MiniBooNE Progress and Little Muon Counter Overview

- Neutrino Introduction and MiniBooNE Motivation
- MiniBooNE Detector and LMC Calibration and Performance
- Progress Toward Physics Results

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Neutrino Characteristics

- **Existence**
  - Pauli postulated existence to explain beta decay energy spectrum (1930).
  - Reines and Cowan made first observation (1953).

- **Neutrinos come in different flavors.**
  - Discovery of $\nu_\mu$ (neutrino associated with muon weak interactions) by Lederman, Schwartz, Steinberger, et al. at Brookhaven (1962).
  - Observation of $\nu_\tau$ by DONUT experiment at Fermilab (2000).

- **Neutrinos have mass contrary to previous assumptions.**
  - Ray Davis detects solar neutrinos at Homestake and observes deficit in expected yield (1968).
  - IMB and Kamiokande experiments detect atmospheric neutrinos and observe deficit (1985).
  - LSND, SNO, KamLAND, Super-Kamiokande provide latest neutrino oscillation measurements raising even more questions about the fundamental nature of neutrinos (1994 - present).
Positive Neutrino Oscillation Results

\[ \mathcal{P}(\nu_{\alpha} \rightarrow \nu_{\beta}) = (\sin^2 2\theta)(\sin^2 \{1.27 \Delta m^2 L/E\}) \]

\( \theta \) is mixing angle between weak and mass eigenstates
\( \Delta m^2 = m_2^2 - m_1^2 \) (eV\(^2\))
L is travel distance of neutrino (km)
E is neutrino energy (GeV)

- oscillation signals:

**LSND:** \( \Delta m^2 \sim 10^0 \text{ eV}^2 \)  
**Atmospheric:** \( \Delta m^2 \sim 10^{-3} \text{ eV}^2 \)  
**Solar:** \( \Delta m^2 \sim 10^{-5} \text{ eV}^2 \)

What to do?
1. Some experiment is seeing something that's not oscillations.
2. Add more sterile neutrinos: 1, 2, 3 ...
3. Something else?

3 neutrinos allow only 2 independent values of \( \Delta m^2 \)
The LSND Experiment
(Liquid Scintillator Neutrino Detector located at Los Alamos)

$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance measurement

The neutrino source:

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

The detector:

- Liquid scintillator detects both Cherenkov and scintillation light. For $\bar{\nu}_e p \to e^+ n$:
  - Č+ scintillation light from $e^+$
  - Scintillation light from $n$ capture
LSND Result

Excess ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, appearance): $87.9 \pm 22.4 \pm 6.0$

Oscillation probability:
$(0.264 \pm 0.067 \pm 0.045)\%$ (muon decay at rest)

$3.8 \sigma$ statistical significance of excess

Combined analysis with KARMEN2 gives large allowed region. Confirmation is crucial!
Enter MiniBooNE

Goal: Test LSND with 5 $\sigma$ sensitivity over whole allowed range.

- Higher statistics
- Different signature
- Different backgrounds
- Different systematics

MiniBooNE!
MiniBooNE Layout at Fermilab

Proton Beam
- 8 GeV protons from Booster
- Into MiniBooNE beamline

Secondary Beam
- Mesons from protons striking Be target
- Focused by horn and monitored by Little Muon Counter

Neutrino Beam
- Neutrinos from meson decay in 50 m pipe
- Pass through 450 m dirt (and oscillate?) to reach detector
The Booster

- 8 GeV proton accelerator supplies beam to all Fermilab experiments.
- To meet demands of all experiments the Booster runs at record intensity.
- MiniBooNE runs simultaneously with collider program with negligible impact on their operations.
Protons and Neutrinos to MiniBooNE

- MiniBooNE has been taking data for a little over 2 ½ years.
- Note that MiniBooNE has
  - Received $6 \times 10^{20}$ protons on target
  - Recorded over 630,000 neutrino events at detector.
Neutrino Candidates/Protons on Target

$\chi^2 / \text{ndf}$ 139 / 93

Mean $1.089 \pm 0.001483$
Magnetic Focusing Horn Basics

- A horn focuses charged particles through a magnetic field.
- The MiniBooNE horn generates a toroidal magnetic field between its conductors through an electric current going
  - along the inner conductor
  - back down the outer conductor along the opposite direction
- Focusing the neutrino parents increases the neutrino flux at the downstream detector.
Target and Magnetic Focusing Horn

- Protons impinge on 71cm long, air cooled beryllium target embedded in horn.
- Horn focusing of secondary beam increases $\nu$ flux by factor of ~7.
- Horn current can be reversed to select $\bar{\nu}$.
- $\bar{\nu}$ running possible for 2006.
- 170 kA pulses, 143 $\mu$s long at ~5 Hz.

