The Gold Standard: MINOS
Jenny Thomas, Stanford 10th November 2023

- The scientific topic
- The history
- The politics
- The money
- Construction
- The experiment
- The results
- Some unexpected developments along the way
Neutrino Oscillations
What they are and how we measure them

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]


c_{12} = \cos\theta_{12}, \ s_{12} = \sin\theta_{12}
\delta = \text{CP violating phase}

- The PMNS matrix factorises into three separate matrices
- These represent (usefully) the three discrete experimental areas of interest and measurement
- 23 = atmospheric, 13 = reactor, 12 solar
- Time evolution introduces dependence on difference of mass squareds
- We still do not know which is the heaviest! (3=normal hierarchy, 1=inverted hierarchy)
Neutrino Oscillations
What they are and how we measure them

\[
\begin{pmatrix}
    v_e \\
v_\mu \\
v_\tau
\end{pmatrix} =
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & c_{23} & s_{23} \\
    0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
    c_{13} & 0 & s_{13}e^{-i\delta} \\
    0 & 1 & 0 \\
    -s_{12} & c_{12} & 0
\end{pmatrix}
\begin{pmatrix}
    v_1 \\
v_2 \\
v_3
\end{pmatrix}
\]


\[
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1991 cast your mind back

SSC was being built in Dallas, Tx

- LEP had measured number of light neutrinos = 3
  - Radiative Corrections were being used to tease out new information from the Z mass and width
- SSC was going to go after the Higgs
- Only a small number of people had eyes on another anomaly….
- Proton Decay Experiments
In 1991 Kamiokande had shown that if neutrino oscillations were the cause of the missing atmospheric neutrinos in their water Cherenkov detector, then the $\Delta m^2$ (difference in mass squared of the two types of neutrinos) was $\sim 10^{-2}$ eV$^2$.

The Kamiokande Experiment

- The Japanese funding agency took it seriously....

“The Super-Kamiokande project was approved by the Japanese Ministry of Education, Science, Sports and Culture in 1991 for total funding of approximately $100 million.”

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 (1.267\Delta m^2 L / E)$$
The Beginning of MINOS
The end of the SSC and the start of NuMI

• There was a call for LOIs in 1994 (3 years after the Kamiokande result) for a long baseline experiment at the planned neutrino facility (NuMI) at FNAL: there was already a short baseline experiment planned

  • COSMOS - later cancelled

• There were three EoIs for LBL experiments

  • Barry Barish and Doug Michael + ex-MACRO collaboration (50-60 people) (Tracker Calo, 15kT)

  • Maury Goodman + Soudan2 collaboration (about 50 people) (Tracker Calo, 1KT)

  • Stan + 0 other people 😁 (Cherenkov Detector at SLAC)

• All proposed to be sensitive to Kamiokande $\Delta m^2$, 700km baseline
The MINOS Experiment

1995 P-875

- MINOS was born with Stan as appointed-by-FNAL leader
- We had a competition for the name
- MINOS was the winner (Main Injector Neutrino Oscillation Search), for yes, we did not know for sure they existed yet!
- And we got a logo! courtesy Angela M. Gonzales, FNAL
- Beam would point at Soudan, Mn

- Huge $$$ contribution from U.Minn made that happen and helped the decision along
- Original 15 kton detector reduced to 5kt
- Detector $50M Beam $70M
The NuMI Beam
An integral part of the MINOS story

• Produce muon neutrinos to check if they were disappearing
Accelerator Neutrino Disappearance

The simplest experiment

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 (1.267\Delta m^2 L / E) \]
Accelerator Neutrino Disappearance
The simplest experiment

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Accelerator Neutrino Disappearance

The simplest experiment

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 (1.267 \Delta m^2 L / E) \]

(Input parameters: \( \sin^2 2\theta = 1.0, \Delta m^2 = 3.35 \times 10^{-3} \text{eV}^2 \))
Baltay Review 1998  
a near catastrophic experience

• Super-K first result showed potential for $\Delta m^2$ to be well below $10^{-3} \text{eV}^2$
• It was asserted in the review that we would not be sensitive, and therefore should be cancelled
• Huge difference from Kamiokande result!
• Super-K people on the review team!!
• Luckily, Charlie came to his senses.....
Ground Breaking Day, 1999
Ground Breaking Day
Construction 1999-2003

- Lehman reviews every 6 months
- Both detector and beam projects
- Beam was discovered to need a re-design
- 3 year delay resulted in beam delivery
Developments unforeseen, 2002
Art came to the Soudan Mine
The MINOS/MINOS+ Experiment

On time, on budget! (beam was late)

- MINOS had two functionally identical, magnetised, tracking, sampling calorimeters.
  - Can distinguish muon charge from the curvature.

- Exposed to the NuMI beam at Fermilab.

- MINOS+ continued the running of the MINOS detectors into the NOvA era at FNAL.
Three Flavour Oscillations

- MINOS was designed to measure the atmospheric scale oscillation parameters $\Delta m^2_{32}$ and $\sin^22\theta_{23}$
  - Look for disappearance of CC $\nu_\mu$ interactions in the FD relative to ND.
  - Continue the search with MINOS+ above oscillation max
- MINOS dominated the neutrino oscillation parameter measurement for 6-7 years before T2K came online.
Developments unforeseen
The best looking building on FNAL site
Stan pioneered measuring electron neutrino appearance in the MINOS detector.

- 1” thick steel planes and 4cm wide scintillator strips could be turned into a great electron detector!

