RESULTS OF THE MiniBooNE NEUTRINO OSCILLATION SEARCH

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High Energy Physics Seminar
May 30, 2007
Search for Neutrino Oscillations

- Neutrino oscillations
- Introduction to MiniBooNE
- The oscillation analysis
- The initial results and their implications
- The next steps
Neutrino Oscillations: Experimental Evidence

- Atmospheric Neutrinos
- Solar Neutrinos
- LSND
Atmospheric Neutrinos

- Definitive discovery of oscillations, 1998 (muon disappearance only)
- $\nu_\mu$ disappearance
- Disappearance confirmed in long-baseline accelerator experiments

$$\Delta m^2 \approx (2 - 3) \times 10^{-3} \text{eV}^2/c^4$$

$$\sin^2 2\theta \approx 1$$

Assuming $\nu_\mu \rightarrow \nu_\tau$
Solar Neutrinos

- Experiments looking for solar $\nu_e$ have seen long-standing deficits in data compared to solar models.

- Sudbury Neutrino Observatory (SNO) observed neutral/charged current ratio, confirming flavor mixing as the solution to solar neutrino “problem.”

- KamLAND observed disappearance of reactor antineutrinos: confirmed oscillations and resolved an ambiguity in $\Delta m^2$.

$$\Delta m^2 \approx 10^{-4} \text{eV}^2/c^4$$

$$\sin^2 2\theta \approx 0.8$$

$\nu_e$ disappearance
LSND

• Liquid Scintillator Neutrino Detector at Los Alamos Meson Physics Facility (LAMPF) accelerator

• Neutrino source: stopped pion and muon decays

• Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

• $L = 30$ m, $E = 30$-$53$ MeV
Stopped $\pi^+$ beam at Los Alamos LAMPF produces $\nu_e$, $\nu_\mu$, $\bar{\nu}_\mu$ but no $\bar{\nu}_e$ (due to $\pi^-$ capture).

**Search for $\bar{\nu}_e$ appearance via reaction:**

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

- Neutron thermalizes, captures ➞ 2.2 MeV $\gamma$-ray
- Look for the delayed coincidence.
- Major background non-beam (measured, subtracted)
- 4 standard dev. excess above background.
- **Oscillation probability:**

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (2.5 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-3}$$
LSND oscillation signal

• LSND “allowed region” shown as band

• KARMEN2 is a similar experiment with a slightly smaller L/E; they see no evidence for oscillations. Excluded region is to right of curve.
LSND Oscillation allowed region

Confidence regions from joint analysis of LSND and KARMEN2 data


• Combined analysis:
  • Consistency at 64% confidence level
  • Restricted parameter region
The Overall Picture

With only 3 masses, can’t construct 3 $\Delta m^2$ values of different orders of magnitude!

• Is there a fourth neutrino?

  • If so, it can’t interact weakly at all because of $Z^0$ boson resonance width measurements consistent with only three neutrinos.

• We need one of the following:
  • A “sterile” neutrino sector
  • Discovery that one of the observed effects is not oscillations
  • A new idea

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Delta m^2$</th>
<th>Oscillations</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>$\Delta m^2 &gt; 0.1 \text{eV}^2$</td>
<td>$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$</td>
</tr>
<tr>
<td>Atmos.</td>
<td>$\Delta m^2 \approx 2 \times 10^{-3} \text{eV}^2$</td>
<td>$\nu_\mu \leftrightarrow \nu_? $</td>
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<tr>
<td>Solar</td>
<td>$\Delta m^2 \approx 10^{-4} \text{eV}^2$</td>
<td>$\nu_e \leftrightarrow \nu_?$</td>
</tr>
</tbody>
</table>
MiniBooNE: E898 at Fermilab

- Purpose is to test LSND with:
  - Higher energy
  - Different beam
  - Different oscillation signature
  - Different systematics

- $L=500$ meters, $E=0.5-1$ GeV: same $L/E$ as LSND.
Results presented here

• A generic search for a $\nu_e$ excess in the $\nu_\mu$-dominated beam

• A fit for neutrino oscillations in a two-flavor, appearance-only scenario

• Tests LSND in models where neutrinos and antineutrinos have same oscillations (and Lorentz invariance is respected)
Oscillation Signature at MiniBooNE

