Neutrino Oscillation Studies with the Fermilab NuMI beam: Episode III

- Historical Introduction: Pre-history, Episodes I and II
- Physics Motivation
- Off-axis Beams
- Backgrounds and Detector Issues
- Sensitivity of NuMI Off-axis Experiments
Pre-history

Stage: Japan, early 1960’s

Progress in Theoretical Physics: many papers by Nagoya group (Sakata and Co.), Kyoto group and others addressing issues:

- Fundamental symmetries of Nature
- Conserved quantum numbers
- Leptons-hadrons symmetry
- Bold predictions

Not enough experimental input/feedback, Second neutrino just barely discovered

MNS: 

\[ \nu_1 = \cos \theta \nu_e + \sin \theta \nu_\mu \]
\[ \nu_2 = -\sin \theta \nu_e + \cos \theta \nu_\mu \]
Neutrino Mixing Leads to Interference Effects (Oscillations)

Amplitude

\[
\begin{bmatrix}
  l_\alpha \\
  l_\beta 
\end{bmatrix}
\]

Components of the initial state have different time evolution
\[\Rightarrow \Psi(t) \odot \Psi(0)\]

Amplitude \[\sum_i\]

\[
A = \sum_i U_{\alpha i}^* e^{-i m_i^2 L / 2E} U_{\beta i}
\]

3-slit interference

Experiment: mass difference \[\Leftrightarrow\]
difference in optical path length
Young Experiment

Three slit interference experiment

$$A \sim e^{ikL_1} + e^{ikL_2} + e^{ikL_3}$$

$$I = |A|^2$$

$I(x)$ - interference pattern is a result of phase differences due to optical path differences
Neutrino Oscillations Primer

- \( P(\nu_\alpha \rightarrow \nu_\beta) = 0 \) if all masses are equal i.e. \( \Delta m^2_{ij} = 0 \) Neutrino oscillations are sensitive to mass differences only.

- \( P(\nu_\alpha \rightarrow \nu_\beta) \) oscillates as a function of \( L/E \)

- \( P(\nu_\alpha \rightarrow \nu_\beta) \geq 0 \) for \( \alpha \neq \beta \) Appearance experiment.

- \( P(\nu_\alpha \rightarrow \nu_\alpha) \leq 1 \) : disappearance experiment

- \( \sum_\beta P(\nu_\alpha \rightarrow \nu_\beta) = 1 \) : total number of neutrinos is conserved

- If \( U_{\alpha i} \) is complex then \( P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\nu_\beta \rightarrow \nu_\alpha) \) hence T (or CP) violation

- Possible Majorana phases do not contribute to oscillations
Episode I: Before the “New Era”

Theory:
• Neutrino mass differences 1-100 eV²
• Neutrino mixing matrix similar to quarks (small or very small mixing angles)

Experiment:
• No evidence for neutrino oscillations in accelerator (BEBC, CDHS, CHARM, CCFR) or reactor (Bugey, Gosgen) experiments
• Confusing ‘solar neutrino problem’

New Era started by **“SuperK revolution”:**
• Neutrinos have mass, mass differences are very small
• Neutrino mixing angles are very large
Episode II: elucidation

Two frequencies of oscillations, large mixing angles, at least two of them:

- $\Delta m_{12}^2 \sim 7(?) \times 10^{-5}$ eV$^2$
- $\theta_{12} \sim 35^\circ$
- Super K, SNO, KamLand

- $\Delta m_{13}^2 \sim 1.5 - 4 \times 10^{-3}$ eV$^2$
- $\theta_{12} \sim 45^\circ$
- SuperK, K2K, MINOS, OPERA, ICARUS

Dawn of physics beyond the Standard Model

Interference of these two amplitudes may lead to relatively large CP-violating effects.
Neutrinos vs Standard Model

Whereas

- There is a major effort to complete the Standard Model (Higgs search)
- There is a broad front of experiments looking for possible deviations from the Standard Model (SUSY searches, B-physics experiments, g-2, EDM, ...)

