MiniBooNE: Status and Prospects

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Outline

- State of neutrino mixing measurements
  - Without LSND
  - LSND and Karmen
- Experiment
  - Beam
  - Detector
  - Calibration and cross checks
  - Analysis
- Recent Results
- Future Plans and outlook
  - Anti-neutrino running
  - Path to oscillation results
Neutrinos are produced and detected as weak eigenstates ($\nu_e, \nu_\mu$, or $\nu_\tau$). These can be represented as linear combination of mass eigenstates. If the above matrix is not diagonal and the masses are not equal, then the net weak flavor content will oscillate as the neutrinos propagate. 

**Example:** if there is mixing between the $\nu_e$ and $\nu_\mu$:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix} = \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

then the probability that a $\nu_e$ will be detected as a $\nu_\mu$ after a distance $L$ is:

\[
P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27 \cdot \Delta m^2 \cdot \frac{L}{E}\right)
\]

Only measure magnitude of the difference of the squares of the masses.
Probing Neutrino Mass Differences

Different experiments probe different ranges of \( \frac{L}{E} \) energy.

**Accelerators** use \( \pi \) decay to **directly** probe \( \nu_\mu \rightarrow \nu_e \)

**Reactors** use use **disappearance** to probe \( \nu_e \rightarrow ? \)

Cerenkov detectors directly measure \( \nu_\mu \) and \( \nu_e \) content in atmospheric neutrinos. Fit to \( \nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau \) mixing hypotheses.

Also probe with “long baseline” accelerator and reactor experiments

**Solar neutrino experiments** typically measure the disappearance of \( \nu_e \).
SuperKamiokande Atmospheric Result

- Huge water Cerenkov detector can directly measure $\nu_\mu$ and $\nu_e$ signals.
- Use azimuthal dependence to measure distance traveled (through the Earth).
- Positive result announced in 1998.
- Consistent with $\nu_\mu \leftrightarrow \nu_\tau$ mixing.
SNO Solar Neutrino Result

- Looked for Cerenkov signals in a large detector filled with heavy water.
- Focus on $^8$B neutrinos
- Used 3 reactions:
  - $\nu_e + d \rightarrow p + p + e^-$: only sensitive to $\nu_e$
  - $\nu_x + d \rightarrow p + n + \nu_x$: equally sensitive to $\nu_e, \nu_\mu, \nu_\tau$
  - $\nu_x + e^- \rightarrow \nu_x + e^-$: 6 times more sensitive to $\nu_e$ than $\nu_\mu, \nu_\tau$
- Consistent with initial full SSM flux of $\nu_e$'s mixing to $\nu_\mu, \nu_\tau$

Favor: $\Delta m^2 \approx 5 \times 10^{-5} \text{eV}^2; \tan^2 \theta \approx .34$
Reactor Experimental Results

- Single reactor experiments (Chooz, Bugey, etc). Look for $\nu_e$ disappearance: all negative
- KamLAND (single scintillator detector looking at ALL Japanese reactors): $\nu_e$ disappearance consistent with mixing.
K2K

- First “long baseline” accelerator experiment
  - Beam from KEK PS to Kamiokande, 250 km away
  - Look for $\nu_\mu$ disappearance (atmospheric “problem”)
  - Results consistent with mixing

No mixing

Allowed Mixing Region

Events / 0.2 (GeV)

$E_{\nu}^{\text{rec}}$ (GeV)

$\Delta m^2$ (eV$^2$)

$\sin^2 2\theta$

Best fit

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Three Generation Mixing (Driven by experiments listed)

- **General Mixing Parameterization**

\[
\begin{pmatrix}
    c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\
    -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\
    s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23}
\end{pmatrix}
\]

- **CP violating phase**

### Quarks

\[
V_{CKM} \approx \begin{pmatrix}
1 & 0.2 & 0.005 \\
0.2 & 1 & 0.04 \\
0.005 & 0.04 & 1
\end{pmatrix}
\]

### Neutrinos

\[
U_{MNS} \approx \begin{pmatrix}
0.8 & 0.5 & ? \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\]

- Almost diagonal
- Third generation weakly coupled to first two
- "Wolfenstein Parameterization"

- Mixing large
- No easy simplification
- Think of mass and weak eigenstates as totally separate
How large is this?

\[ \Delta m^2 \sim 2 \times 10^{-3} \text{ eV}^2 \]

atmospheric

\[ \Delta m^2 \sim 8 \times 10^{-5} \text{ eV}^2 \]

solar

? "Normal" hierarchy

"Inverted" hierarchy

Which one?
The LSND Experiment (1993-1998)

- 800 MeV proton beam from LANSCE accelerator
- Water target
- Copper beamstop
- ~30 m
- LSND Detector
- Energy 20-50 MeV

**Signature**
- Cerenkov ring from electron
- Delayed $\gamma$ from neutron capture

\[ \nu_e + p \rightarrow e^+ + n \]
- Only exclusive appearance result to date
- Problem: $\Delta m^2 \sim 1 \text{ eV}^2$ not consistent with other results with simple three generation mixing
Possibilities

- 4 neutrinos?
  - We know from Z lineshape there are only 3 active flavors
  - Sterile?