- Oscillation signature is charged-current quasielastic scattering:
  \[ \nu_e + n \rightarrow e^- + p \]

- Dominant backgrounds to oscillation:
  - Intrinsic \( \nu_e \) in the beam
    \[ \pi \rightarrow \mu \rightarrow \nu_e \text{ in beam} \]
    \[ K^+ \rightarrow \pi^0 e^- \nu_e, \quad K^0_L \rightarrow \pi^0 e^{\pm} \nu_e \text{ in beam} \]
  - Particle misidentification in detector
    Neutral current resonance:
    \[ \Delta \rightarrow \pi^0 \rightarrow \gamma\gamma \text{ or } \Delta \rightarrow n\gamma, \text{ mis-ID as } e \]
• 8 GeV primary protons come from Booster accelerator at Fermilab

• Booster provides about 5 pulses per second, $5 \times 10^{12}$ protons per 1.6 $\mu$s pulse under optimum conditions
Beam Delivery Milestones

1st horn failure

NUMI intensity ramp-up

Horn polarity switch (horn-off running during changeover)

First oscillation result uses the 2002-2005 E898 data set (5.7E20 pot).
Secondary beam: horn and target

- Target is beryllium, 71 cm (1.7λ).
- Cooling tube and target are cantilevered into the neck of the horn.
- MiniBooNE horn runs at 174 kA, 140 μs pulse.
- This horn survived 96 million pulses – a world record! -- before failing in July 2004.
- Replacement has already seen >10^8 pulses and shows no sign of deterioration.
• Decay region is filled with stagnant air shared with target pile.

• The 25m Absorber is designed to be lowered in for cross-checks if MiniBooNE sees a signal.

• Both absorbers contain muon monitors.

• Shielding provided by gravel fill and earth berm above decay pipe.
MiniBooNE neutrino detector

- Pure mineral oil
- 800 tons; 40 ft diameter
- Inner volume: 1280 8” PMTs
- Outer veto volume: 240 PMTs
**DAQ Events and Subevents**

- Every 100 ns clock cycle, the detector records:
  - Total charge on each PMT (Resolution $\sim 1$ photoelectron)
  - Time of first hit on each PMT above threshold (Resolution $\sim 1.5$ ns)
  - All hits recorded in a 20 $\mu$s window surrounding the 1.6 $\mu$s beam pulse

- We resolve stopping muons and their decay electrons ("Michel") as two subevents: clusters of hits within $\sim 100$ ns, within the full 20$\mu$s event.

- The Michel electron subevent provides muon tag as well as a very well-understood charge/energy calibration

- Muons capture on nucleus with 8% probability; these capture events cannot be tagged.
Event types:

- Electrons: showers, scattering \(\Rightarrow\) blurred ring
- Muons: straight, long track \(\Rightarrow\) well-defined ring
- \(\pi^0\rightarrow\gamma\gamma\): two electron-like rings
Event display: Cherenkov Rings

A cosmic-ray muon enters the tank and stops...
Event display: Cherenkov Rings

Charge (Size)

Time (Color)

...then the Michel electron is observed a few μs later.
Oscillation Analysis

• Steps to an oscillation result:
  • Predict flux
  • Model neutrino interactions in detector
  • Model detector response
  • Reconstruct events; particle ID
  • Oscillation fit
Flux model: Pion production

• Data from HARP experiment at CERN (taken with beryllium target at correct MiniBooNE beam momentum: hep-ex/0702024)

• Fit data to Sanford-Wang parametrization

• Sanford-Wang model used in GEANT4 beam Monte Carlo
Flux model: kaon production

- Kaon production data from many experiments, with primary beam momentum 9→24 GeV
- Fit data to a Feynman scaling parametrization
- Sanford-Wang model used as well; errors cover the differences in flux predictions for MiniBooNE
Predicted flux at detector