The first evidence for physics beyond the standard model is here:
- Neutrino mass and oscillations

Where does it lead us?
- Just an extension (additional 9? 7? Parameters)?
- First glimpse at physics at the unification scale? (see-saw??)
- Extra dimensions?
- Unexpected? (CPT violation???)
Surprising pattern of mixing angles: WWSS?

• We have large mixing angles. How very interesting... I thought that mixing angles tend to be small... Hmm.. $\sin^2 2\theta_{23}$ is very close to 1.

$$\nu_{\mu,\tau} \approx \frac{1}{\sqrt{2}} (\nu_2 \pm \nu_3)$$

Maximal mixing $\leftrightarrow$ symmetry. What is this new symmetry of Nature?

• We have $\sin^2 2\theta_{12}$ and $\sin^2 2\theta_{23}$ large, yet $\sin^2 2\theta_{13}$ rather small. How very interesting... How small is it, really? What makes it so small? Protected by some new symmetry?? What symmetry?
Three outstanding questions
AD 2003

• Neutrino mass pattern:

This?

Or that?

• Electron component of $\nu_3 (\sin^2 2\theta_{13})$

• Complex phase of $s \leftrightarrow CP$ violation in a neutrino sector
  $\leftrightarrow (?)$ baryon number of the universe
\( \beta \) and \( 0\nu\beta\beta \) decay experiments and mass hierarchy

- Coupling primarily to \( \nu_1 \) and \( \nu_2 \)
- In case of inverted hierarchy \( m \sim 50 \text{ meV} \) required. Challenging..
- In case of normal hierarchy required mass sensitivity in a few meV range. Tough!
- Want to know the mass pattern
The key: $\nu_\mu \rightarrow \nu_e$ oscillation experiment

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2 \theta_{23} \sin^2 \theta_{13} \left( \frac{\Delta_{13}}{B_\pm} \right)^2 \sin^2 \frac{B_\pm L}{2}$$

$$P_2 = \cos^2 \theta_{23} \sin^2 \theta_{12} \left( \frac{\Delta_{12}}{A} \right)^2 \sin^2 \frac{AL}{2}$$

$$P_3 = J \cos \delta \left( \frac{\Delta_{12}}{A} \right) \left( \frac{\Delta_{13}}{B_\pm} \right) \cos \Delta_{13} L \sin \frac{AL}{2} \sin \frac{B_\pm L}{2}$$

$$P_4 = J \sin \delta \left( \frac{\Delta_{12}}{A} \right) \left( \frac{\Delta_{13}}{B_\pm} \right) \sin \Delta_{13} L \sin \frac{AL}{2} \sin \frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2}G_F n_e;$$

$$B_\pm = |A \pm \Delta_{13}|;$$

$$J = \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$P = f(\sin^2 2\theta_{13}, \delta, \text{sgn}(\Delta m_{13}^2), \Delta m_{12}^2, \Delta m_{13}^2, \sin^2 2\theta_{12}, \sin^2 2\theta_{23}, L, E)$$

3 unknowns, 2 parameters under control $L, E$, neutrino/antineutrino

Need several independent measurements to learn about underlying physics parameters
Observations

\[ |s|^2 = |U_{e3}|^2 = \sin^2 \theta_{13} \approx \frac{1}{4} \sin^2 2\theta_{13} \approx \frac{1}{2} \sin^2 \theta_{\mu e} \]

- First 2 terms are independent of the CP violating parameter \( \delta \)
- The last term changes sign between \( \nu \) and \( \nu' \)
- If \( \theta_{13} \) is very small (\( \leq 1^\circ \)) the second term (subdominant oscillation) competes with 1st
- For small \( \theta_{13} \), the CP terms are proportional to \( \theta_{13} \); the first (non-CP term) to \( \theta_{13}^2 \)
- The CP violating terms grow with decreasing \( E_{\nu} \) (for a given \( L \))
- CP violation is observable only if all angles \( \neq 0 \)
- Two observables dependent on several physics parameters: need measurements at different \( L \) and \( E \)
Telling the Mass Hierarchy: Neutrino Propagation in Matter