- CP or CPT Violation?

- More exotic scenarios?

- LSND Wrong?
  - Can’t throw it out just because people don’t like it.
Karmen II Experiment: not quite enough

- Pulse 800 MeV proton beam (ISIS)
- 17.6 m baseline
- 56 tons of liquid scintillator
- Factor of 7 less statistical reach than LSND
- \( \rightarrow \) NO SIGNAL
- Combined analysis still leaves an allowed region
Role of MiniBooNE

- Boo(ster) N(eutrino) E(xperiment)
  - Full “BooNE” would have two detectors
- Primary Motivation: Absolutely confirm or refute LSND result
  - Optimized for L/E ~ 1
  - Higher energy beam -> Different systematics than LSND
- Timeline
  - Proposed: 12/97
  - Began Construction: 10/99
  - Completed: 5/02
  - First Beam: 8/02
  - Began to run concurrently with NuMI: 3/05
  - Presently ~7E20 proton on target in neutrino mode
    - More protons that all other users in the 35 year history of Fermilab combined!
  - Oscillation results: 2006
MiniBooNE Neutrino Beam (not to scale)

- 8 GeV Protons
  - ~ \(7 \times 10^{16}\) p/hr max
  - ~ 1 detected neutrino/minute
  - L/E ~ 1

“Little Muon Counter” (LMC): to understand K flux
Detector

- 950,000 l of pure mineral oil
- 1280 PMT’s in inner region
- 240 PMT’s outer veto region
- Light produced by Cerenkov radiation and scintillation

Trigger:
- All beam spills
- Cosmic ray triggers
- Laser/pulser triggers
- Supernova trigger
Neutrino Detection/Particle ID

\[ \nu_e \rightarrow \nu_e + e^- \]

\[ \nu_\mu \rightarrow \nu_\mu + \mu^- \]

Important Background!!!
Delivering Protons

- Requirements of MiniBooNE greatly exceed the historical performance of the 30+ year old 8 GeV Booster, pushes...
  - Average repetition rate
  - Above ground radiation
  - Radiation damage and activation of accelerator components

- Intense Program to improve the Booster
  - Shielding
  - Loss monitoring and analysis
  - Lattice improvements (result of Beam Physics involvement)
  - Collimation system

- Very challenging to continue to operate 8 GeV line during NuMI/MINOS operation
  - Once believed impossible
  - Element of lab’s “Proton Plan”
  - Goal to continue to deliver roughly $2 \times 10^{20}$ protons per years to the 8 GeV program for at least the next few years.
Running MiniBooNE with NuMI

Note: these projections do not take into account the collider turning off in 2009

- NuMI rates would go up at least 20%, possible higher
- Major operational changes could make continued operation of 8 GeV line very difficult
Beam to MiniBooNE

NuMI Running

Number of Horn Pulses
To date: 167.12 million
Largest week: 2.46 million
Latest week: 1.89 million

Number of Protons on Target
To date: 6.8491 E20
Largest week: 0.1084 E20
Latest week: 0.0787 E20

Number of Neutrino Events
To date: 711507
Largest week: 11447
Latest week: 3091

~7 x 10^{20} protons
Analysis: Modeling neutrino flux

- Production
  - GEANT4 model of target, horn, and beamline
  - MARS for protons and neutrons
  - Sanford-Wang fit to production data for $\pi$ and $K$
  - Mesons allowed to decay in model of decay pipe.
  - Retain neutrinos which point at target
  - Soon hope to improve model with data from the HARP experiment taken from a target identical to MiniBooNE

![Graph showing flux distribution]
**$\nu_\mu$ Interactions**

- **Cross sections**
  - Based on NUANCE 3 Monte Carlo
    - Use NEUT and NEUEN as cross checks
  - Theoretical input:
    - Llewellyn-Smith free nucleon cross sections
    - Rein-Sehgal resonant and coherent cross-sections
    - Bodek-Yang DIS at low-$Q^2$
    - Standard DIS parametrization at high $Q^2$
    - Fermi-gas model
    - Final state interaction model

- **Detector**
  - Full GEANT 3.21 model of detector
  - Includes detailed optical model of oil
  - Reduced to raw PMT hits and analyzed in the same way as real data
Background

- If the LSND best fit is accurate, only about a third of our observed rate will come from oscillations.
- Backgrounds come from both intrinsic $\nu_e$ and misidentified $\nu_\mu$.