- Predicted flux:
  - 99.5% $\nu_\mu + \bar{\nu}_\mu$
  - 0.5% $\nu_e + \bar{\nu}_e$:
    - $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ (52%)
    - $K^+ \rightarrow \pi^0 \ e^+ \nu_e$ (29%)
    - $K^0 \rightarrow \pi^+ e^- \bar{\nu}_e$ (7%)
    - $K^0 \rightarrow \pi^- e^+ \nu_e$ (7%)
    - $\pi^+ \rightarrow e^+ \nu_e$ (4%)
    - Other ( <2%)
- Total antineutrino content is 6% (much of it at very low energy)
Further constraint on muon-decay $\nu_e$

- These pions also produce $\nu_\mu$ in detector, which are easily observed.
- Kinematic correlation allows tight constraint on $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ chain.

Muons originate predominantly from pion decays in secondary beam.
High energy events constrain kaon decay flux

- Kaon decay has much higher $Q$-value than pion decay
- Kaons produce higher energy neutrinos
- Particularly true for two-body $K^+ \rightarrow \mu^+ \nu\mu$
- Use the high energy $\nu\mu$ events to constrain the kaon flux that produces $\nu_e$ background

Dominated by $\pi$ decay

Dominated by $K$ decay
In-situ cross-check on kaon flux: Little Muon Counter (LMC)

- Phase space in two-body decays limits the accessible kinematic region of the products:
- High-$p_T$ μ’s come from $K^+$ decay (mostly)
- Select off-axis decay muons by collimation, to turn $p_T$ separation into an effective $|p|$ separation.
- Scintillating fiber tracker / magnetic spectrometer measures muon spectrum

Use kinematics of the muons in the decay pipe to isolate kaon-decay contribution.
In-situ cross-check on kaon flux:
Little Muon Counter (LMC)

Data/MC ratio is constraint on the $K^+$ flux normalization:

- MC simulates $\pi$ and $K$ decays.
- No hadronic interaction backgrounds simulated yet.
- Plot shows data vs MC for well-identified muons in a region where we expect lower backgrounds.

Upper limit on the $K^+$ flux normalization is $1.32$ ($\sim 1\sigma$ on the Feynman scaling fit).
Predicted event spectrum, fractions before cuts
(NUANCE Monte Carlo)

D. Casper, NPS, 112 (2002) 161
**Charged-current quasielastic (CCQE)**

Neutrino scatters off nucleon in target:

- **Golden signal mode for oscillation search**: clean events; neutrino energy can be calculated given known neutrino direction:
  
  \[
  E_{\nu}^{CCQE} = \frac{m_N E_\ell - \frac{1}{2} m_\ell^2}{m_N - E_\ell + p_\ell \cos \theta_\ell}; \quad Q^2 = -2E_\nu(E_\nu - p_\ell \cos \theta_\ell) + m_\ell^2
  \]

- Nucleus may break up
- Final state nucleon not excited: no resonance, no pion, no (hard) gamma
- Physics to measure: axial form factor \( F_A \), parametrized by \( M_A \) (axial mass)
Cross-section parameters need tuning

- From $Q^2$ fits to MiniBooNE $\nu_\mu$ CCQE data:
  - $M_A^{\text{eff}}$: effective axial mass
  - $E_{lo}^{\text{SF}}$: Pauli-blocking parameter

- From electron scattering data:
  - $E_b$: binding energy
  - $p_F$: Fermi momentum
Charged-current quasielastic (CCQE)

- MiniBooNE $E_{\nu}^{\text{CCQE}}$ Reconstruction
- Resolution 8-15% in region of interest (300-1200 MeV)
Neutral Current $\Delta$ Resonances

- No Michel electron to tag events
- Gamma rays, electrons indistinguishable in the detector
- $\Delta \rightarrow N\pi^0$: large decay branching ratio, but can usually detect both gammas
- $\Delta \rightarrow N\gamma$ radiative decay: small branching ratio (\(<1\%)\), softer photon, but looks exactly like electron.
- Neutral current $\Delta$ resonance production is our largest source of particle misidentification background.
Neutral Current Δ Resonances

