ν_e Oscillation Analysis
Progress at MiniBooNE

1. Motivation and Overview
2. Components of the Oscillation Analysis
3. Incorporating Constraints from ν_μ Data

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**MiniBooNE Motivation: LSND Result**

**Signals:**
- **Solar:** $\Delta m^2 \sim 10^{-5} \text{ eV}^2$ (SNO, KamLAND, ...)
- **Atmospheric:** $\Delta m^2 \sim 10^{-3} \text{ eV}^2$ (Super-K, K, ...)
- **Accelerator:** $\Delta m^2 \sim 10^0 \text{ eV}^2$ (LSND)

**Explanation for $\Delta m^2$ problem?**
1. LSND interpretation may be wrong - confirm or refute with MiniBooNE
2. Add sterile neutrinos: 1, 2, 3 ...
3. (More) exotic possibilities

**ν Oscillations**

Weak eigenstates ($ν_e$, $ν_μ$, $ν_τ$) ≠ mass eigenstates ($ν_1$, $ν_2$, $ν_3$)

Parameters $Δm_{i,j}^2 = |m_i^2 - m_j^2|$, $\sin^2 θ_{i,j}$, $i,j=1,3$

2-ν oscillation probability:

$$P(ν_α \rightarrow ν_β) = \sin^2 2θ \sin^2 \left( \frac{1.27Δm^2 L}{E_ν} \right)$$

3 vs allow only 2 independent values of $Δm^2$
MiniBooNE Overview: Beam and Detector

MiniBooNE is searching for an excess of $\nu_e$ in a $\nu_\mu$ beam

**Protons:** 4E12 protons per 1.6 $\mu$s pulse, at a rate of 3 - 4 Hz from Fermilab Booster accelerator, with $E=8.9$ GeV

**Mesons:** mostly $\pi^+$, produced in p-Be collisions, + signs focused in horn. 50m decay region.

**Neutrinos:** 450 m soil berm before the detector hall. Intrinsic $\nu_e$ flux $\sim 0.4\%$ x $\nu_\mu$ flux.

**Detector:** 1280 PMTs, 250,000 gallons of mineral oil, Cherenkov and scintillation light. 240 PMTs in optically isolated veto region.

Beam $\nu_\mu$ s from:

- $\pi^+ \rightarrow \mu^+ \nu_\mu$ (99.99%)  
- $K^+ \rightarrow \mu^+ \nu_\mu$ (63%)

Beam $\nu_e$ s from:

- $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ (99.99%)  
- $K^+ \rightarrow \pi^0 e^+ \nu_e$ (5%)  
- $K^0_L \rightarrow \pi^\pm e^\pm \nu_e$ (39%)
MiniBooNE Beam: Pion Production

$\pi^+ \text{ prediction}$ comes from a fit to $\pi^+$ production data from E910, HARP experiments ($p_p = 6\text{-}12 \text{ GeV/c}$)

**Fit** uses Sanford-Wang parameterization of inclusive meson production in p-Be collisions.

**HARP** $\pi^+$ data at 8.9 GeV/c beam momentum shown (right) with prediction and error, data has excellent phase space coverage for MiniBooNE (below).

$\pi^-$ similarly parameterized, but comprise negligible contribution to neutrino flux.
MiniBooNE Beam: **Kaon Production**

*K*\(^+\) *prediction* comes from a fit to *K*\(^+\) production data from past experiments \((= 10\text{--}24 \text{ GeV/c})\)

**Fit** uses a parameterization based on Feynman scaling (developed by MiniBooNE)

**K*\(^+\) data from past experiments**, scaled to 8.9 GeV/c beam momentum, shown with prediction and error (right), data has reasonable phase space coverage for MiniBooNE (below)

**K*\(^0\) similarly parameterized, but comprise much smaller background than K*\(^+\)
**MiniBooNE Detector: Neutrino Cross Sections**

![Graph of neutrino cross sections](image)

- **CC / NC quasi-elastic scattering (QE)**
  - 42% / 16%
- **CC / NC resonance production (1π)**
  - 25% / 7%
- **multi-π /DIS production**
  - ~13%

**Cross Section Predictions from NUANCE Monte Carlo event generator:**

A variety of theoretical models for exclusive processes, joined smoothly to reproduce the total CC cross section data, with model parameters tuned on free-nucleon data.

Use CCQE events for oscillation analysis signal channel:

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

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MiniBooNE Detector: Reconstruction and Particle ID

Reconstruction:
PMTs collect $\gamma$s, record $t$ and $q$, fit time and angular distributions to find tracks

Final State Particle Identification:
muons have sharp rings due to Cherenkov emission, long tracks
electrons have fuzzy rings, from multiple scattering, and short tracks
neutral pions decay to 2 $\gamma$s, which convert and produce two fuzzy rings,
\textit{easily mis-identified as electrons if one ring gets lost!}
MiniBooNE Detector: **NuMI “Calibration Beam”**

We need to verify our PID with $\nu_e$ in the signal energy range, but we are doing a blind analysis.