- First horn lasted over 90 million pulses.
- Current horn has received over 35 million pulses.
Expected $\nu$ Flux at MiniBooNE Detector

- Fluxes generated with GEANT4-based beam Monte Carlo.
- Intrinsic $\nu_e$ flux about 3 orders of magnitude smaller than $\nu_\mu$ flux but $\nu_e$ flux from kaons not well measured.
- Intrinsic $\nu_e$ flux is comparable to $\nu_e$'s from oscillations.
- Sources of intrinsic $\nu_e$'s will be constrained through
  - Observed $\nu_\mu$ (from $\mu$ decay) rate at detector
  - Absorbers at 25 m and 50 m from target.
  - Improved particle production modeling.
  - Cross section measurements from HARP and Brookhaven E910.
  - In situ kaon monitoring with the Little Muon Counter.

Signal $\nu_e$'s: $\nu_e$'s from $\nu_\mu$ oscillations
Intrinsic $\nu_e$'s: $\nu_e$'s from kaon and muon decay
The LMC will measure momenta of muons from

\[ K \rightarrow \mu \nu, \pi \mu \nu \quad (p_{T,\text{max}} = 236 \text{ MeV/c}, 216 \text{ MeV/c}) \]

\[ \pi \rightarrow \mu \nu \quad (p_{T,\text{max}} = 30 \text{ MeV/c}) \]

At large angles, high momentum muons come from kaons.

Goal: Determine the rate of \( \nu_e \)’s from kaons to less than 10% uncertainty.
The Neutrino Detector

- 40' (12 m) diameter sphere
- 250,000 gallons of pure mineral oil (3:1 Cherenkov:scintillation light output)
- Optically isolated inner region with 1280 PMT's (10% coverage)

- Veto region (240 PMT's)
- Muon tracker for cosmic rays
Selecting Beam Events

- MiniBooNE DAQ collects data during 20 μs window starting just before beam pulse.
- Even with no cuts, the 1.6 μs beam pulse is clearly visible.
- With 2 simple cuts, our signal-to-noise ratio is about 1000/1.
- Unlike LSND, non-beam backgrounds aren't a concern for MiniBooNE.
Seeing $\nu_\mu$ and $\nu_e$ Interactions in the Detector

Look for outgoing charged particles produced with no activity in the veto.

charged current quasi-elastic

$\nu_\mu$ $\mu^-$

$\nu_e$ $e^-$

single pion production

$\nu_\mu$ $\nu_\mu$

$\Delta$ $\pi^0$
Particle ID

PMT's measure:

- Charge (Cherenkov and scintillation light, light output $\propto$ size.)
- Times (Red is early, Blue is late.)
Understanding the Detector

To calibrate PMT's, we measure

- PMT charge
- Timing response
- Oil attenuation length

Laser Flasks

- 397 nm laser light
- Four Ludox-filled flasks fed by optical fiber from laser
Stopping Muon Calibration System

Scintillator tracker above the tank

Sample consists of muons with energies up to 700 MeV. This sample calibrates:
- energy measurements
- vertex reconstruction
- angle reconstruction

Optically isolated scintillator cubes in tank:
- six 2-inch (5 cm) cubes
- one 3-inch cube

Muon Tracker Data
400 MeV < E_μ < 500 MeV

Fit func: C_1 \cdot e^{\left(\frac{\theta^2}{2\sigma^2}\right)}
σ = 4.5°

PRELIMINARY
Cosmic Ray/Beam Data Agreement

Cosmics and beam data agree $\Rightarrow$ cosmics good for calibration
Michel Electron Measurements (electrons from the decay of stopped muons)