• $\pi^0$ events
  - Most $\pi^0$ events have two reconstructible photon rings.
  - Mass peak identifies neutral pions
Neutral Current $\Delta$ Resonances

- Total NC $\Delta$ rate is measured from these fully-reconstructed $\pi^0$ events.
- Use measured $\pi^0$ total rate and momentum spectrum to reweight the $\Delta$ Monte Carlo
- Reduces error on unreconstructed/misidentified $\pi^0$ and radiative decays
- Also improves agreement in other distributions
- Fit for coherent $\pi^0$ contribution
External backgrounds

• “Dirt” events: neutrino interactions outside the detector

• Most events are cut by veto

• Background is dominated by $\pi^0$ where only one photon enters detector

• Cosmic/other beam-unrelated background is very small: 2.1±0.5 events, measured with beam-off data
Neutrino detector modeling: “optical” issues

- **Primary light sources**
  - **Cherenkov**
    - Emitted promptly, in cone
    - Known wavelength distribution
  - **Scintillation**
    - Emitted isotropically
    - Several lifetimes, emission modes
    - Studied oil samples using Indiana Cyclotron test beam
    - Particles below Cherenkov threshold still scintillate

- **Optical properties of oil, detectors:**
  - Absorption (attenuation length >20m at 400 nm)
  - Rayleigh and Raman scattering
  - Fluorescence
  - Reflections
  - PMT response
Neutrino detector: “optical” issues

- Timing distribution for PMT hits
  - Calibration laser source inside tank
  - Monte Carlo with full optical model describes most of the timing structure
Calibration sources up to \( \sim 1 \) GeV

Tracker system

Michel electrons

\( E \) resolution at 53 MeV

\( \Delta M_e \sim 20 \) MeV

\( \pi^0 \) photon energies

Visible energy range of oscillation signal
Event Reconstruction and Particle ID

- Parallel approaches to analysis: independent event reconstructions and PID algorithms
  - Track/likelihood-based (TB) analysis: detailed reconstruction of particle tracks; PID from ratio of fit likelihoods for different particle hypotheses. Less vulnerable to detector modeling errors.
  - Boosted decision trees (BDT): algorithmic approach, able to extract particle ID information from larger set of lower-level event variables. Better signal/background, but more sensitive to detector modeling.
Start with “precuts” to find neutrino-like subevents:

First subevent arrival time (μs).
Beam pulse is from 4.5 to 6 μs.

**ALL SUBEVENTS**
Cosmic rays dominate

**<6 VETO HITS**
Cosmic rays reduced (except for Michel electrons)

**>200 TANK HITS**
Cosmic rays nearly eliminated; only beam neutrinos survive
The Blindness Procedure

• Philosophy: hide any event that could be an oscillation candidate from detailed analysis, while allowing aggregate or low-level information on all events to be examined.

• Early stages: highly restrictive, as particle ID was being developed: neutrino events closed by default. To open a sample of events for study, must show it is (nearly) oscillation-free.

• Later stages: MC and algorithms become more stable and trustworthy. Look in regions closer and closer to the signal; eventually all data open by default, and only the signal "box" (1% of events) was closed.

• Final stages: Open box in a series of steps, starting with fit quality values only, ending in full spectrum and oscillation fit.
The Track-based Analysis: Reconstruction

- A detailed analytic model of extended-track light production and propagation in the tank predicts the probability distribution for charge and time on each PMT for individual muon or electron/photon tracks.

- Prediction based on seven track parameters: vertex \((x, y, z)\), time, energy, and direction \((\theta, \varphi) \Rightarrow (U_x, U_y, U_z)\).

- Fitting routine varies parameters to determine 7-vector that best predicts the actual hits in a data event.