Solution: use someone else’s beam!

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**Sitting off axis, we see a beam which is enhanced in $\nu_e$ and is in a useful energy range.**
Oscillation Search: Signal Event Selection #1

Method #1: to find $\nu_e$ CCQE final state:

1. apply simple cuts on event time and number of hit PMTs to eliminate cosmics
2. eliminate muons by requiring 1 sub-event in time
3. employ Boosted decision tree discriminant or cut on $e-\mu$ and $e-\pi$ likelihood variables to eliminate mis-IDs

placement of cut determined by requiring 99.9% rejection of $\nu_\mu$ CC, 99% rejection of $\pi^0$, ~50% $\nu_e$ CC efficiency

“calibration beam” data shown here is from the MiniBooNE detector and the NuMI beam, which is out of time, off-axis, enhanced in $\nu_e$, and spans the relevant energy range
Method #2: to find $\nu_e$ CCQE final state:

1. apply simple cuts on event time and number of hit PMTs to eliminate cosmics
2. eliminate muons by requiring 1 sub-event in time
3. employ Boosted decision tree discriminant or cut on $e^{-}\mu$ and $e^{-}\pi$ likelihood variables to eliminate mis-IDs

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“calibration beam” data shown here is from the MiniBooNE detector and the NuMI beam, which is out of time, off-axis, enhanced in $\nu_e$, and spans the relevant energy range
Oscillation Search: Signal Extraction

Raster scan in \((\Delta m^2, \sin^2 2\theta)\), calculate

\[
\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \sum_{j=1}^{N_{\text{bins}}} (m_i - t_i) \mathcal{M}^{-1}_{ij} (m_j - t_j)
\]

what we predict for the existing data set (5.3E20 protons on target)...

Example oscillation signal
- \(\Delta m^2 = 1 \text{ eV}^2\)
- \(\sin^2 2\theta = 0.004\)

Fit for excess as a function of reconstructed \(\nu_e\) energy
Oscillation Search: Signal Extraction

Raster scan in \((\Delta m^2, \sin^2 2\theta)\), calculate

$$\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \sum_{j=1}^{N_{\text{bins}}} (m_i - t_i) M_{ij}^{-1} (m_j - t_j)$$

what we predict for the existing data set (5.3E20 protons on target)...

\(\nu_e\) from \(K^+\) and \(K^0\)

Use High energy \(\nu_e\) and \(\nu_\mu\) for normalization

Use fit to kaon production data for shape
Raster scan in $\left(\Delta m^2, \sin^2 2\theta\right)$, calculate

$$\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \sum_{j=1}^{N_{\text{bins}}} (m_i - t_i) M_{ij}^{-1} (m_j - t_j)$$

what we predict for the existing data set (5.3E20 protons on target)...
Oscillation Search: Signal Extraction

Raster scan in $(\Delta m^2, \sin^2 2\theta)$, calculate

$$\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \sum_{j=1}^{N_{\text{bins}}} (m_i - t_i) M_{ij}^{-1} (m_j - t_j)$$

what we predict for the existing data set (5.3E20 protons on target)...

MisID $\nu_\mu$

$\sim 83\% \pi^0$
- Only $\sim 1\%$ of all $\pi^0$s are misIDed
- Determined by clean $\pi^0$ measurement

$\sim 7\% \Delta \gamma$ decay
- Use clean $\pi^0$ measurement to estimate $\Delta$ production

$\sim 10\%$ other
- Use $\nu_\mu$ CCQE rate to normalize and MC for shape
Oscillation Search: Signal Extraction

Raster scan in \((\Delta m^2, \sin^2\theta)\), calculate

\[
\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \sum_{j=1}^{N_{\text{bins}}} (m_i - t_i) M_{ij}^{-1} (m_j - t_j)
\]

what we see for the existing data set (5.3E20 protons on target)...

High energy \(\nu_e\) data

(remainder normalized)

Events below \(~1.5\) GeV still “in the box”

we are doing a “closed box” analysis in order to obtain the most convincing result!

- isolate data with the signature for \(\nu_\mu \rightarrow \nu_e\)
- use the rest (99%) to calibrate and constrain
Oscillation Search: Analysis Strategy

in-situ data is incorporated wherever possible...

0. MC tuning with calibration data
   - energy scale
   - PMT response
   - optical model of light propagation in the detector

1. MC fine-tuning with neutrino data
   - neutrino cross section nuclear model parameters
   - $\pi^0$ rate constraint

2. constraining systematic errors with neutrino data
   - combined oscillation fit to high-statistics $\nu_\mu$ data set and $\nu_e$ oscillation data set
   - example: $\nu_e$ from $\mu$ decay background

"I think you should be more explicit here in step two."
Oscillation Search: Analysis Strategy

in-situ data is incorporated wherever possible...

