Accelerator Neutrino Experiments

And DEEP CORE

Scott Menary – York University
MiniBooNE - A search for $\nu_e$ appearance at $\Delta m^2 \sim 1 \text{ eV}^2$

LSND Best fit: $\sin^2(2\theta) = 0.003$, $\Delta m^2 = 1.2 \text{ eV}^2$
Observed no excess consistent with the LSND two-neutrino oscillation

\[ \nu_\mu \rightarrow \nu_e \text{ signal region} \]

low energy excess region
128.8 ± 43.4 excess events (3.0σ)

No sign of excess in recent \( \overline{\nu}_\mu \rightarrow \overline{\nu}_e \) data
Neutrino Beam (NuMI)

- 120 GeV protons strike target
- 10 μs long pulse of $3 \times 10^{13}$ protons every 2.2 seconds (275 kW)
- Two magnetic horns focus secondary $\pi/K$ decay
  - decay of $\pi/K$ produce neutrinos
- Variable neutrino beam energy

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$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2$

(68% C.L.)
Far Detector Energy Spectrum

- A blind analysis was performed:
  - all procedures for calculating background and signal were finalised before the Far detector data were looked at
- Expected background: \(27 \pm 5\) (stat) \(\pm 2\) (sys)
- Observed events: \(35\)
- A 1.5\(\sigma\) excess over background prediction

Fit the data to the oscillation hypothesis, obtain the signal prediction for the best fit point
Allowed Region

- A Feldman-Cousins method was used
- Fit simply to the number of events from 1-8 GeV
- Best fit and 90% C.L. limits are shown:
  - for both mass hierarchies
  - at MINOS best fit value for $\Delta m^2_{32}$ & $\sin^2(2\theta_{23})$

**Results:**

Normal hierarchy ($\delta_{CP}=0$):
$$\sin^2(2\theta_{13}) < 0.29 \text{ (90\% C.L.)}$$

Inverted hierarchy ($\delta_{CP}=0$):
$$\sin^2(2\theta_{13}) < 0.42 \text{ (90\% C.L.)}$$
long base-line appearance experiment:

- Produce muon neutrino beam at CERN
- Measure tau neutrinos in Gran Sasso

Experiments:
OPERA (1200 ton), ICARUS (600 ton)

4.5 \times 10^{19} \text{ pot/year (200 days, nominal intensity)}

\rightarrow 2.2 \times 10^{17} \text{ pot/day } \sim 10^{17} \nu_\mu/\text{day} \sim 10^{11} \nu_\mu/\text{day in detector}

\rightarrow 3600 \nu_\mu \text{ interactions/year in OPERA (charged current interactions)}

\rightarrow 2-3 \nu_\tau \text{ interactions detected/year in OPERA}

\sim 1 \nu_\tau \text{ observed interaction with } 2 \times 10^{19} \text{ pot}

CNGS Run 2008: \ 1.78 \times 10^{19} \text{ pot}
The Known and Unknown in Neutrino Physics

Three Neutrino PMNS Mixing Matrix:

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

\[
= \begin{pmatrix}
    1 & 0 & 0 \\
    0 & c_{23} & s_{23} \\
    0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
    c_{13} & 0 & s_{13}e^{-i\delta} \\
    0 & 1 & 0 \\
    -s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
    c_{12} & s_{12} & 0 \\
    -s_{12} & c_{12} & 0 \\
    0 & 0 & 1
\end{pmatrix}
\]

From Atmospheric and Long Baseline Disappearance Measurements
From Reactor Disappearance Measurements
From Long Baseline Appearance Measurements
From Solar Neutrino Measurements
In Vacuum the Oscillation Probability is:

- \( P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4 \)
  - \( P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27 \Delta m_{13}^2 \text{ L/E}) \)
  - \( P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27 \Delta m_{12}^2 \text{ L/E}) \)
  - \( P_3 = J \sin(\delta) \sin(1.27 \Delta m_{13}^2 \text{ L/E}) \)
  - \( P_4 = J \cos(\delta) \cos(1.27 \Delta m_{13}^2 \text{ L/E}) \)

where \( J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times \sin(1.27 \Delta m_{13}^2 \text{ L/E}) \sin(1.27 \Delta m_{12}^2 \text{ L/E}) \)
MINOS MC Event Composition in 2 Detectors

- **Primary background from NC events, also**
  - high-$\nu_\mu$ CC, beam $\nu_e$, oscillated $\nu_\tau$ at Far detector

  - **Right plot:** *purple* shows an appearance signal at the Chooz limit ($\sin^22\theta_{13}=0.15$)
- In matter, $P_1$ will be approximately multiplied by $(1 \pm 2E/E_R)$ and $P_3$ and $P_4$ will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

- Different baselines “pick out” different terms which helps to break some of the degeneracies.

