range, one can then either:
  - look for a total electron candidate excess (*"counting experiment"*)
  - look for energy-dependence of excess (*"energy fit"*)

Neutrino Energy Reconstruction

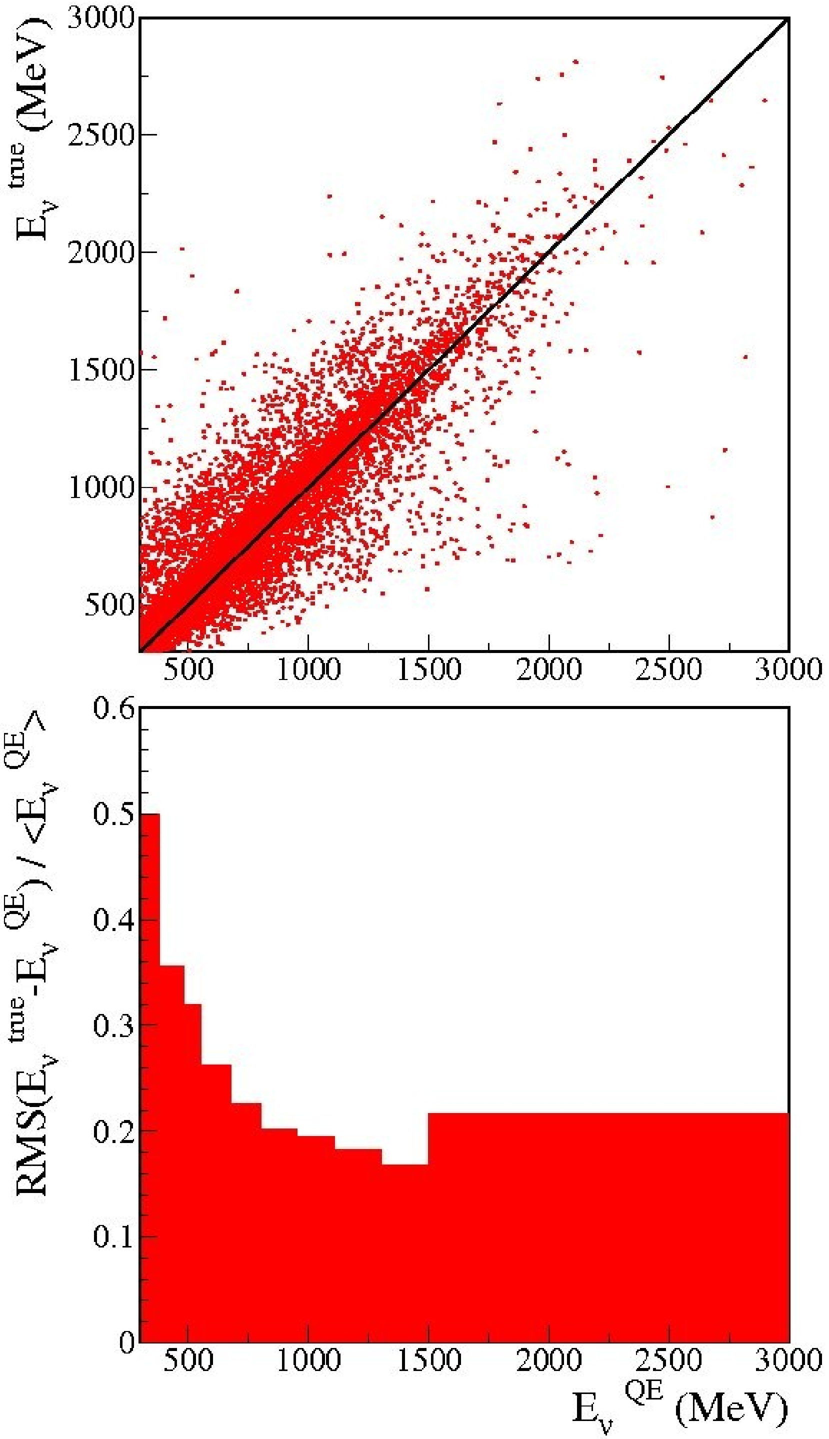


- Reconstruct neutrino energy in CCQE interactions (assuming target at rest) from:

• known neutrino direction
• measured charged lepton energy and direction wrt neutrino beam

$$E_\nu^{QE}=\frac{E_e(m_N-V)+\frac{1}{2}(m_N^2-(m_N-V)^2-m_e^2)}{(m_N-V)-E_e+p_e\cos\theta_{\nu e}}$$

- MC study of all fully oscillated ν_μ->ν_e events surviving cuts give 20-30% RMS resolution



Reconstruction and Particle Identification (BDT)