- Development of LEM (Library Event Matching) enabled the analysis, an early precursor to ML.
• MINOS and T2K had similar precision the value of the product $2\sin^2(2\theta_{13})\sin^2\theta_{23}$ was lower for MINOS

• Daya Bay came online in 2012 and made the definitive measurement
Developments unforeseen, 2011

No-one expected a fire in the mine!
Developments unforeseen

No-one expected such a great clean up operation!
Developments unforeseen, 2011

That neutrinos might go faster than light!!!

- OPERA

- MINOS was encouraged with $$ to remake their old measurement

- $\nu_v = c \pm 1 \times 10^{-6}$
  

- MINOS best measurement existing of actual travel time of the neutrino

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Neutrino time-travel jokes have proliferated on the Internet. Example: “We don't serve faster-than-light neutrinos here,” said the bartender. A neutrino walks into a bar.
MINOS is sensitive to three sterile neutrino parameters

- $\theta_{24}$, $\theta_{34}$ and $\Delta m^2_{41}$

Oscillations visible in ND also have a measurable effect in the FD

Low $\Delta m^2_{41}$ only affects FD

High $\Delta m^2_{41}$ causes rapid oscillations in the ND and a constant deficit in FD

Using covariance matrix to constrain the signal allowed in both detectors means there is nowhere to hide in such an experiment over large parameter range
Unitarity and Disappearance
Is there any room for a 4th neutrino?

- Previous experiments looked for $\nu_\mu$ disappearance but with only one detector.
- MINOS/MINOS+ put a large footprint on this plot using newly realised power of the 2 detector covariance technique to weigh in with some very large exclusions.
- Blue area was the theorists attempt to combine all existing “positive hints” of the day onto this parameter space.
- Clearly, all ruled out.
Sterile Neutrinos
They just wont go away

• MINOS/MINOS+ when combined with Daya Bay and Bugey3 reactor experiments, transforms the disappearance parameter space to the appearance parameter space

• at 90% everything observed was ruled out
Cross Sections

No neutrino experiment would be complete without

- MINOS contributed cross sections measurements with its near detector across large range of energy
- Dominates still between 10-50 GeV
Cross Sections

No modern experiment would be complete without

- MINOS contributed cross sections measurements with its near detector across large range of energy
The Numbers

- 250 collaborators (at the peak)
- 10 years from proposal to beam (1995-2005)
- 11 years to collect data (2006-2016)
- 8 Targets (8 MINOS, 1 NOVA)
- 4 horns
- 4 FNAL Directors
- 5 Co-Spokespeople
- 42 papers (so far...)

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Improved search for muon-neutrino to electron-neutrino oscillations in MINOS

MINOS Collaboration • P. Adamson (Fermilab) et al. (Aug, 2011)

Observation of muon neutrino disappearance with the MINOS detectors and the NuMI neutrino beam

MINOS Collaboration • D.G. Michael (Caltech) et al. (Jul, 2006)

Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam

MINOS Collaboration • P. Adamson (Fermilab) et al. (Jun, 2008)

Search for sterile neutrinos in MINOS and MINOS+ using a two-detector fit

MINOS+ Collaboration • P. Adamson (Fermilab) et al. (Oct 17, 2017)
The Numbers

2008 paper: 42 individuals moved into academia
Sterile Neutrinos

- MINOS delivered a 99% C.L. limit in the supplementary information data release.
The cross check

Is the MiniBooNE result consistent with oscillations at all?

New MiniBooNE paper – arXiv:1805.12028

Best fit: $\Delta m^2 = 0.041$ eV$^2$ and $\sin^2 2\theta_{\mu e} = 0.958$

$$\sin^2_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14} \sin^2 \theta_{24}$$

Take $\sin^2 2\theta_{14} = 1$ to minimize $\nu_\mu$ disappearance

If you accept Unitarity

If you accept Unitarity

\[\nu_\mu \rightarrow \nu_x \quad 37 \quad \rightarrow \nu_e\]
The NuMI Beam
Neutrino beam (10.71 × 10^{20} POT) contained-vertex $\nu_\mu$

- MINOS data
- Best fit oscillations

Reconstructed $\nu_\mu$ Energy (GeV)

Ratio to No Oscillations
Energy (GeV) | ν \text{μ}ν
---|---
Reconstructed Ratio to No Oscillations
0.5 | 1
1.5 | 2
2.5 | 3
5 | 10
15 | 20
30 | 50

MINOS Far Detector Data

\begin{align*}
\text{MINOS, MINOS+ Far Detector Data} \\
\text{MINOS, MINOS+ Combined Fit} \\
\text{2014 MINOS Fit}
\end{align*}

\begin{align*}
10.71 \times 10^{20} \text{ POT } \nu_\mu \text{-mode MINOS} \\
3.36 \times 10^{20} \text{ POT } \overline{\nu}_\mu \text{-mode MINOS} \\
2.99 \times 10^{20} \text{ POT } \nu_\mu \text{-mode MINOS+} \\
\text{MINOS+ Preliminary}
\end{align*}
Energy (GeV) 

Reconstructed Ratio to No Oscillations

0.5 1 1.5 2 2.5

0 5 10 15 20 30 50

MINOS Far Detector Data

MINOS, MINOS+ Far Detector Data

MINOS, MINOS+ Combined Fit

2014 MINOS Fit

-POT $10^{20} \times 10.71$

-POT $10^{20} \times 3.36$

-POT $10^{20} \times 2.99$

MINOS+ Preliminary

2020