- Michel electrons from cosmic rays and beam-induced muons
- Cosmic ray muon lifetime in oil
  - measured: $\tau = 2.15 \pm 0.02$ $\mu$s
  - expected: $\tau = 2.13$ $\mu$s
    (8% $\mu^-$ capture)
- Energy scale and resolution at Michel endpoint (53 MeV)
Data/MC Agreement in Vertex Reconstruction

Beam events:
- NHIT > 200
- NVETO < 6
- r < 450cm
- Timing
Little Muon Counter Analysis

- Description of components
- LMC event reconstruction and data
- Preliminary muon spectrum
Little Muon Counter Schematic Drawing

- **Incoming muon**
- **Collimator**
- **Fiber tracker**
- **Permanent Magnet**
- **Tungsten Plates**
- **Muon filter range stack**
- **Veto counters**
- **Fiber tracking planes** (4 x-planes, 2 upstream y planes)
- **Muon filter counters**
- **Muon acceptance counters**

Axes:
- **x**
- **y (out of page)**
- **z**
Little Muon Counter Collimator and Veto Counters

Collimator

- 81 inches long consisting of steel with inner tungsten core.
- Inner hole tapered so that tracks traveling down the hole must have originated from MiniBooNE secondary beam.
- Downstream hole diameter is 6 mm and upstream hole diameter is 10 mm.

Veto counters – 4 scintillation counters between the collimator and fiber tracker surrounding downstream hole of collimator.
Fiber Tracker Spectrometer

- Permanent magnet provides 2.27 kgauss magnetic field over 23 cm.
- 6 planes of 1 mm diameter scintillating fibers.
  - Each of 6 planes consists of 2 parallel subplanes staggered by ½ fiber diameter to remove inefficiencies of tracks going between fibers.
  - 4 planes instrumented along magnetic field bend direction, 2 upstream of the magnet and 2 downstream of the magnet.
  - 2 planes instrumented along direction perpendicular to both bend direction and beam direction, both upstream of the magnet.
Little Muon Counter Muon Acceptance Counter and Muon Range Stack

Muon Acceptance Counters – 4 scintillation counters after tracker
  - 2 counters in LMC beamline
  - 1 counter above beamline and 1 below beamline

Muon Filter – Range stack to identify muons
  - 8 layers of alternating tungsten sheets and scintillation counters.
  - Each tungsten layer is 2 inches thick.
  - 1.3 GeV/c and higher muons will penetrate all 8 layers.
LMC Event Reconstruction

- Coincidences from 6 layers of the scintillating fiber tracker are formed.
  - All hits within 5 ns of the mean time of hits are kept.
  - We allow for multiple hit combinations in a coincidence.
- For each 6-fold coincidence, a tracking algorithm determines
  - momentum
  - momentum uncertainty
  - a track reconstruction $\chi^2$ for the 4 x-hits (magnet field bend coordinate) coming from a single charged track bent by the magnetic field.
- All hits from the filter, veto counters, and muon acceptance counters within 5 ns of the tracker coincidence mean time are added to the event.
- A filter penetration range is determined from the filter hits
  - Muon momentum is proportional to range while hadrons will penetrate only one or two layers.
  - One inefficient layer is allowed in the range determination.
- LMC analysis is being done on data events and Monte Carlo samples.
Determining Momentum With the Fiber Tracker

Small angle approximation allows track trajectory to be taken as two line segments connected at middle of magnet.

From the locations and location uncertainties of the 4 x hits, the optimum upstream slope, downstream slope, and intersection point can be determined analytically by minimizing a $\chi^2$.

- 4 x hits
- 2 slopes
- 1 intersection point
- $\Rightarrow \chi^2$ with one degree of freedom

Optimization provides $p$, $\sigma_p$, and $\chi^2$.

\[ p = q B L \cot(\theta) \]
\[ B = 2.27 \text{ kgauss}, \]
\[ L = 23 \text{ cm} \]
Veto Counter Arrangement

4 veto counters are between collimator and spectrometer.

The 10 mm diameter hole is the same as the downstream collimator hole diameter, and is designed to be the defining aperture of reconstructed tracks.
4 scintillator counters located between fiber tracker and muon range stack.