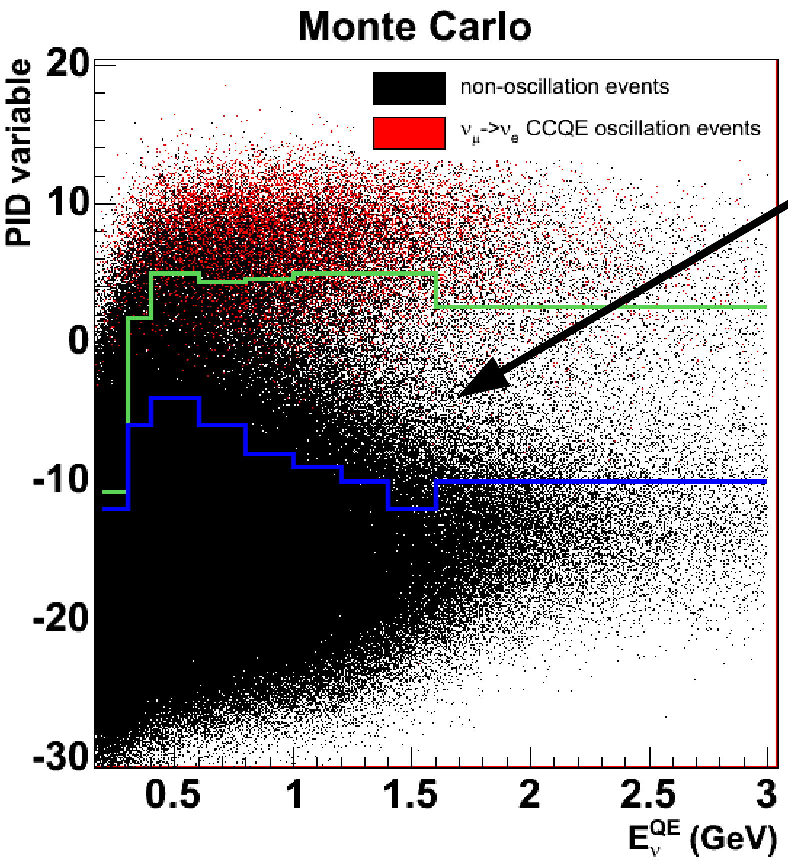
Reconstruction:

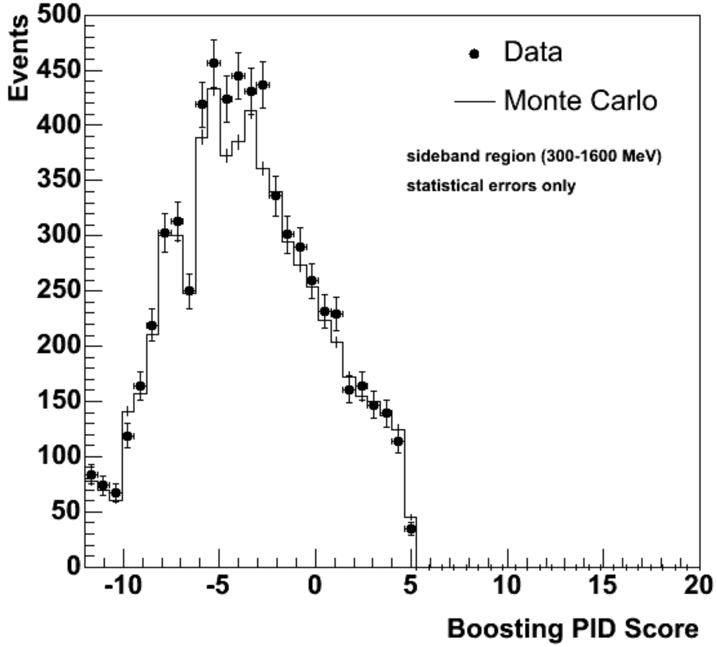
- Slightly less detailed (and performing):

- 24 cm resolution for ν_e event vertex
- 3.4 deg for electron track direction
- 14% for electron track energy

Particle Identification:

- Use sophisticated machine learning technique (*Boosted Decision Tree*) with 172 PID input variables (see B. Roe's talk)
- “Sideband” region in Boosting PID score nearest to oscillation signal, containing mostly ν_μ NC π^0 and ν_μ CCQE events:

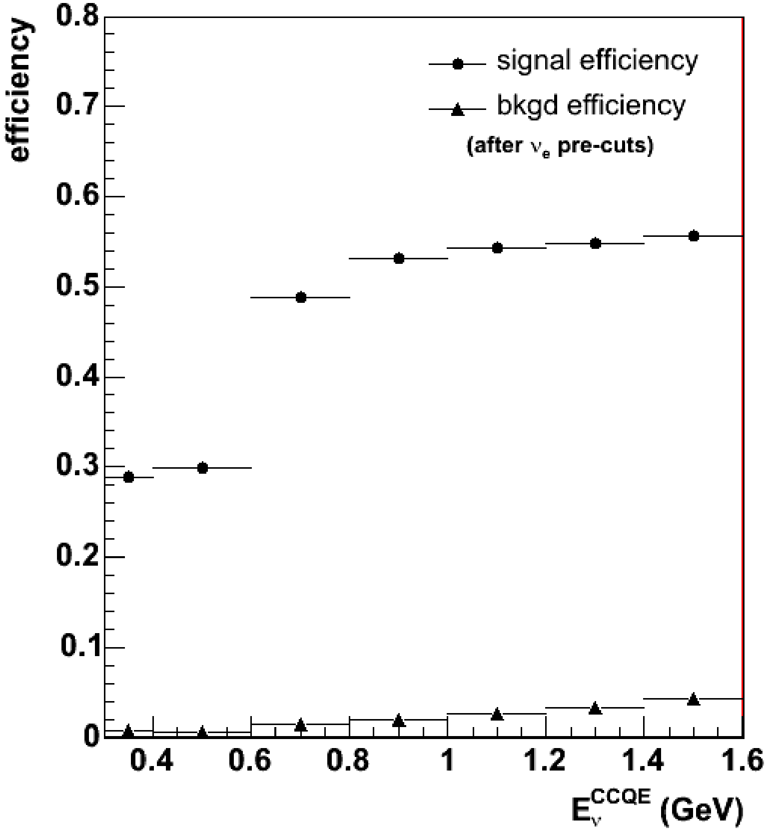


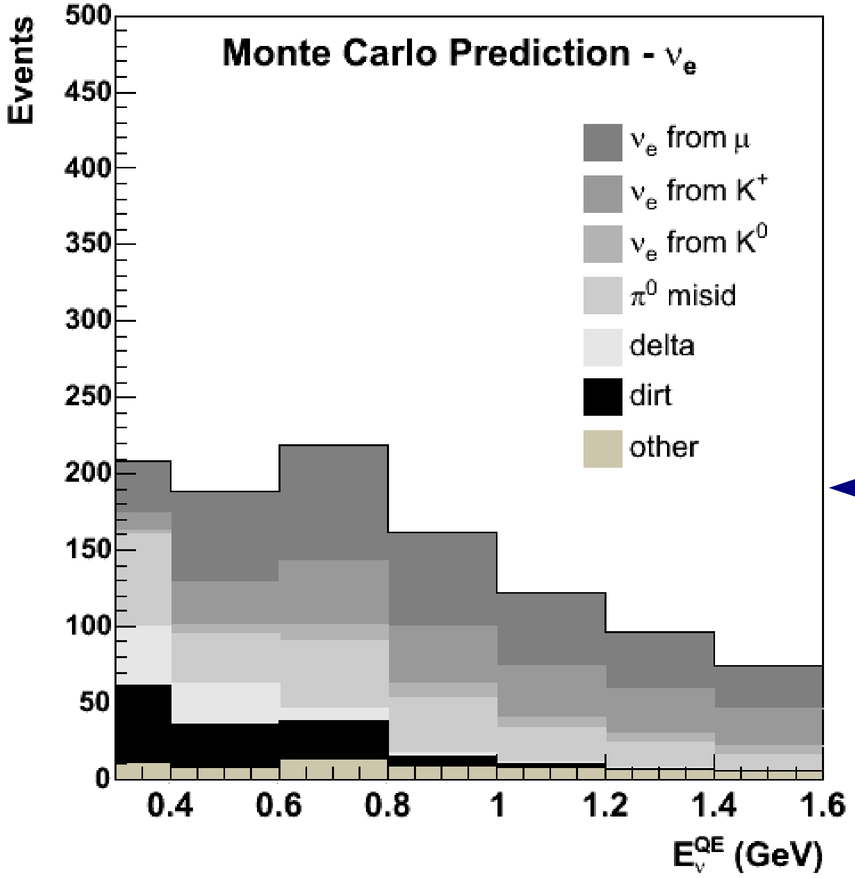


Signal Efficiency and Background Composition (BDT)

- *Signal and background efficiency:*

Single subevent, hit-level, fiducial volume cuts
+ E-dependent Boosting PID score cut





- *Expected background composition in signal region (300-1600 MeV)*
- Background events constrained by:
  - ν_μ events
  - ν_e-like events in low (200-300 MeV) and high (1600-3000 MeV) energy regions, containing negligible oscillation events

Electron Candidate Events in Two Analyses

- Simple and effective way of understanding independence of two analyses is to quantify how independent their ν_e-like data samples are
- Out of all events selected by either one (or both) analyses in respective signal regions, only *19% in common*