- Particle identification comes from ratios of likelihoods from fits to different parent particle hypotheses.
The Track-based Analysis: Reconstruction

<table>
<thead>
<tr>
<th>FIT HYPOTHESIS</th>
<th>NUMBER OF PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single muon</td>
<td>7</td>
</tr>
<tr>
<td>Single electron/photon</td>
<td>7</td>
</tr>
<tr>
<td>Two photons from common vertex, mass unconstrained</td>
<td>12</td>
</tr>
<tr>
<td>Two photons from common vertex, mass constrained to $m(\pi^0)$</td>
<td>11</td>
</tr>
</tbody>
</table>
The Track-based Analysis: Reconstruction

Effects included in the reconstruction model:

- Extended source of light ("track")
- Scattering, absorption of light
- Prompt light (Cherenkov, scattering, some scintillation)
- Delayed light (scintillation, fluorescence)
- Angular distribution of light from particles (due to showers, MCS)
- PMT efficiency and geometry
- \( \frac{dE}{dx} \)
The Track-based Analysis:

Event Selection

- Start with events that pass “precuts”
  - Exactly one subevent in event
- Perform all four fits: electron; muon; two-track, with and without $\pi^0$ mass constraint
- Fiducial cuts:
  - Radius must be less than 500 cm (calculated from electron fit)
- Make track energy-dependent cuts on likelihood ratios, to reject specific backgrounds in order from easiest to hardest
The Track-based Analysis: Muon rejection

- $\log(L_e/L_\mu)$: compare likelihoods returned by $e$ and $\mu$ fits.
- $\log(L_e/L_\mu) > 0$ indicates electron hypothesis is favored.
- Analysis cut is parabola whose parameters selected to optimize oscillation sensitivity.
- Discrimination easier at higher energy (increasing muon track length)
The Track-based Analysis:
Neutral pion rejection

- Free mass 2-track fit (2T) employed to reconstruct invariant mass
- Background $\pi^0$ reconstruct near $m(\pi^0)$; signal $\nu_e$ have smaller mass
The Track-based Analysis:
Neutral pion rejection

- Fixed mass 2-track fit used to form $L_\pi$
- $\log(L_e/L_\pi) > 0$ indicates electron hypothesis produces a better fit
The Track-based Analysis:

Neutral pion rejection

- These events have no observed Michel electron, and have passed the muon-rejection cut
- Events that are signal-like in either $\pi^0$ variable are excluded for now
- Neutral pion population shows up well, matches MC
The Track-based Analysis: Neutral pion rejection

- Next step: look in these sidebands: $e$-like in one variable, $\pi^0$-like in other

ν_e signal region
The Track-based Analysis: Looking in the sidebands

- Look at full mass range for events with $\log(L_e/L_\pi) < 0$
- These are signal-like in mass, but background-like in $\log(L_e/L_\pi)$
- Nice data/MC agreement
The Track-based Analysis: Efficiency and backgrounds

- Log(Le/Lμ) + Log(Le/Lμ) + invariant mass

Stacked backgrounds:
- νe^K
- νe
- νμ
- π^0
- dirt events
- Δ → Nγ
- other

Background MC after all cuts

Signal MC after precuts
x1500 μ rejection
x200 π^0 rejection
Boosted Decision Trees (BDT)

- An algorithm optimized to combine many weakly discriminating variables into one that provides powerful separation
- Idea: Go through all analysis variables and find best variable and value to split a Monte Carlo data set.
  - For each of the two subsets repeat the process
  - Proceeding in this way, a “decision tree” is built, whose final nodes are called leaves
A Decision Tree

Variable 1

N_{signal} 40000
N_{bkgd} 40000

Variable 2

bkgd-like
signal-like

9755 23695

Variable 3

bkgd-like
signal-like

30,245 16,305
Boosted Decision Trees (BDT)

- A tree is not unique
- After the tree is built, additional trees are built with the leaves re-weighted to emphasize the previously misidentified events (since those are hardest to classify). This is “boosting.”
- Each data event is sent through every tree, and in each tree is assigned a value:
  - +1 if the event ends up on a signal leaf
  - −1 if the event ends up on a background leaf.
- PID output variable is a sum of event scores from all trees: background at negative values, signal at positive values.
Analysis variables used in BDT:

• Low-level functions of fundamental variables like hit time, charge, etc.