Middle two counters may be helpful in selecting tracks which went through all 6 tracker layers.
LMC Event Displays – Data Pion Candidate

Muon Filter
Muon Acceptance Counters
4 x Tracker layers
Magnet between 2X and 3X (field into page)

2 y Tracker Layers
Veto Counters

SUBEVENT 8
$\chi^2 = 0.15$
$p = -1.27 \text{ GeV/c}$
LMC Event Displays – Data Muon Candidate

Muon Filter
Muon Acceptance Counters
4 x Tracker layers
Magnet between 2X and 3X (field out of page)

2 y Tracker Layers
Veto Counters
Momentum/Muon Range Correlation, Data

- Range (x coordinate) from muon filter.
- Momentum (y coordinate) from tracker.
- Expected distributions:
  - Muons: Momentum proportional to penetration depth.
  - Hadrons: Penetrate up to about 2 layers.
-Muon and hadron populations demonstrate
  - Momenta are well-measured by tracker.
  - Muon filter is identifying muons.

Momentum (GeV/c) vs. Range
Preliminary Muon Spectrum at the LMC, Signal and Background Muons

Clean muons: Signal for muon spectrum. Dirt muons: Background to muon spectrum.

LMC collimator designed to let in clean muons and reject dirt muons.
Muon Spectrum Procedure

- Use the tracker for momentum measurements and the filter for muon range.
- Apply the following tracker cuts:
  - Good track reconstruction.
  - Track must project to active areas of all 6 tracker planes.
  - Track must project to upstream hole of LMC collimator. This is to keep clean muons and reject dirt muons. This cut is loose for now.
- Plot all events whose momentum and range are consistent with correlation expected for muons.
Fluctuations in distributions caused by low Monte Carlo statistics.

Data muon spectrum looks roughly like this MC simulation, but plot is not yet approved for posting on public web pages.
Next Steps for LMC Momentum Spectrum

- Refine and develop muon spectrum measurement
  - Understand dirt muon background
  - Determine amount of non-muon backgrounds
  - Account for tracker and filter efficiencies
  - Incorporate momentum uncertainties

- Possible special data runs with collimator at different positions to understand alignment issues and which may be helpful for understanding dirt muon contributions.

- Determine kaon content of MiniBooNE secondary beam to 10% uncertainty.
$\nu_e$ Appearance Sensitivity

Preliminary estimates of backgrounds and signal based on $10^{21}$ protons on target.

Cover LSND allowed region at 5 $\sigma$.
Currently expect results in 2005.
MiniBooNE Non-Oscillation Physics

**CC quasi-elastic**
- abundance ~40%
- simple topology
- one muon-like ring
- proton rarely above Cherenkov threshold
- ~88% purity
- kinematics: $E_\mu, \theta_\mu, E_\nu, Q^2$
- relatively well-known cross-section and will be used for oscillation analysis

**CC $\pi^+$**
- proton rarely above Cherenkov threshold: only muon ring reconstructed in primary event
- $\pi^+$ and primary $\mu^-$ both leave stopped $\mu$-decay electrons.
- kinematics: $E_\mu, \theta_\mu, E_\nu, Q^2$
- Measure (CC $\pi^+$/CC quasi-elastic) cross-section ratio.

**NC $\pi^0$ production**
- resonant:
  $\nu + (p/n) \rightarrow \nu + \Delta$
  $\Delta \rightarrow (p/n) + \pi$
- coherent:
  $\nu + C \rightarrow \nu + C + \pi^0$
- abundance ~7%
- $\pi^0 \rightarrow \gamma \gamma$ two rings
- $E_1, E_2$ from Cherenkov intensities
- reconstruct invariant mass of two photons
- background to $\nu_e$ appearance and limits on sterile $\nu$
CC $\nu_\mu$ Quasi-Elastic Events

- Event selection
  - Topology
    - Ring sharpness
    - on- vs. off-ring hits
  - Timing
    - Single $\mu$-like ring
    - Prompt vs. late light
- Variables combined in a Fisher discriminant
- Data and MC relatively normalized
- **Red Band**: MC with current uncertainties from
  - Flux prediction
  - $\sigma_{\text{CCQE}}$
- **Yellow Band**: MC with current uncertainties from
  - Flux prediction
  - $\sigma_{\text{CCQE}}$
  - Optical property variations
CC $\nu_\mu$ Quasi-Elastic Events

(used for oscillations analysis)

$E_\nu$ reconstruction:

• Assume $\nu_\mu n \rightarrow \mu^- p$.
• Use $E_\mu$, $\theta_\mu$, to get $E_\nu$.

