Fermilab Neutrino Experiments
Present and Future

DOE Annual Program Review
Niki Saoulidou
September 24 2007
Outline

- Introduction
- Neutrino Cross Sections and Flux
  - MINERvA
  - SciBooNE
  - MIPP
- Neutrino Oscillations
  - MiniBoone
  - MINOS
  - NOνA
  - Future Long Baseline Experiments: FNAL-BNL Study and ProjectX Capabilities
- Summary and Outlook
Introduction

- **Neutrinos** were invented in order to solve a **“mystery”** (energy non-conservation in beta decays)...

- Since their birth, they have created even more **mysteries** themselves ...
  
  - Solar neutrino “problem” (ν_e’s from the Sun are less than expected)
  - Atmospheric neutrino “problem” (ν_µ’s from the atmosphere are less than expected)

- The “problem” of missing neutrinos can be nicely explained if they possess non-degenerate masses, in which case they can oscillate between the different flavors: (Strong evidence from many experiments, SuperK, K2K, SNO, KAMLAND ... indicate that this is the case)
  
  - 3 active (LEP/SLC)
  - n sterile (After latest MiniBoone results sterile neutrinos highly disfavoured)
Are there more questions to answer??

- Is there CP violation in the neutrino sector?? (which might explain why we are here!!!) (NoVA + T2K)

- What is the value of the “third” mixing angle ?? (the other two indicate nearly maximal mixing, the limit for the third indicates a pretty low value...) (Reactor experiments, NoVA, T2K)

\[
\begin{align*}
\nu_{e(\mu)(\tau)} &= \sum_{i=1}^{3} U^*_{e(\mu)(\tau)i} \nu_i \\
U &= \begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & -s_{23} \\
0 & s_{23} & c_{23}
\end{bmatrix} \begin{bmatrix}
c_{13} & 0 & -s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
s_{13} e^{-i\delta} & 0 & c_{13}
\end{bmatrix}
\end{align*}
\]

- Atmospheric Cross Mixing

- Solar

- 0νββ decays

Are there sterile neutrinos???

(MiniBoone)

What is after all, the neutrino MASS?? (absolute value not mass squared difference)

(Kinematics of beta decay)

- Are “man made” nu’s oscillate?

- Do “man made” nu’s oscillate? Which is after all, the mass squared difference and the mixing angle? (K2K-MINOS)

- Are neutrinos and anti neutrinos the same ?? (Majorana particles) (neutrino-less double beta decays)

\[
\begin{align*}
\sum = 3 \\
\nu_{e(\mu)(\tau)} &= \sum_{i=1}^{3} U^*_{e(\mu)(\tau)i} \nu_i \\
U &= \begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & -s_{23} \\
0 & s_{23} & c_{23}
\end{bmatrix} \begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
e^{ia_1/2} & 0 & 0 \\
0 & e^{ia_2/2} & 0 \\
0 & 0 & 1
\end{bmatrix}
\end{align*}
\]
Accelerator $\nu$ Oscillation Measurements Require:

Intense beam

$\pi, \pi, \pi, \pi, K$

protons

$\Phi_{\nu}(E)$

Neutrino Detectors

oscillation

$\nu, \nu, \nu, \nu$

MINOS

MiniBooNE

T2K/Near

SciBooNE

NOvA/Near

MINER

$\sigma(E) \cdot \Phi_{\nu} \text{near}(E) \Leftrightarrow \sigma(E) \cdot \Phi_{\nu} \text{far}(E)$
MINERvA

- MINERvA is a compact, fully active neutrino detector designed to study neutrino-nucleus interactions with unprecedented detail.