- Matter effects reduce mass of $\nu_e$ and increase mass of $\bar{\nu}_e$

- Matter effects increase $\Delta m^2_{23}$ for normal hierarchy and reduce $\Delta m^2_{23}$ for inverted hierarchy for neutrinos, opposite for antineutrinos
Anatomy of Bi-probability ellipses

Observables are:
• $P$
• $\overline{P}$

Interpretation in terms of $\sin^2 2\theta_{13}$, $\delta$ and sign of $\Delta m^2_{23}$ depends on the value of these parameters and on the conditions of the experiment: L and E

Minakata and Nunokawa, hep-ph/0108085
Varying the mixing angle..

- Parameter correlation: even very precise determination of $P_{\nu}$ leads to a large allowed range of $\sin^2 2\theta_{23} \Rightarrow$ antineutrino beam is more important than improved statistics.

- CP violation effects (size of the ellipse) $\sim \sin 2\theta_{13}$, overall probability $\sim \sin^2 2\theta_{13} \Rightarrow$ relative effect very large.

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June 11, 2003 1st Yamada Symposium, NDM 2003
Adam Para, Fermilab
**Recipe for an $\nu_e$ Appearance Experiment**

- Large neutrino flux in a signal region
- Reduce background (neutral currents, intrinsic $\nu_e$)
- Efficient detector with good rejection against NC background
- Large detector

**Lucky coincidences:**

- distance to Soudan = 735 km, $\Delta m^2$=0.025-0.035 eV$^2$
- \[ \frac{1.27 \Delta m^2 L}{E} = \frac{\pi}{2} \Rightarrow E = \frac{2.54 \Delta m^2 L}{\pi} \approx 1.6 - 2.2 \text{ GeV} \] => 'large' cross section
- Below the $\tau$ threshold! (BR($\tau$-$e$)=17%)
$\nu_\text{e}$ Appearance Counting Experiment: a Primer

$$P = \frac{\#\text{of } \nu_\text{e} \text{ cand.} - \varepsilon \nu_\text{e}^{\text{beam}} - \eta \text{NC}}{\varepsilon \int dE \Phi_\nu (E) \sigma^{CC}_{\nu} (E) P_{\nu_\mu \rightarrow \nu_\text{e}} (E, 100\%)}$$

$$P_{\text{sens}}^{90\%\text{CL}} = \frac{1.28 \sqrt{\varepsilon \nu_\text{e}^{\text{beam}}} + \eta \text{NC}}{\varepsilon \int dE \Phi_\nu (E) \sigma^{CC}_{\nu} (E) P_{\nu_\mu \rightarrow \nu_\text{e}} (E, 100\%)}$$

**Systematics:**
- Know your expected flux
- Know the beam contamination
- Know the NC background*rejection power (Note: need to beat it down below the level of $\nu_\text{e}$ component of the beam only)
- Know the electron ID efficiency

This determines sensitivity of the experiment
Off-axis NuMI Beams: unavoidable byproduct of MINOS experiment

- Beam energy defined by the detector position (off-axis, Beavis et al)
- Narrow energy range (minimize NC-induced background)
- Simultaneous operation (with MINOS and/or other detectors)
- ~ 2 GeV energy:
  - Below $\tau$ threshold
  - Relatively high rates per proton, especially for antineutrinos
- Matter effects to amplify to differentiate mass hierarchies
- Baselines 700 - 1000 km
NuMI Challenge: “have” beam, need a new detector

- Surface (or light overburden)
  - High rate of cosmic $\mu$’s
  - Cosmic-induced neutrons
- But:
  - Duty cycle $0.5 \times 10^{-5}$
  - Known direction
  - Observed energy $> 1$ GeV

Principal focus: electron neutrinos identification
- Good sampling (in terms of radiation/Moliere length)

Large mass:
- maximize mass/radiation length
- cheap

Off-axis collaboration: Letter of Intent 2002,
Proposal in preparation (October 2003), forthcoming workshops at Fermilab: July 10-12, September 11-13
NuMI Off-axis Detector

Low Z imaging calorimeter:
- Glass RPC or
- Liquid or solid scintillator

Electron ID efficiency ~ 40% while keeping NC background below intrinsic $\nu_e$ level

Well known and understood detector technologies

Primarily the engineering challenge of (cheaply) constructing a very massive detector

How massive??