• Examples of analysis variables:
  • Physics reconstruction variables ($\cos\theta_\mu$, vertex radius, ...)
  • Lower-level quantities (charge in theta range, etc)
Efficiency of BDT PID cut

Efficiency after precuts

Background MC

signal

background
Cross-checks and Systematic Errors

- Constraints from CCQE sample
- Cross-sections
- Optical model
- Error propagation
- Final estimate of errors and backgrounds
Constraints from $\nu_\mu$ CCQE sample

Event rate normalization

- Total $\nu_\mu$ CCQE rate compared to Monte Carlo: appearance-only search will tie electron rate to this normalization

- Track-based: $1.32 \pm 0.26$

- Boosting: $1.22 \pm 0.29$
Constraints from $\nu_\mu$ CCQE sample

- Each analysis approaches this differently:
- Track-based: Reweight MC prediction to match measured $\nu_\mu$ result
- Boosting: include the correlations of $\nu_\mu$ to $\nu_e$ in the error matrix of a combined $\nu_\mu + \nu_e$ fit:

$$
\chi^2 = \left( \begin{array}{cc}
\Delta_{ij}^{\nu_e} & \Delta_{ij}^{\nu_\mu} \\
\end{array} \right) \left( \begin{array}{cc}
M_{ij}^{e,e} & M_{ij}^{e,\mu} \\
M_{ij}^{\mu,e} & M_{ij}^{\mu,\mu} \\
\end{array} \right)^{-1} \left( \begin{array}{c}
\Delta_{ij}^{\nu_e} \\
\Delta_{ij}^{\nu_\mu} \\
\end{array} \right)
$$

where $\Delta_{ij}^{\nu_e} = \text{Data}_{ij}^{\nu_e} - \text{Pred}_{ij}^{\nu_e}(\Delta m^2, \sin^2 2\theta)$ and $\Delta_{ij}^{\nu_\mu} = \text{Data}_{ij}^{\nu_\mu} - \text{Pred}_{ij}^{\nu_\mu}$

- Systematic (and statistical) uncertainties are included in $(M_{ij})^{-1}$
Neutrino cross-section errors for oscillation analysis

These cross-sections and several others will be the subject of upcoming dedicated MiniBooNE analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error/Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{A}^{QE}$, $E_{l_{o}}^{SF}$ QE σ norm</td>
<td>6%, 2% (stat+bkg)</td>
<td>MiniBooNE $\nu_{\mu}$ CCQE</td>
</tr>
<tr>
<td>NC $\pi^{0}$ rate</td>
<td>few % (depends on $p_\pi$)</td>
<td>MiniBooNE NC $\pi^{0}$ data</td>
</tr>
<tr>
<td>$\Delta \rightarrow N\gamma$ rate</td>
<td>$\sim 10%$</td>
<td>MiniBooNE NC $\pi^{0}$ data, $\Delta \rightarrow N\gamma$ BR</td>
</tr>
<tr>
<td>$E_B$, $p_F$</td>
<td>9 MeV, 30 MeV</td>
<td>External data</td>
</tr>
<tr>
<td>$\sigma_{DIS}$</td>
<td>25%</td>
<td>External data</td>
</tr>
</tbody>
</table>
Optical model uncertainties

- Optical model depends on 39 parameters such as absorption, scintillation, fluorescence behavior.

- Use "Multisim" technique to estimate error: vary the parameters according to a full covariance matrix, and run 70 full GEANT Monte Carlo "experiments" to map the space of detector responses to the parameters.

- Space of output results is used to produce error matrix for the oscillation candidate histogram.

- Example of multisim outputs in a single osc. bin:

<table>
<thead>
<tr>
<th># of multisims</th>
<th># events passing signal cuts in bin $500 &lt; E_{\nu}^{QE} &lt; 600$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Value</td>
<td></td>
</tr>
</tbody>
</table>

70 Optical Model multisims

# of multisims

0 2 4 6

60 80

Central Value MC

# events passing signal cuts in bin $500 < E_{\nu}^{QE} < 600$ MeV
Handling other uncertainties

- Flux and neutrino cross-section parameter variations do not affect the hit distributions for a given event, only the probability of that event occurring in the first place.