0. MC tuning with calibration data
- energy scale
- energy extrapolation
- PMT response
- optical model of light propagation in the detector
Oscillation Search: Analysis Strategy

*in-situ data is incorporated wherever possible...*

0. MC tuning with calibration data
   - energy scale
   - PMT response
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"I think you should be more explicit here in step two."
Incorporating $\nu_\mu$ Data: $\nu_\mu$ CCQE Event Selection

To find $\nu_\mu$ CCQE final state:

1. apply simple cuts on event time and number of hit PMTs to eliminate cosmics
2. tag muons by requiring 2 sub-events in time, with distance between $< 1m$
3. employ Fisher discriminant to get rid of CC1$\pi$ background
   - "single muon final state hypothesis" for inputs (proton ~invisible)
     result: 91% CCQE purity, ~100k events

PRELIMINARY unit-area normalization

- Data
  --- MC total
  ---- MC bgnd

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Incorporating $\nu_\mu$ Data: CCQE Cross Section

The $\nu_\mu$ CCQE data $Q^2$ distribution is fit to tune empirical parameters of the nuclear model ($^{12}$C target) this results in good data-MC agreement for variables not used in tuning.

The tuned model is used for both $\nu_\mu$ and $\nu_e$ CCQE, the only difference between these is lepton mass.
Incorporating $\nu_\mu$ Data: $\pi^0$ Mis-ID Background

Clean $\pi^0$ events are used to tune the MC rate vs. $\pi^0$ momentum

This results in good data-MC agreement for variables not used in tuning

$\pi^0$ events can reconstruct outside of the invariant mass peak when:

1. asymmetric decays fake 1 ring
2. 1 of the 2 photons exits the detector
3. high momentum $\pi^0$ decays produce overlapping rings
Oscillation Search: Analysis Strategy

in-situ data is incorporated wherever possible...

0. MC tuning with calibration data
   - energy scale
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1. MC fine-tuning with neutrino data
   - neutrino cross section nuclear model parameters
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2. constraining systematic errors with neutrino data
   - combined oscillation fit to high-statistics $\nu_\mu$ CCQE data set and $\nu_e$ oscillation data set
     - example: $\nu_e$ from $\mu$ decay background

"I think you should be more explicit here in step two."
**Incorporating $\nu_\mu$ Data: $\mu^+$-Decay $\nu_e$ Background**

$\nu_\mu$ CCQE events can infer the $\pi^+$ spectrum, which constrains $\mu^+$-decay $\nu_e$ & $\pi^+$-decay $\nu_\mu$ flux predictions

how to implement $\mu^+$-decay $\nu_e$ background constraint:

1. simulation based on external data predicts a central value and some range of possible $\nu_\mu(\pi)$ fluxes

2. make Data/MC ratio vs. $E_{\nu_{\text{QE}}}$ for the $\nu_\mu$ CCQE data set,

3. reweight each possible MC flux by the ratio from (2) including the $\nu_\mu$, the parent $\pi^+$, the sister $\mu^+$, and the niece $\nu_e$ 

*this works well because the $\nu_\mu$ energy is highly correlated with the parent $\pi^+$ energy*
Impact of reweighting the simulation using “fake data” (MC):

\begin{align*}
\nu_e (\mu^+) : &
\begin{cases}
\text{Before Cuts: } E_{\nu MC} \text{ (GeV)} \\
\text{Reweighted Before Cuts: } E_{\nu MC} \text{ (GeV)}
\end{cases}
\end{align*}

This reduction in the spread of possible fluxes translates directly into a reduction in the $\mu^+$-decay $\nu_e$ background uncertainty.
Incorporating $\nu_\mu$ Data: Combined Fit Example

Fit the $E_\nu^{QE}$ distributions of $\nu_e$ and $\nu_\mu$ events for oscillations, together

Raster scan in $\Delta m^2$ and $\sin^2 2\theta_{\mu e}$ ($\sin^2 2\theta_{\mu e} = 0$), calculate $\chi^2$ value over $\nu_e$ and $\nu_\mu$ bins

$$\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} (m_i - t_i) \ M_{ij}^{-1} (m_j - t_j)$$

For this example, systematic error matrix $M_{ij}$ includes predicted $\pi^+$ flux uncertainties only, for $\nu_e$ and $\nu_\mu$ bins

$$M_{ij} = \begin{pmatrix} \nu_\mu & \nu_\mu \nu_e \\ \nu_e \nu_\mu & \nu_e \end{pmatrix}$$