Main CC Physics Topics (Statistics in CH)

- Quasi-elastic: 0.8 M events
- Resonance Production: 1.7 M total
- Transition: Resonance to DIS: 2.1 M events
- DIS, Structure Functions & high-\(x\) PDFs: 4.3 M DIS events
- Coherent Pion Production: 89 K CC / 44 K NC
- Strange and Charm Particle Production: > 240 K fully reconstructed
- Generalized Parton Distributions: order 10 K events
- Nuclear Effects: He: 0.6 M, C: 0.4 M, Fe: 2.0 M and Pb: 2.5 M
Example: MINERvA Coherent $\pi^0$ production

- $\pi^0$'s cleanly identified
- $\pi^0$ energy resolution: $6\% / \sqrt{E}$
- $\pi^0$ angular resolution better than smearing from physics

Coherent, resonance events with $\pi^0$

"Coherent Pion Production"

$(\nu + A \rightarrow \nu/\mu^- + A + \pi, \, 85 \, K \, CC / 37 \, K \, NC)$

- Precision measurement of $\sigma(E)$ for NC and CC channels
- Measurement of $A$-dependence
- Comparison with theoretical models
Example: MINERvA CC Quasi-Elastic

Precision measurement of $\sigma(E_\nu)$ and $d\sigma/dQ$ important for neutrino oscillation studies.

Late 2007 – early 2008: Construction of “Tracking Prototype”
- 20 detector modules
- Will use to study tolerance stackup, tracking, etc.

Late 2008: Test beam detector taking data
2008-2009: Construction of full detector
SciBooNE Detector

- SciBar Detector
  - From KEK, Japan

- Electron Catcher
  - From KEK, Japan (CHORUS Reused ECAL)

- Muon Range Detector (MRD)
  - Being built at FNAL from old fixed-target parts (FNAL-E605, KTeV, NuTeV).

- Measurements
  - CC-$1\pi$ cross section
  - CCQE $s,M_A$ measurement
  - NC $\pi^0$ measurement
  - Search for CC coherent $\pi$
  - Search for NC coherent $\pi^0$

Comparison of $\nu_\mu$ flux spectra at K2K, T2K
SciBooNE Example : NC1π₀

- Same detector used to measure NC1π₀ in two beams!
  - Map out $\sigma_\nu$ vs. $E_\nu$

- Combined with MINERνA, great coverage of NC1π₀ induced backgrounds for T2K
Started anti-neutrino running in June 2007 (Half of projected for anti-neutrino mode!)
Switch to neutrino mode running from October and run one more year.

More in Steve’s Talk!
Neutrino Flux is Important: MIPP

- Better knowledge of Neutrino Flux is important for all accelerator neutrino oscillation experiments (in order to reduce systematic uncertainties).

- Better knowledge of Neutrino Flux is also important for MINERvA, SciBooNE and in general all “Near Detectors” (MINOS included) that want to measure neutrino cross sections precisely (in order to also reduce systematic uncertainties for oscillation measurements).

- MIPP has taken 1.9M events with 120 GeV protons on the MINOS target.
- MIPP has also taken 20, 58, and 120 GeV secondaries on thin carbon targets and will use them to “reconstruct” the MINOS (or any other carbon target).
MIPP Results

MIPP has taken 1.9M events with 120 GeV protons on the MINOS target (First results already available!)

More in Holger’s talk!
MiniBooNE

Long Standing LNSD “anomaly” solved
(at least as an interpretation of muon neutrino to electron neutrino oscillations)

Boosted Decision Tree analysis shows no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.

Energy-fit analysis:
solid: TB
dashed: BDT

Independent analyses are in good agreement

MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance only interpretation of LSND at 98% CL.
MiniBooNE : Outlook

- Further investigation of the “low energy excess”
- Further analysis of neutrino data including exotic models for the LSND effect
- Anti-neutrino data taking mode has started

More in Steve’s Talk!

As planned before opening the box....
Report the full range: 300<E_{\nu,QE}<3000 MeV

96 ± 17 ± 20 events above background, for 300<E_{\nu,QE}<475MeV
Deviation: 3.7σ

Background-subtracted:
MINOS is a two detector long baseline neutrino oscillation experiment.