50 kton detector, 5 years run =>
- 10% measurement if $\sin^2 2\theta_{13}$ at the CHOOZ limit, or
- $3\sigma$ evidence if $\sin^2 2\theta_{13}$ factor 10 below the CHOOZ limit (normal hierarchy, $\delta=0$), or
- Factor 20 improvement of the limit
Backgrounds Summary

- $\nu_e$ component of the beam
  - Constrained by $\nu_\mu$ interactions observed in the near MINOS detector ($\pi$)
  - Constrained by $\nu_\mu$ interactions observed in the near MINOS detector ($\mu$)
  - Constrained by pion production data (MIPP)
- NC events passing the final analysis cuts ($\pi^0$?)
  - Constrained by neutrino data from K2K near detector
  - Constrained by the measurement of EM 'objects' as a function of $E_{had}$ in the dedicated near detector
- Cosmics
  - Cosmic muon induced 'stuff' overlapped with the beam-induced neutrino event
  - (undetected) cosmic muon induced which mimics the 2 GeV electron neutrino interaction in the direction from Fermilab within 10 $\mu$sec beam gate

- Expected to be very small
- Measured in a dedicated setup (under construction)
Beam-Detector Interactions

- Optimizing beam can improve signal
- Optimizing beam can reduce NC backgrounds
- Optimizing beam can reduce intrinsic $\nu_e$ background
  - Easier experimental challenge, simpler detectors
- # of events $\sim$ proton intensity $\times$ detector mass
  - Allocate the resources to maximize the product, rather than individual components
# NuMI and JHF experiments in numbers

<table>
<thead>
<tr>
<th></th>
<th>NuMI Off-axis</th>
<th>JHF to SK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 kton, 85% eff,</td>
<td>Phase I, 5 years</td>
</tr>
<tr>
<td></td>
<td>5 years, $4 \times 10^{20}$ pot/y</td>
<td></td>
</tr>
<tr>
<td>all</td>
<td>After cuts</td>
<td>all</td>
</tr>
<tr>
<td>After cuts</td>
<td></td>
<td>After cuts</td>
</tr>
<tr>
<td>$\nu_\mu$ CC (no osc)</td>
<td>28348</td>
<td>10714</td>
</tr>
<tr>
<td></td>
<td>6.8</td>
<td>1.8</td>
</tr>
<tr>
<td>NC</td>
<td>8650</td>
<td>4080</td>
</tr>
<tr>
<td></td>
<td>19.4</td>
<td>9.3</td>
</tr>
<tr>
<td>Beam $\nu_e$</td>
<td>604</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td>31.2</td>
<td>11</td>
</tr>
<tr>
<td>Signal ($\Delta m_{23}^2 = 2.8/3 \times 10^{-3}$, NuMI/JHF)</td>
<td>867.3</td>
<td>302</td>
</tr>
<tr>
<td></td>
<td>307.9</td>
<td>123</td>
</tr>
<tr>
<td>FOM (signal/$\Delta bckg$)</td>
<td>40.7</td>
<td>26.2</td>
</tr>
</tbody>
</table>

June 11, 2003
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Two phase program

Phase I (~ $100-200 M, running 2007 - 2014)
• 50 kton (fiducial) detector with $\varepsilon \sim 35-40\%$
• $4 \times 10^{20}$ protons per year
• 1.5 years neutrino ($6000 \nu_\mu \text{ CC, 70-80\% 'oscillated'}$)
• 5 years antineutrino ($6500 \nu_\mu \text{ CC, 70-80\% 'oscillated'}$)