- Rather than repeating hit-level MC, determine effect of varying by mocking up 1000 multisims by reweighting the same MC events: reduced MC statistics error and greatly reduced CPU usage.

- Similar procedure to produce error matrix for the oscillation candidate histogram.

- Example of multisim outputs in a single osc. bin:

<table>
<thead>
<tr>
<th>Central Value MC</th>
<th># of reweighting multisims</th>
</tr>
</thead>
<tbody>
<tr>
<td># of multisims</td>
<td></td>
</tr>
<tr>
<td>Central Value MC</td>
<td></td>
</tr>
</tbody>
</table>

# events passing signal cuts in bin $500 < E_{\nuQE} < 600$ MeV
The error matrix

\[ E_{ij} = \frac{1}{M} \sum_{\alpha=1}^{M} (N_{i}^{\alpha} - N_{i}^{MC}) (N_{j}^{\alpha} - N_{j}^{MC}) \]

- \( N \): Number of events passing cuts
- \( MC \): Central value Monte Carlo
- \( \alpha \): index represents a given multisim
- \( M \): total number of multisims
- \( i, j \): \( E_\nu \)QE bins

- Brings in correlations among the input parameters, and the resulting correlations among the data bins
- Total error matrix is sum from each source (optical model, \( K \) production, QE cross-section, etc...)
- Track-based: uses error matrix in \( \nu_e \) \( E_\nu \)QE only (\( \nu_\mu \) CCQE information comes in reweighting instead of fit)
- Boosting: uses combined error matrix in \( \nu_\mu + \nu_e \) \( E_\nu \)QE bins

Correlations between \( E_\nu \)QE bins from the optical model:
# Expected background events by source

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>EVENTS AFTER SELECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEAM UNRELATED</td>
<td>2</td>
</tr>
<tr>
<td>DIRT</td>
<td>17 ± 3</td>
</tr>
<tr>
<td>NEUTRAL CURRENT $\pi^0$</td>
<td>62 ± 10</td>
</tr>
<tr>
<td>NC RADIATIVE Δ DECAY</td>
<td>20 ± 4</td>
</tr>
<tr>
<td>NC COHERENT AND RADIATIVE</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$\nu_\mu$ QUASIELASTIC</td>
<td>10 ± 2</td>
</tr>
<tr>
<td>NEUTRINO-ELECTRON ELASTIC</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>OTHER $\nu_\mu$</td>
<td>13 ± 5</td>
</tr>
<tr>
<td>INTRINSIC $\nu_e$ FROM MUONS</td>
<td>132 ± 10</td>
</tr>
<tr>
<td>INTRINSIC $\nu_e$ FROM $K^+$</td>
<td>71 ± 26</td>
</tr>
<tr>
<td>INTRINSIC $\nu_e$ FROM $K^0$</td>
<td>23 ± 7</td>
</tr>
<tr>
<td>INTRINSIC $\nu_e$ FROM $\pi^+\rightarrow e^+\nu_e$</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>TOTAL BACKGROUND</td>
<td>358 ± 35(syst)</td>
</tr>
<tr>
<td>0.26% $\nu_\mu \rightarrow \nu_e$</td>
<td>163</td>
</tr>
</tbody>
</table>
Oscillation sensitivity

- Track-based algorithm has slightly better sensitivity to 2-neutrino oscillations
- This will therefore be our primary result
Unblinding

• First step:
  • Perform fit, but do not report results
  • Return $\chi^2$ probability for a set of diagnostic variables, not including the quasielastic energy on which the fit is performed, compared to Monte Carlo with (still hidden) best-fit signal

• Second step:
  • Compare these plots directly, with no normalization info

• Third step:
  • Report the $\chi^2$ for the oscillation parameter fit

• Final step:
  • Report the results of the fit and the full energy distribution
Results

