Neutrinos & the MINOS Experiment

Krzysztof Wojciech Fornalski
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supervisor:
Dr Katarzyna Grzelak
UW
Overview of the talk

- neutrinos’ theory and physics goals
- introduction to the MINOS experiment
- neutrinos’ beam & MINOS detectors
- detectors’ construction
- components technology
- software analyze
- my postgraduate work & data
- summary
A little bit of theory
Standard model

- there are 3 generations of neutrinos
- neutrinos are non-charged leptons
- neutrinos have a very low mass
- neutrinos are not visible!
- we can detect them thanks to particle collisions
in many neutrino experiment scientists proved, that neutrinos oscillated into each other

the neutrino „flavour” is changing on the long way

\[ \nu_\mu \leftrightarrow \nu_\tau \leftrightarrow \nu_e \leftrightarrow \nu_\mu \text{ etc.} \]
The approximate formula describing oscillations is:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

where $L$ (source to detector distance) and $E$ (neutrino energy) are experimental parameters

$2\theta$ (mixing angle) and $\Delta m^2$ (mass squared difference) are oscillation parameters
Experimental implications

- Accelerator experiments are done at fixed L (both locations fixed)
- If oscillations are present, we can see ν flux changes as a function of ν energy
- Ideally, one would want to observe at least 1 wavelength

- For fixed L and given Δm², there is an ideal $E_\nu$ because:
  - At high energy, the effect is small
  - At low energy, the effect is smeared out by resolution limitations
- Since $\Delta m^2$ is uncertain up to a factor of 10, we need to be able to adjust $E_\nu$ by up to a factor of 10
Physics goals

- Test the neutrinos oscillation hypothesis, especially $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$
  - Measure precisely parameters of oscillation: $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$

- Digits 3 and 2 means number of quantum states of neutrinos

- Each flavour ($e, \mu, \tau$) is a result of 3 quantum states with different mass
Physics goals

In the MINOS experiment it is possible to measure the appearance probability:

\[
\begin{pmatrix}
  e \\
  \nu_e \downarrow \\
  \nu_\mu \uparrow
\end{pmatrix}
= \begin{pmatrix}
  U_{e1} & U_{e2} & U_{e3} \\
  U_1 & U_2 & U_3 \\
  U_1 & U_2 & U_3
\end{pmatrix}
\begin{pmatrix}
  1 \\
  2 \\
  3
\end{pmatrix}
\]

\[P(\nu_1 \rightarrow \nu_3) = 1 - \sin^2 2 \sin^2 \left( \frac{1.267 m^2 L}{E} \right) \]

if \(m^2_{23} >> m^2_{12}\)
Actual values of parameters

- Fit includes penalty terms for three main systematic uncertainties.
- Fit is constrained to physical region: \( \sin^2(2\theta_{23}) \leq 1 \)

\[
|\Delta m_{32}^2| = 2.74_{-0.26}^{+0.44} \times 10^{-3} \text{ eV}^2
\]
\[
\sin^2 2 \theta_{23} = 1.00_{-0.13}
\]
MINOS Experiment
First informations

- **Minos** - mythical Greek king of Creta, son of Zeus and Europe
- **Main Injector Neutrino Oscillation Search** - a long-baseline neutrino oscillation experiment
  - Two detectors and the base in FermiLab
  - The MINOS experiment measures the neutrino oscillation between the detectors
- Experiment started in 2005
- First data at the beginning of 2006
Beam production
Production of the beam

- FermiLab National Laboratory near Chicago
- 120 GeV protons from the Main Injector accelerator
- one pulse is 1.867 second long
- $4 \times 10^{13}$ protons/pulse
- after that the protons beam is focuses on the target
Producing the neutrino beam - the scheme

Proton beam collides with a graphite target. As a result there are many short-life particles (pions, kaons, etc.), which decay into muons. Muons decay into muon neutrinos. In such a way is the neutrino beam formed.
The NuMI beamline

- Target Service Building
- Main Injector
- Carrier Tunnel
- Target Hall
- MINOS Service Building
- Beam Absorber Muon Detectors
- Minos Hall
- Minos Near Detector
- To Soudan
- ±105 M

Primary proton line

Target hall

Decay pipe
MINOS long-baseline experiment detectors
MINOS Near Detector (ND)

- Located at FNAL
- 1040m from target
- 103m underground
- 980 ton mass
- 3.8m x 4.8m x 16m
- 282 steel + 153 scintillator planes
Why „long-baseline” experiment?

- neutrino beam travels from the near detector to the far detector in Soudan Mine (Minnesota)
MINOS Far Detector (FD)

- 735 km from target
- 705m underground
- 5.4 kton mass
- 8m x 8m x 30m
- 484 scintillator planes
- Veto shield for cosmic ray rejection in atmospheric $\nu$ analysis
- GPS time stamping to synchronize FD to ND
- Main Injector spill times sent to FD for beam trigger
Building the FD

Built ‘99 Summer at Fermilab
Detectors’ technology
Detectors construction

- Near & Far detectors are functionally identical
- They share the same basic detector technology and granularity:
  - Iron/Scintillator tracking calorimeters
  - 2.54cm thick magnetized steel planes \(<B> = 1.2T\)
  - 1cm thick scintillator planes
  - Alternate planes rotated by \(\pm 90^\circ\) (U,V)
- thanks to this rotate we can find a track of the particle
FD’s scintillator plane structure

