Recent Results from MiniBooNE and the Future Project LBNE

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Outline

• Overview of MiniBooNE
• Recent Oscillation Results
• Introduction to the Next Generation of Long-Baseline Experiment
• Sensitivity Potential of LBNE
• Conclusions
MiniBooNE motivated by LSND Result

- MiniBooNE designed to test LSND result: $3.8\sigma$ appearance of electron antineutrino in muon antineutrino beam
- Use the same L/E but in different energy regime – different systematics:
  - LSND $L=30\text{m} \ E \sim 30\text{MeV}$
  - MiniBooNE $L=500\text{m} \ E \sim 500\text{MeV}$
• Standard neutrino beam generation
• Since August 2002
  – $6.46 \times 10^{20}$ POT neutrino mode
  – $4.86 \times 10^{20}$ POT antineutrino mode
• Began antineutrino running for additional $5.0 \times 10^{20}$ POT in September
Well-understood neutrino beam

- Neutrino mode:
  - wrong-sign background ~6%
  - Intrinsic electron neutrino ~0.5%

- Antineutrino mode:
  - Wrong-sign background ~18%
  - Intrinsic electron neutrino ~0.6%
MiniBooNE Detector

- 12m diameter tank
- 900 tons pure mineral oil
- Optically isolated inner region with 1280 PMTs – photocathode coverage ~ 10%
Particle Identification in MiniBooNE

- Predominantly Cherenkov light
Neutrino Results

- Consistent with no oscillation above 475 MeV
- Anomalous results below 475 MeV
Low Energy Excess Observed

128.8 ± 20.4 ± 38.3 events
Antineutrino Results

- $3.4 \times 10^{20}$ POT (low statistics)
- No large excess is observed at low energy (below 475 MeV) unlike for neutrinos $-0.5 \pm 11.7$ events
- $4.86 \times 10^{20}$ POT currently being analyzed
Antineutrino Oscillation Results

- Results consistent with no oscillation and with LSND
- Need more data!
MiniBooNE Conclusions

- Unexplained low energy excess in neutrinos
- No low-energy excess is observed in antineutrino data
- Standard Model explanations for low-energy excess would require excess for anti-neutrinos
- Need more data in antineutrino mode
- Excess could be evidence for CPT non-conservation
- Need a thorough study for future long-baseline experiments searching for electron neutrino appearance
The MiniBooNE Collaboration

Long-Baseline Neutrino Experiment (LBNE)

The future Fermilab to DUSEL flagship particle physics experiment
Long-Baseline Neutrino Physics

- Motivated by observation of neutrino oscillations
- Atmospheric oscillations (Super-Kamiokande, K2K, MINOS):
  - $\Delta m^2 \sim 2 \times 10^{-3} \text{ eV}^2$
  - $\sin^2 2\theta > 0.9$
- Solar neutrino oscillations (SNO, Super-Kamiokande, SAGE, Homestake, GNO; KamLAND (antineutrinos)):
  - $\Delta m^2 \sim 8 \times 10^{-5} \text{ eV}^2$
  - $\tan^2 \theta \sim 0.4$
Case of only three light neutrino flavors. From: hep-ph/0411274
Mixing Matrix and Oscillation Probabilities

- The "solar" mixing angle is associated with $\theta_{12}$
- The "atmospheric" mixing angle is associated with $\theta_{23}$
- There are now only three remaining unmeasured quantities relevant to neutrino mixing
  - the mass hierarchy, sign of $\Delta m_{31}^2$
  - the CP violating phase, $\delta$
  - the mixing angle, $\theta_{13}$
- Our chances of measuring $\delta$ depend on the size of $\theta_{13}$
Long-baseline $\nu_e$ appearance $\theta_{13}$, $\delta_{\text{CP}}$, sign of $\Delta m_{13}^2$

\[ P_{\mu e} \simeq |\sin 2\theta_{13}\sin \theta_{23} \sin \Delta_{31} e^{i(\Delta_{32}\pm\delta_{\text{CP}})} + \cos \theta_{13}\cos \theta_{23} \sin 2\theta_{12} \sin \Delta_{21}|^2 \]

\[ \simeq \sin^2 2\theta_{13}\sin^2 \theta_{23} \sin^2 \Delta_{31} \]

\[ \mp \alpha \sin 2\theta_{13} \sin \delta_{\text{CP}} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \Delta_{31} \sin^2 \Delta_{31} \]

\[ + \alpha \sin 2\theta_{13} \cos \delta_{\text{CP}} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \Delta_{31} \cos \Delta_{31} \sin \Delta_{31} \]

\[ + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \Delta_{31}^2. \] (7)

\[ \Delta_{ij} \equiv \Delta m_{ij}^2 L/(4E) \]

\[ \alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2 \]