- **Verify** $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis and make a precise (<10%) measurement of the oscillation parameters *Phys. Rev. Lett.* 97 (2006) 19180

- **Search for sub-dominant** $\nu_\mu \rightarrow \nu_e$ oscillations (not yet seen at this mass-scale)

- **Search for/rule out** exotic phenomena:
  - Sterile neutrinos
  - Neutrino decay

- **Use magnetized MINOS Far detector to study neutrino and anti-neutrino oscillations**
  - Test of CPT violation
  - Atmospheric neutrino oscillations:
MINOS Oscillation Results for $2.5 \times 10^{20}$ pots (new!)

Updating analysis for total of $3 \times 10^{20}$ pots for RunI and RunII

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• **MC** error band includes contributions from beam, cross-section and energy scale uncertainties
• Both methods (high and low multiplicity data cleaning) give results consistent with each other and with expectations.
MINOS Physics Analyses

- $\nu_\mu$ CC disappearance: $\Delta m^2_{32}$ and $\sin^2(2\theta_{23})$
  - An updated analysis will be presented this summer with a factor of two larger exposure

- Neutral Currents: Set limits on $f_{sterile}$
  - Collaboration has blessed the “ND” NC spectrum
  - Plan 1st “box opening” this fall.

- Electron neutrinos
  - $\nu_e$ search will see a signal if $\theta_{13}$ is around the Chooz limit (aiming for a box opening with the $3.2 \times 10^{20}$ pots)

- Beam $\nu_\mu$-bar
  - Measure oscillations -> Limits on CPT invariance

- Atmospheric neutrinos ($\nu + \bar{\nu} + \nu_e$)
  - $\nu$-induced muon events + contained vertex events (1st results on 2-3 years of exposure)
  - Now doing a combined analysis

- Cosmic rays (13/sec Near; 1/2sec Far)
  - Charge sign, seasonal variations, moon/sun shadow

- Near Detector Physics
  - Millions of events in a broad band beam
  - Cross sections: $\nu + \bar{\nu} + \nu_e$

More in Cat’s talk!
NO\textnu A is an approved Fermilab experiment optimized for measuring $\nu_e$ appearance with the goal of improving MINOS $\nu_\mu \rightarrow \nu_e$ measurement by approximately an order of magnitude.

The NO\textnu A far detector will be

1. A 15 kT “totally active” liquid scintillator detector
2. Located 15 mrad (12 km) off the NuMI beamline axis near Ash River, MN, 810 km from Fermilab
3. Constructed with a TPC of $260M (including NUMI Upgrade to 700 kW)

Depending on the value of the third mixing angle NO\textnu A could determine the neutrino mass hierarchy (normal or inverted)
NOvA Physics Reach: $\nu_\mu \rightarrow \nu_e$

3 $\sigma$ Sensitivity to $\sin^2(2\theta_{13}) \neq 0$

- $L = 810$ km, 15 kT
- $\Delta m^{2}_{32} = 2.4 \times 10^{-3}$ eV$^2$
- $\sin^2(2\theta_{23}) = 1$

3 years at 700 kW, 1.2 MW, and 2.3 MW for each $\nu$ and $\bar{\nu}$
- $\Delta m^2 > 0$
- $\Delta m^2 < 0$

95% CL Resolution of the Mass Ordering

- $L = 810$ km, 15 kT
- $\Delta m^{2}_{32} = 2.4 \times 10^{-3}$ eV$^2$
- $\sin^2(2\theta_{23}) = 1$
- $\Delta m^2 > 0$

3 years for each $\nu$ and $\bar{\nu}$
- NOvA at 700 kW, 1.2 MW, and 2.3 MW + T2K 6 years of $\nu$
NOvA Physics Reach: $\nu_\mu \rightarrow \nu_\mu$

Sensitivity Contours (18 kt*36E20 POT)

95% CL Resolution of the $\theta_{23}$ Ambiguity

$\Delta m_{32}^2 = 2.7 \times 10^{-3}$ eV$^2$

3 years for each $\nu$ and $\bar{\nu}$
NOvA at 1.2 MW and 700kW
+ a reactor with $\sigma = 0.005$
NOvA Status and Plan