- 192 scintillator strips by plane
- scintillator strips are parallel to each other
- strips are connected to the electronics system by fibers
Scintillator strip

- polystyrene in TiO₂
- 1 cm thick
- 4,1 cm wide
- max. length: 8m
- green fiber inside
Signal from the scintillator

- ionizing particle (muon, electron, etc.) makes photons, which are transported by wavelength shifting fiber.
- optical readout with multi-anode PMTs (photomultiplier)
- in the next step the signal is analyzed by computer
Computer’s analyze
How you can see the signal

On the picture you can see track of the muon in ND as a result of neutrino interaction. Each point is a signal from one scintillator strip.
How you can see the signal

- **µ** - view
- **'u'** - view
- **crosstalk**
- **'v'** - view

plane #  →
strip #
ND - low energy example

Reconstruction Summary

- # Tracks: 1
- # Showers: 1

Primary Track:
- Len: 2.4 GeV
- Range E: 1.5 GeV
- Fit P: -1.8 GeV

Primary Shower:
- PEs: 41.6
- Energy: 0.22 GeV
ND - medium energy example
ND - high energy example
ND - multievent example

Reconstruction Summary
# Tracks: 3  # Showers: 3

Run: 6067  Shift: 80  All 5 Slices
ND - muon from the rock
FD - cosmic muon (simulation MonteCarlo)

Reconstructed front view

Timing
FD - low energy example
FD example

You can see electromagnetic shower-the result of $\nu_e$ interaction
What can I do?
My postgraduate work

- study the theory
- learn the software in ROOT
- make some new software
- use the terabytes of data and MonteCarlo
- select the neutral current (NC) and charged current (CC) events
- estimate and compare the oscillation parameters
Run: 32133, Snarl: 97235, Slice: 1/1, Event 1/1

Reco
#Trks: 1
#Shws: 2
q/p: 0.517 +/- 0.034, p/q: -1.935
TrkRangeEnergy: 2.042  RecoShwEnergy: 0.196
Vtx: -0.52, -2.42, 6.20

Truth
N/A
N/A
N/A
N/A
N/A

Transverse vs Z view - U Planes

Low energy (2 GeV) neutrino event - you can see the muon track

Transverse vs Z view - V Planes

Crosstalk
Neutral Current or Charged Current?

\[ \nu_\mu \text{ CC Event} \]

\[ \nu_e \text{ CC Event} \]

\[ \text{NC Event} \]

- We have \( \mu \) with long \( \mu \) track + hadronic shower
- short event, often diffuse
- the neutrino is “deflected”!

\[ \text{UZ} \]

\[ \text{VZ} \]

\[ 3.5 \text{m} \]

\[ 1.8 \text{m} \]

\[ 2.3 \text{m} \]

- short, with typical EM shower profile
- no \( \mu \)!
Overview of the Oscillation Measurement

In order to perform the oscillation analysis, we need to predict the Far detector unoscillated true neutrino spectrum.

The goal is to perform this procedure in such a way that we are as insensitive as possible to uncertainties related to beam modelling and cross-sections built-in to our nominal Monte Carlo.

This is exactly the purpose of the Near detector, and therefore we directly use the Near detector data to perform the extrapolation, using our Monte Carlo to provide necessary corrections due to energy smearing and acceptance.
Example of a $\nu_\mu$ disappearance measurement

Look for a deficit of $\nu_\mu$ events at FD

$$P(\nu_\mu \rightarrow ) = 1 - \sin^2 2 \sin^2 (1.267 \frac{m^2 L}{E})$$

- **Unoscillated**
- **Oscillated**

**Monte Carlo**

**Spectrum**

**Spectrum ratio**
MINOS Best-Fit Spectrum

Best-fit spectrum for $1.27 \times 10^{20}$ POT

$|m_{32}^2| = 2.74^{+0.44}_{-0.26} (\text{stat + syst}) \times 10^{-3} \text{ eV}^2$

$\sin^2 2 \theta_{23} = 1.00_{-0.13}^{+0.44} (\text{stat + syst})$

Normalization = 0.98

$\chi^2 = \sum_{i=1}^{\text{nbins}} [2(e_i - o_i) + 2o_i \ln(o_i/e_i)] + \sum_{j=1}^{\text{nsys}} s_j^2 / s_j^2$

Measurement errors are 1
Candidate FD $\nu_e$ Event

PH vs Strip vs Plane – U View

TPos vs Plane view - U Planes

Beam direction

PH per Plane

Run: 32617  Snarl: 105322
Reco Shower Energy: 8.7 GeV
ANN PID: 0.99

TPos vs Plane view - V Planes

PH with Transverse Position

Strip Position - Shower Vertex (U+V Combined)

Mean -0.002381
RMS 0.04618

Plane Position - Shower Vertex Plane (U+V Combined)

Mean 5.615
RMS 2.792

Reco Shower Energy: 8.7 GeV

PH vs Strip vs Plane – V View
Summary

- MINOS is a new neutrino experiment in USA
- the main goal is to test oscillation hypothesis and measure the oscillation parameters
- it will give a new physics
- thanks to that I will get a new knowledge
- and the MSc...
And after that...

MSc
References

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THANK YOU!

www.fuw.edu.pl/~minos

fornalski@knf.pw.edu.pl