- Vacuum oscillations, matter effect creates more complicated appearance probability
- Current/Near future accelerator searches for $\theta_{13}$ use this method (T2K, NOvA)
Reactor method search for $\theta_{13}$

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{13}^2 L}{4E_\nu} \right) \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

- Look for disappearance of $\nu_e$ at a short distance from a nuclear reactor
- High flux – systematics limited
- Matter effects negligible
- Two-flavor-like neutrino oscillations

Reactor and accelerator measurements are complementary!
Next Generation Long-Baseline Experiment

- Enhanced study of $\theta_{13}$
- Measurement of the mass hierarchy
- Measurement of $\delta_{CP}$
- Longer-baseline to explore more than one oscillation maximum
LBNE Baseline

300 kT water Cherenkov and LAR 50kT
Basic Layout

- Start with 700 kWatt beam
- Project X -> 2 Mwatt beam
Layout at Fermilab

ν Beam Facility: Target Hall + Decay Pipe + Absorber + Near Hall
Water Cherenkov Detector

- Large mass, low cost
- Existence proof – Super-Kamiokande 50 kiloton detector (22.5 kT fiducial)
- Current default plan – modules with 100 kT of fiducial volume
- Excellent showering vs. non-showering separation: $\nu_\mu/\nu_e$ separation
- We could start building tomorrow
300 kT example
Data in 300 kT of Water Cherenkov

- Intrinsic $\nu_e$ – measure in a near detector
- NC background – mostly neutral pion
- Uncertainties on NC backgrounds large – measure in a near detector
- Better resolution of the first maximum
- 90k CC interactions total after oscillations, three years running, 1.2 MWatts

arXiv:0705.4396
LAr TPC

- Much better background rejection than water Cherenkov
- Potentially "not-so-expensive" for large masses
- Currently under development
  - ICARUS 600 tons, installed in Gran Sasso, previously run on the surface
  - MicroBooNE 200 tons, planned for Fermilab

Courtesy of Kevin Lee
LANNDD detector concept

- Evacuable modular structure – better argon purity
- Stackable in a frame
- Can run while still building

Courtesy of Kevin Lee
Data in a large LAr TPC

- 100 kT of liquid argon
- 3\times 10^{21} \text{ POT}
- background almost entirely intrinsic $\nu_e$
- 30k CC interactions total after oscillations, 3 years running, 1.2 MWatt

arXiv:0705.4396
Sensitivities

Water Cherenkov

Liquid Argon TPC

arXiv:0705.4396
LBNE Near Detector Challenge

The near detector complex will measure the neutrino flux, flavor composition and cross-sections required for all oscillation analyses. This is a particular challenge where the far detector is water Cherenkov. The spectra differ near to far. The cross-section uncertainties for NC pion backgrounds is large.

Anticipated backgrounds:
- intrinsic $\nu_e$
- NC events which mimic intrinsic $\nu_e$ appearance such as single $\pi^0$ events

Far/Near Flux Ratio

The high energy tail will generate NC interactions in the signal region.

Uncertainties are large.

Plots courtesy of Sam Zeller
LBNE Near Detector

- Need fine-grained ND with a water target to study backgrounds in detail
- For LAr, we are exploring simply moving MicroBooNE or using a module similar to ICARUS
Project Status

• Strongly recommended in the P5 Report
• Currently awaiting CD-0 approval from DoE
• DUSEL will be reviewed by the National Science Board – February 2011
• Attempt CD-1 approval at a similar time
• Collaboration ~ 35 institutions (and counting)
Other physics

- Proton decay
- Diffuse SN background neutrinos
- Galactic SN detection
- Atmospheric neutrinos
- Solar neutrinos
$p \rightarrow e^+ \pi^0$

Proton lifetime vs. time (1995-2030)

540 kt WC
270 kt WC

SK I+II, SK2, SK3+
IMB

Courtesy of Bob Svoboda
Plot courtesy of Bob Svoboda
Long-Baseline Neutrino Experiment

Conclusions

• We have a lot of physics to explore
• LBNE will provide the most extensive study of standard neutrino oscillation physics yet – the only experiment with hierarchy and $\delta_{CP}$ reach for $\sin^2 2\theta \sim 0.01$
• A large detector at DUSEL will have a rich physics program and generate exciting results for us to ponder for years to come
LBNE physics

Primary Measurement

• Search for $\nu_e$ appearance in a $\nu_\mu$ beam
• Two oscillation maxima – 2.1 GeV, 700 MeV
• Far detector options –
  – Water Cherenkov
  – Liquid Argon

Near Detector Mission

• Determine the flavor composition and energy spectrum of the neutrino flux near and far
• Measure backgrounds to $\nu_e$ appearance
  – intrinsic $\nu_e$’s
  – Processes mimicking $\nu_e$’s – NC $\pi^0$’s, NC $\gamma$’s
• Accomplish by measuring parent hadron fluxes in the target hall and neutrino fluxes in the ND hall