For this example, $m_i = "fake data" = MC with no oscillation signal

combined fit constrains uncertainties common to $\nu_e$ and $\nu_\mu$
Incorporating $\nu_\mu$ Data: Combined Fit Example

Example fit result for $\pi^+$ flux errors

To calculate an oscillation sensitivity curve:

1. assume no signal in the data, therefore best-fit point is always at $\sin^2 2\theta_{\mu e} = 0$ for all $\Delta m^2$ values (such that $m_i \approx t_i$)

2. calculate $\chi^2$ for all $(\Delta m^2, \sin^2 2\theta_{\mu e})$:

$$
\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \sum_{j=1}^{N_{\text{bins}}} (m_i - t_i) M^{-1}_{ij} (m_j - t_j)
$$

3. find $\sin^2 2\theta_{\mu e}$ where $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}} = 1$ for each $\Delta m^2$, systematic errors come in via $\Delta \chi^2$

90, 99% confidence level allowed regions from LSND

these sensitivities are only examples to illustrate what the combined fit does
Incorporating $\nu_\mu$ Data: Combined Fit Example

Example fit result for $\pi^+$ flux errors

90, 99% confidence level allowed regions from LSND

MiniBooNE 90% confidence level sensitivity limit with:

statistical errors only

these sensitivities are only examples to illustrate what the combined fit does
Incorporating $\nu_\mu$ Data: Combined Fit Example

Example fit result for $\pi^+$ flux errors

90, 99% confidence level allowed regions from LSND

MiniBooNE 90% confidence level sensitivity limit with:

- statistical errors only
- $\pi^+$ flux errors from prediction, $\nu_e$ fit only

these sensitivities are only examples to illustrate what the combined fit does
Incorporating $\nu_\mu$ Data: Combined Fit Example

Example fit result for $\pi^+$ flux errors

90, 99% confidence level allowed regions from LSND

MiniBooNE 90% confidence level sensitivity limit with:

- Statistical errors only
- $\pi^+$ flux errors from prediction, $\nu_e$ fit only
- $\pi^+$ flux errors from reweighted prediction, $\nu_e$ fit only

these sensitivities are only examples to illustrate what the combined fit does

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90, 99% confidence level allowed regions from LSND

Example fit result for $\pi^+$ flux errors

MiniBooNE 90% confidence level sensitivity limit with:

- statistical errors only
- $\pi^+$ flux errors from prediction, $\nu_e$ fit only
- $\pi^+$ flux errors from reweighted prediction, $\nu_e$ fit only
- $\pi^+$ flux errors from prediction, combined $\nu_e$ and $\nu_\mu$ fit

these sensitivities are only examples to illustrate what the combined fit does

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Of course, there are many other sources of systematic error as well...

Summary of systematic error sources:

1. neutrino flux predictions
   - $\pi^+$, $\pi^-$, $K^+$, $K^-$, $K^0$, n, and p total and differential cross sections
   - secondary interactions
   - focusing horn current
   - target + horn system alignment

2. neutrino interaction cross section predictions
   - nuclear model
   - rates and kinematics for relevant exclusive processes
   - resonance width and branching fractions

3. detector modelling
   - optical model of light propagation in oil
   - PMT charge and time response
   - electronics response
   - neutrino interactions in dirt surrounding detector hall

MiniBooNE expected sensitivity covers LSND 90% C.L. allowed region at -3σ
Incorporating the $\nu_\mu$ data set provides a valuable constraint for the $\nu_e$ appearance oscillation search.

- uncertainty on $\nu_e$ from $\mu$ decay is highly constrained
- combined fit naturally incorporates $\nu_\mu$ data constraint for all sources of systematic error
- can constrain and cross-check \textit{all} of the $\nu_e$ and $\nu_\mu$ backgrounds with in-situ data

MiniBooNE is close to the finish line, oscillation results soon!
Other Slides
**MiniBooNE Overview: Optical Model Tuning**

The optical model describes light propagation in the detector:

- Cherenkov and scintillation emission
- scattering, fluorescence, and extinction
- PMT detection efficiency

**External measurements & laser calibration**

**First calibration with michels**

**Calibration of scintillation light with NC events**

**Final calibration with michels**

**Validation with cosmic muons, $\nu_\mu$ events, and NuMI $\nu_e$ events**

This is hard: need wavelength, angular, and time dependence + normalization for each process!
MiniBooNE Overview: Boosting

“A procedure that combines many weak classifiers to form a powerful committee”

A decision tree that is forced to try harder on mis-classified events

This tree is not unique!
A set of decision trees can be developed

Each data event is then sent through the full set of trees.
For each tree, the data event is assigned
+1 if it is identified as signal,
-1 if it is identified as background.

The total for all trees is then combined.
The resulting “score” for the event can be thought of as a probability that it is signal.