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

3 unknowns, 3 parameters under control $L,E + \nu_\mu$ /anti $\nu_\mu$

To fight neutral-current background could use a narrow-band beam and a detector technology which does a good job of $e$ VS $\pi^0$ identification.

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The “Off-axis” Beam

\[ P_{\max} \text{ for } L/E \sim 500 \text{ so for } E \sim 2 \text{ GeV you want detector at } L\sim1000 \text{ km} \] - Canada
Where to Put NO\textsubscript{v}A?

“The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NO\textsubscript{v}A’s sensitivity to the mass ordering.”
M. Goodman, NOW 2008 (Sept)

\begin{equation}
\left( \frac{L}{E} \right)_{\text{NuMI}} \gtrsim \left( \frac{L}{E} \right)_{\text{T2K}}
\end{equation}

was found in order to yield synergistic physics, which translates to $L_{\text{NuMI}} \gtrsim 862$ km for 0.72° off-axis angle. Hence, a longer baseline, $L \approx 810$ km to the Ash River site in Minnesota, has been proposed for the NO\textsubscript{v}A experiment\cite{32}. A typical off-axis angle suggested is 0.85°, corresponding to 12 km off-axis at this baseline. In addition, a Totally Active Scintillating Detector (TASD) is the now accepted detector technology, often considered with a mass of 25 kt. Alternative sites with longer baselines in Canada (because of the beam geometry), such as Vermillion Bay, with potentially attractive physics potential are not actively being considered.

V. Barger, P. Huber, D. Marfatia, W. Winter


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T2K – J-PARC to SuperK

• 30 GeV Protons first transported to J-PARC Hadron Experimental Hall in January of this year.
• Were on track for first neutrinos this year.
• Opposite situation to NOvA – here they have a detector but not a beam.
• Much smaller matter effect than NOvA
Main T2K Measurements: $\sin^2 2\theta_{23}$, $\Delta m^2_{23}$

- **Phase 1:**
  - 5 years × 0.75 MW beam
  - $5 \times 10^{21}$ pot
  - Measurement of mixing angles

- $\nu_\mu$ disappearance

- Use CC Quasi Elastic Events
  - Can reconstruct Neutrino Energy.
  - Background from non-CCQE interactions.
The narrow-band beam at first seemed ideal but the energy at which the oscillation maximum occurs can be quite dependent on the value of $\delta_{cp}$. The Report of the US long baseline neutrino experiment study [arXiv:0705.4396](http://arxiv.org/abs/0705.4396) recognized that there is a great deal of power in using a wide-band beam (the first two oscillation maxima in the same experiment) but you must have excellent $\mu$ versus $\pi^0$ recognition - you need a Liquid Argon TPC (LArTPC).
Electrons versus $\pi^0$'s at 1.5 GeV in a Liquid Argon TPC

Dot indicates hit- colour indicates collected charge
green=1 mip, red=2 mips

Electrons- Single track (mip scale) starting from a single vertex
Use both topology and dE/dx to identify interactions

Multiple secondary tracks can be traced back to the same primary vertex
Liquid Argon TPC R&D Path in the US

Program underway
Spring 2008
Data: ~2011-2012
Data: ~2015-2016
Data 20??

N. Saoulidou, Fermilab, 3rd Project
X Workshop 06-07-08
In the US, a wideband $\nu_\mu$ beam from Fermilab to DUSEL (Homestake)
Far (ever?) Future

- **H-linac**: 2.2 GeV, 4 MW
- **Linac**: → 2 GeV
- **Recirculating Linacs**: 2 → 50 GeV
- **Decay ring**: 50 GeV, ≈2000 m circumference
- **Ionization cooling**
- **Phase rotation**
- **Magnetic capture**
- **Drift**
- **Accumulator ring + bunch compressor**
- **Target**
- **Linac → 2 GeV**
- **Recirculating Linacs 2 → 50 GeV**
- ** Decay ring – 50 GeV**
- v beam to far detector
- v beam to near detector

**EURISOL**
- Existing at CERN
- **PSB**

**T2KK**
- Beta-Beam
- Proton driver
- Isol target & ion source
- New RFQ
- Linac
- PSB

**DECAY RING**
- B = 5T
- L = 6880 m

**SPS**

**Neutrino Factory**

**Muon Collider**

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Conclusions

• Long-baseline neutrino accelerator experiments will always have the advantage of control of the neutrino source.

• There are a number of upcoming experiments designed to measure/improve the limit on $\theta_{13}$ but, of course, one is constrained by a complete lack of knowledge of this angle. If it has a high value (near the Chooz limit) then “traditional” long-baseline experiments have a chance but if it is “small” then really only a Neutrino Factory has a chance of making useful measurements.