Energy Resolution vs. $\nu_\mu$ Energy

PRELIMINARY, MC, no background

$$\left( \frac{\Delta E_\nu}{E_{\nu,\text{Gen}}} \right)^2 = a^2 + \left( \frac{b}{E_{\nu,\text{Gen}}} \right)^2 + \left( \frac{c}{E_{\nu,\text{Gen}}} \right)^2$$

$a = 3.788008e-02$
$b = 8.364264e-02$
$c = 0.000000e+00$

$<10\%$ for $E_\nu>800$ MeV
CC $\pi^+$ Analysis, Muon Reconstruction

- Reconstruct CC $\pi^+$ events from events with $\mu^-$ and $\mu$-decay electrons from $\pi^+$ and $\mu^-$.  
- Data and Monte Carlo samples are relatively normalized.
- Monte Carlo uncertainties are from 
  - Neutrino cross section
  - light extinction
  - light scattering length uncertainties
  - Uncertainties from flux predictions are not included as cross-section is measured relative to CC quasi-elastic cross-section.
- Reconstructed muon angle and energy distributions not yet approved for posting on public web pages.
CC $\pi^+$ Analysis, Neutrino Reconstruction

- Reconstruct neutrino energy from measured muon energy and direction.
- Assume 2-body quasi-elastic kinematics and that $\pi^+$ and $p'$ parent is $\Delta^{++}(1232)$.
- Monte Carlo uncertainties are from
  - Neutrino cross section
  - light extinction
  - light scattering length uncertainties
- Reconstructed neutrino energy distribution not yet approved for posting on public web pages.
CC $\pi^+$ Analysis, Relative Cross Section Measurement

- Normalize CC $\pi^+$ cross section to CC quasi-elastic cross section as a function of neutrino energy.

- Cross section ratio cut efficiency corrections from
  - High energy CCQE degradation from exiting muon.
  - Low energy cut-off by kinematic threshold.

- Systematic errors from
  - Neutrino cross section uncertainties
  - Photon extinction and scattering length uncertainties
  - Energy scale uncertainty
NC $\pi^0$ Production – Mass

- $N_{\text{TANK}} > 200$, $N_{\text{VETO}} < 6$, no decay electron
- Perform two-ring fit on ALL events.
- Ring energies $> 40$ MeV
- Fit mass peak to extract signal yield including background shape from MC.

- resonant:
  \[ \nu + (p/n) \rightarrow \nu + \Delta \]
  \[ \Delta \rightarrow (p/n) + \pi \]

- coherent:
  \[ \nu + \pi \rightarrow \nu + \pi + \pi^0 \]

PRELIMINARY

No. $\pi^0$'s = 7208±144
\[ \chi^2/\text{NDF} = 150.06/98 \]
Mass = 0.1391 ± 0.0005 GeV/c$^2$

note bkgd also peaking
NC $\pi^0$ Production – Production Angle

- Production angle is sensitive to production mechanism: coherent is highly forward-peaked.

- Data and MC are relatively normalized.

- MC shape assumes Rein-Sehgal cross-sections.

- Discrepancy near $\cos(\theta_{\pi^0}) = 1$ may indicate that coherent cross-section is lower than expected.
NC $\pi^0$ Production – Decay Angle and Momentum

$\theta_{\text{CM}}$ is angle of $\pi^0$ decay photons in $\pi^0$ rest frame with respect to neutrino direction.
Conclusions

- All detector and reconstruction algorithms are working and are providing our first physics results.
- MiniBooNE has made important preliminary measurements of neutrino interaction processes important for the oscillation analysis.
  - CC quasi-elastic cross-section
  - CC $\pi^+$ cross-section
  - NC $\pi^0$ cross-section
- $\nu_\mu \rightarrow \nu_e$ oscillation measurement is expected in late 2005.