• Step 1 ($\chi^2$ probability for a set of diagnostic variables):
  • Only probabilities revealed, not full histograms
  • 12 variables for track-based analysis: 11 look good
  • 46 variables for boosting analysis: all look good
• $E_{\text{visible}}$ (not $E_{\nu}^{\text{QE}}$) distribution in track-based analysis returned a probability of <1%:
  • Track-based analysis revised to limit oscillation fit range to $E_{\nu}^{\text{QE}} > 475$ MeV, eliminating two low-energy bins where backgrounds known to rise.
  • New sensitivity almost identical to old
  • No change to the Boosting analysis
Results

• Track based analysis: $475 < E_{\nu}^{QE} < 1250$ MeV

• Expected background:
  $358 \pm 19$ (stat) $\pm 35$ (syst)

• Observed: 380  Discrepancy: 0.55 $\sigma$

NO EVIDENCE FOR OSCILLATIONS IN COUNTING ANALYSIS
Energy fit and spectrum

- Good agreement with background only (93% CL)
- Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (0.001, 4 \text{ eV}^2)$, 99% fit CL
Oscillation Limit

- Single-sided 90% confidence limit
- Best fit (star): 
  \[(\sin^2 2\theta, \Delta m^2) = (0.001, 4 \text{ eV}^2)\]
The full spectrum

- Extending the plot down to the 300 MeV threshold
- A significant data/MC discrepancy exists in the lower bins

Focusing on the lowest two bins only:

- Excess is $96 \pm 17 \pm 20$ events
2-neutrino fit to full spectrum

- Best fit has 18% probability
  
  \((\sin^2 2\theta, \Delta m^2) = (1.0, 0.03 \text{ eV}^2)\)

- These parameters are completely excluded by reactor experiments in 2-nu model

- Null hypothesis has 3% probability

- Spectrum does not resemble LSND-type oscillations
Oscillation fit in Boosting Analysis

- Best fit probability is 62%
- Less significant excess at low energy (but larger normalization error)
- Only diagonal errors shown – fit uses full error matrix
- Counting Experiment: $300 < E_{\nuQE} < 1600$ MeV
  - Data: 971 events
  - Background expectation: $1070 \pm 33 \text{ (stat)} \pm 225 \text{ (sys)}$ events
  - Overall counting significance: $-0.38 \sigma$
Comparing the limits

- Solid: Track-based
- Dashed: Boosting
- The two analyses have very consistent fit results.
- Track-based fit remains our primary result.
Ways to present limits:

- Single sided raster scan (historically common, our default)
- Global $\chi^2$ scan
- Unified approach (Feldman-Cousins)
MiniBooNE vs. LSND: A simple compatibility test

• For each $\Delta m^2$, determine the MiniBooNE ($M$) and LSND ($L$) measurement of $\sin^2(2\theta)$:
  - $z_M \pm \sigma_M, \ z_L \pm \sigma_L$ where $z \equiv \sin^2(2\theta)$ and $\sigma_M, \sigma_L$ evaluated at that $\Delta m^2$

• For each $\Delta m^2$, form $\chi^2$ between MiniBooNE and LSND measurement:
  \[
  \chi^2_0 = \frac{(z_M - z_0)^2}{\sigma_M^2} + \frac{(z_L - z_0)^2}{\sigma_L^2}
  \]
  • $M$: MiniBooNE
  • $L$: LSND

• Find $z_0$ that minimizes $\chi^2$ (weighted average of two measurements of $\sin^2(2\theta)$); this gives $\chi^2_{\text{min}}$

• Find probability of $\chi^2_{\text{min}}$ for 1 dof; this is the joint probability at this $\Delta m^2$ if the two experiments are measuring the same thing.
MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance-only interpretation of LSND at 98% CL.
Next Steps

• Further investigation of low-energy excess

• Cross-sections? (Further MiniBooNE, SciBooNE studies)

• Other non-oscillation effects?

• Further interpretation of oscillation limit

• Full MiniBooNE+LSND+KARMEN joint analysis

• Combined track-based and boosting analysis
Conclusions

- MiniBooNE sets a limit on $\nu_\mu \rightarrow \nu_e$ oscillations. We strongly exclude LSND in a CP-conserving two-neutrino model.

- Data show discrepancy vs. background at low energies, but spectrum inconsistent with two-neutrino oscillation.