- DOE Lehman Review scheduled for Oct 23.
- DOE External Independent Review scheduled for Nov 26
- Successful reviews lead to CD-2/3a approval in Feb 2008.
- **Baseline Schedule:**
  - Feb 2008 - start construction of accelerator components
  - April 2008 - start building access road to Ash River site
  - Nov 2008 - R&D Integration Prototype Near Detector ready for data in MINOS Service Building
  - March 2010 - beneficial occupancy of Ash River detector hall, start detector construction (15 kt = 6 superblocks)
  - Oct 2010 - start 9 month accelerator shutdown, startup in Aug 2011 with Recycler slip-stacking
  - June 2011 - First Far Detector superblock ready for data
  - Dec 2011 - Near Detector ready (requires excavation in 9 mo shutdown)
  - April 2012 - start 3 month accelerator shutdown for NuMI upgrades, startup in July 2012 ready to commission 700 kW beam.
  - Dec 2012 - Far Detector complete
Future $\nu$ Oscillation Experiments

- **Phase II**: Develop a Plan based on Phase I Results (NOvA, T2K, Double-Chooz & Daya Bay will inform us of $\sin^22\theta_{13}$ down to ~0.02 by ~2012-2014).

- In the Future Long Baseline Neutrino Study (Joint Fermilab - BNL study) we explored indicative configurations of detectors (and detector masses), off axis and on-axis locations and protons on target (beam power).

- **Main options for Neutrino Beams are**:
  
  Off Axis Beam. This is a **Narrow Band Beam** but if we choose to place 2 detectors @ different off axis angles we get an off - axis “Pseudo - Wide Band Beam”

  **Wide Band Neutrino Beam** which gives the ability to study energy dependence on oscillation phenomena.

- **Main options for Detectors are**:
  
  Liquid Argon TPC (~ 100 kton mass)
  Water Cerenkov Detectors (~ 300 kton mass)
Phase II Example

It all depends on the Angle and the available Beam Power.

For example if Project X is an option then:

If $\sin^2 2\theta_{13} > 0.02$
Use NUMI Narrow Band Beam and upgraded detector (LAr)

If $\sin^2 2\theta_{13} < 0.02$
Construct New Wide Band Beam and upgraded detector (LAr or Water Cerenkov) pointing to a detector at ~1300 km distance
## Resources (People+Money)

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<th>FY07</th>
<th>FY08</th>
<th>FY09</th>
<th>M&amp;S</th>
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<td><strong>6997</strong></td>
<td><strong>7565</strong></td>
<td><strong>Total M&amp;S</strong></td>
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Excluding projects NOvA and MINERvA
# Fermilab Leadership in Neutrino Program

- **MINERVA**
  - Co-spokesperson: J. Morfin
  - Project Manager: D. Harris

- **MIPP**
  - Spokesperson: R. Raja

- **MiniBoone**
  - Co-Spokesperson: S. Brice

- **SciBooNE**
  - Project Manager: R. Tesarek

- **MINOS**
  - Co-spokesperson: R. Plunkett
  - MINOS Executive Committee: G. Rameika
  - NC Analysis Coordinator: N. Saoulidou (WF), B. Rebel (RA)
  - ND Analysis Coordinator: P. Shanahan

- **NOvA**
  - Project Managers: J. Cooper, R. Ray, N. Grossman
  - NOvA Executive Committee: G. Rameika, P. Shanahan
  - Simulations Coordinator: P. Shanahan

- **Fermilab Future Neutrino Experiment Study Group**
  - G. Rameika
  - N. Saoulidou (WF)
Summary and Outlook

- So far the behavior of the “little neutral one” has been full of many “big” surprises.
- Some of the questions in neutrino physics have been answered, but the remaining ones are more challenging.
- Fermilab has a broad neutrino program aiming to address many of these remaining important issues with respect to neutrino physics and neutrino oscillations:
  - **Neutrino Cross Sections (and Neutrino Flux)**
    - MINERvA
    - SciBooNE
    - (MIPP)
  - **Neutrino Oscillations**
    - MINOS
    - MiniBooNE
    - NOvA
    - Study of future plans (FNAL-BNL Joint Study)