Energy distribution can help separate...
Blindness

- Given the low signal to background ratio and the inherent difficulty of the analysis, there are many opportunities for unintentional bias.
- Therefore, we consider a blind analysis essential.
- General philosophy: guilty until proven innocent.
- Events go “into the box” unless they are specifically tagged as being non-signal events, e.g.
  - **Muons**
    - Single $\mu$-like ring
    - Topological cuts
  - $\pi^0$
    - No Michel electron
    - Clear two-ring fit, both with $E>40$ MeV
- Will only look at remaining data when we are confident that we model the beam and detector well.
- Note: This still allows us to look at the majority of our data!
Characterizing the Detector

- **Laser Calibration**
  - Laser pulses illuminate one of 4 flasks which scatter light isotropically
  - Used to understand PMT response

- **Cosmic Muons**
  - Muon Tracker used in conjunction with “cubes” to trigger on a particular endpoint (energy)
  - Vital in understanding energy scale
- Electrons from muon decay (Michel electrons)
  - Vital for understanding signal events.

- $\pi^0$ Events
  - Help to understand higher energy $\nu_e$
  - Help fix energy scale
Selecting Neutrino Events

- Collect data from -5 to +15 usec around each beam spill trigger.
- Identify individual “events” within this window based on PMT hits clustered in time.
Muon Reconstruction

- Muon reconstruction is based on a fit to PMT's clustered in time.
- Position and time of arrival are used to reconstruct the origin, direction and path length of the muon track segment.
Charged Current Quasi-elastic Events

- Veto hits < 6
- Tank hits > 200
- PMT position/time fit consistent with muon

Preliminary
Monte Carlo error bars from:
- neutrino σ,
- light extinction,
- & light scattering length uncertainties

Angular distribution
Recent Results: $\nu_\mu + X \Rightarrow X' + \mu + \pi^+$ (CCPiP)*

Important for understanding backgrounds and nuclear cross sections.

*analysis by M. Wascko and J. Monroe
Signature of CCpiP Event

(only charged tracks shown)

- Look for exactly three events:
  - First promptly with the beam
  - Second two within the ~15 usec trigger window
- First event consistent with CC muon
- Second two consistent with Michel decays.
**CCPiP Results**

- **CCPiP/CCQE ratio**
- **Corrected for efficiencies**

PRELIMINARY

Monte Carlo error bars from:
- neutrino $\sigma$,
- light extinction,
- light scattering length uncertainties

![Graph showing CCpiP/CCQE ratio](image)

![Graph showing reconstructed E. (GeV) after CC1x+ Cuts](image)

![Graph showing reconstructed $\cos(\theta_p)$ after CC1x+ Cuts](image)

PRELIMINARY

$$(\text{CCPiP/CCQE}) \sigma \text{ vs. } E_\nu \text{ (GeV)}$$
Additional Cross-checks: Neutrinos from NuMI beamline*

- NuMI decay pipe extends to almost just below the MiniBooNE detector

*primarily analysis of A. Aguilar

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Path to “opening the box”

- Our present sample neutrino data is sufficient to release an oscillation result
  - We are not yet confident enough in our analysis to do so
- Continue to refine Monte Carlo until open box samples agree within errors
  - HARP data on MiniBooNE target an important constraint
- Generate systematic error matrix by varying all important production and optical model parameters (“Unisim Monte Carlo”).
- When confident, practice on a fake oscillation signal.
Experimental Sensitivity

- No signal
  - Can exclude most of LSND at 5σ

- Signal
  - Can achieve good $\Delta m^2$ separation

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Accommodating a Positive Signal

- We know from LEP that there are only 3 active, light neutrino flavors.
- If MiniBooNE confirms the LSND results, it might be evidence for the existence of sterile neutrinos.

Diagram showing 3+1 and 3+2 models with masses $m_1$, $m_2$, $m_3$, and $m_4$. The LSND primarily $\nu_s$.
Everybody Loves a Mystery

- **3+2 Sterile neutrinos**
- **MaVaN & 3+1**
  - Hung (hep-ph/0010126)
- **Sterile neutrinos**
  - Kaplan, Nelson, and Weiner (hep-ph/0401099)
    - Explain Dark Energy?
- **CPT violation and 3+1 neutrinos**
  - Barger, Marfatia & Whisnant (hep-ph/0308299)
    - Explain matter/antimatter asymmetry
- **Lorentz Violation**
  - Kostelecky & Mewes (hep-ph/0406035)
- **Extra Dimensions**
  - Pas, Pakvasa, & Weiler (hep-ph/0504096)
- **Sterile Neutrino Decay**
  - Palomares-Ruiz, Pascoli & Schwetz (hep-ph/0505216)
Near Future: MiniBooNE antineutrino running

As we speak, MiniBooNE is switching the horn polarity to run in antineutrino mode

- Inherently interesting
  - Not much anti-neutrino data
- Directly address LSND signal
- Important for understanding our own systematics and those of other experiments
- Problems:
  - Cross section not well known
  - Lower rate (about $\frac{1}{4}$)
  - Wrong sign background

Example of new physics:
Conclusions and Outlook

- MiniBooNE has been running for over three years, and continues to run well in the NuMI era.
- The analysis tools are well developed and being refined to achieve the quality necessary to release the result of our blind analysis.
- Recent results for CCQE and CCPiP give us confidence on our understanding of the detector and data.
- Look forward to many interesting results in 2006.