Phase II (running 2014-2020)
• 200 kton (fiducial) detector with $\varepsilon \sim 35-40\%$
• $20 \times 10^{20}$ protons per year (new proton source?)
• 1.5 years neutrino ($120000 \nu_\mu \text{ CC, 70-80\% 'oscillated'}$)
• 5 years antineutrino ($130000 \nu_\mu \text{ CC, 70-80\% 'oscillated'}$)
Combination of different baselines: NuMI + JHF extends the range of hierarchy discrimination to much lower angles mixing angles.
Physics related to neutrino masses

A quest for a neutrino mass spectrum $\leftrightarrow$ mass generation mechanisms:
- Neutrinos have non-zero mass
- $0.05 < m_3 < 0.23$ eV
- Mass differences too small to be detectable by direct measurements $\Rightarrow$ interference experiments [remember $\Delta m_K = m(K^0_S) - m(K^0_L)$]

A search for fundamental symmetries:
- Conserved 'family lepton' number
- Conserved lepton number
- CP conservation in a lepton sector $\leftrightarrow$ leptogenesis $\leftrightarrow$ baryon number of the Universe $\leftrightarrow$ our existence
- CPT conservation
- New, hereto unknown symmetries of Nature?
Conclusions

- Neutrino Physics is an **exciting field** for many years to come.
- Most likely **several experiments** with different running conditions will be **required** to unravel the underlying physics. Healthy complementary program is shaping up (see Ichikawa-san).
- **Fermilab/NuMI beam** is **uniquely matched** to this physics in terms of **beam intensity, flexibility, beam energy, and potential source-to-detector distances** that could be available.
- **Important element** of the **HEP program in the US** for the next 20 years.
NuMI Of-axis Sensitivity for Phases I and II

We take the Phase II to have 25 times higher POT $\times$ Detector mass

Neutrino energy and detector distance remain the same
Two body decay kinematics

At this angle, 15 mrad, energy of produced neutrinos is 1.5-2 GeV for all pion energies ➔ very intense, narrow band beam

'On axis': $E_\nu = 0.43 E_\pi$

\[
p_L = \gamma (p^* \cos \theta^* + \beta E^*)
\]
\[
p_T = p^* \sin \theta^*
\]
Signal and background

Fuzzy track = electron
Clean track = muon (pion)
Background examples

\[ \nu_\mu \text{ CC - with } \pi^0 - \text{muon} \]

\[ \text{NC - } \pi^0 - 2 \text{ tracks} \]
Sources of the $\nu_e$ background

At low energies the dominant background is from $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$ decay, hence

- $K$ production spectrum is not a major source of systematics
- $\nu_e$ background directly related to the $\nu_\mu$ spectrum at the near detector

$\nu_e / \nu_\mu \sim 0.5\%$
## Mass Textures and $\theta_{13}$ Predictions, Examples

<table>
<thead>
<tr>
<th>Texture</th>
<th>$\theta_{13}$</th>
<th>$\sin^2 2\theta_{13}$</th>
<th>Perturbations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degenerate neutrinos, spontaneously broken flavor SO(3)</td>
<td>$r \left( \frac{\Delta m^2_{\text{sun}}}{\Delta m^2_{\text{atm}}} \right)^{1/2}$</td>
<td>$\approx 0.064$</td>
<td>$\epsilon \sim \delta$</td>
</tr>
<tr>
<td>Degenerate neutrinos, democratic mass matrix</td>
<td>$r \left( \frac{m_e}{m_\mu} \right)^{1/2}$</td>
<td>$\approx 0.019$</td>
<td></td>
</tr>
<tr>
<td>Inverted hierarchy</td>
<td>$\approx \frac{\Delta m^2_{\text{sun}}}{\Delta m^2_{\text{atm}}}$</td>
<td>$\approx 0.001$</td>
<td>$\eta \sim \delta$</td>
</tr>
<tr>
<td>Normal hierarchy</td>
<td>$\approx \frac{\Delta m^2_{\text{sun}}}{\Delta m^2_{\text{atm}}}$</td>
<td>$\ll 0.001$</td>
<td>$\eta \sim \delta$</td>
</tr>
</tbody>
</table>

Altarelli, Feruglio, hep-ph/0206077