Recent Results from the NOvA Experiment

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Wichita State University Seminar
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Neutrinos
Neutrino Oscillations

• While measuring the neutrino flux from the Sun Ray Davis found fewer electron neutrinos then predicted.

• In 1998 Super Kamiokande discovered with atmospheric neutrinos that neutrinos were undergoing flavor oscillations

• Neutrino oscillations indicate that neutrinos have non-zero mass

• This is physics beyond the standard model

2002 Nobel Prize
Ray Davis Jr.    Masatoshi Koshiba

2015 Nobel Prize
Takaaki Kajita    Arthur McDonald
Neutrino Oscillations

- Neutrinos are created and observed in flavor eigenstates, but travel through space in mass eigenstates.
- The PMNS matrix describes flavor oscillations
- Analogous to mixing in the quark sector, except the mixing angles are large

\[ |\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^* |\nu_i\rangle \]

\( i = 1, 2, 3 \) (mass states) \( \alpha = \mu, \tau, e \) (flavor states)
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\( i = 1, 2, 3 \) (mass states) \hspace{1cm} \( \alpha = \mu, \tau, e \) (flavor states)

\[ c_{ij} = \cos \theta_{ij} \]
\[ s_{ij} = \sin \theta_{ij} \]

\[ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \]

\( \nu_\mu \rightarrow \nu_\mu \) \hspace{1cm} \( \nu_e \rightarrow \nu_e \) \hspace{1cm} \( \nu_e \rightarrow \nu_\mu + \nu_\tau \)

atmospheric and long-baseline \hspace{1cm} reactor and long-baseline \hspace{1cm} solar and reactor
Matter Effect

- The electrons in the earth create an additional scattering channel for electron neutrinos passing through.
- This creates a “drag” on the neutrino beam, altering the oscillation probabilities.
- Can enhance or suppress oscillations depending on neutrinos/antineutrinos and the ordering of neutrino masses.

\[ \nu_e \rightarrow e^- \rightarrow W^+ \rightarrow \nu_e \quad \nu \rightarrow q, e^- \rightarrow Z^0 \rightarrow \nu, q, e^- \]
Unanswered Questions in Neutrino Physics

- Is the mass hierarchy normal or inverted?
- Is $\delta_{\text{CP}}$ non-zero?
- Is $\theta_{23}$ maximal ($45^\circ$)?
  - If not does $m_3$ couple more to $\nu_\mu$ or $\nu_\tau$?
- Are there sterile neutrinos?
- Is the neutrino a Dirac or Majorana particle?
- What is the absolute mass scale?
Requirements of a Neutrino Oscillation Experiment

- High power neutrino source
- Large detector
- Oscillations a function of L/E
  - Optimized baseline and beam energy for the parameters of interest
- Clear separation of signal events from backgrounds
- Control of systematic uncertainties
The NOvA Experiment
The NOvA Experiment

• Two functionally identical detectors
• Located 14.6 mrad off axis from NuMI neutrino beam line at Fermilab
• 810 km baseline, the longest in the world
• Uses four oscillation channels:
  \[ \nu_\mu \to \nu_\mu, \quad \bar{\nu}_\mu \to \bar{\nu}_\mu, \quad \nu_\mu \to \nu_e, \quad \bar{\nu}_\mu \to \bar{\nu}_e \]
• Measure \( \theta_{13}, \theta_{23}, \) mass hierarchy, and \( \delta_{\text{CP}} \)
• Also used for sterile neutrino searches, exotic searches, neutrino cross sections
NuMI Beam

- 120 GeV protons extracted from the Main Injector at Fermilab in 10 μs spills
- Magnetic focusing horns allow selection of charge sign for selecting a neutrino or anti-neutrino beam
- Beam 97.5% $\nu_\mu$ with 0.7% $\nu_e$ and 1.8% wrong-sign contamination
- 14.6 milli-radians off-axis, narrow beam around oscillation maximum
NuMI Beam Performance

- Beam has been running at 560 kW
- Achieved 700 kW design goal in brief tests on June 13th, 2016
- Data analyzed between February 6, 2014 and May 2, 2016
- Data equivalent to $6.05 \times 10^{20}$ protons-on-target in a full 14 kT detector, more than doubling the previous exposure.

$v_\mu \rightarrow v_\mu$: Phys.Rev.D93.051104
$v_\mu \rightarrow v_e$: PRL.116.151806
NOvA Detectors

- fine grained, low-z, tracking calorimeter
- 64% liquid scintillator by mass
- 344,000 channels in the Far Detector, located on surface
- Near Detector located 100m underground at Fermilab
Far Detector 550 μs Readout Window

Cell hits colored by charge deposition
Far Detector 10 μs NuMI Beam Window

Beam Direction

Cell hits colored by charge deposition
Far Detector Neutrino Interaction

Cell hits colored by charge deposition

Beam Direction
Event Topologies

- **$\nu_\mu$ CC**
- **$\nu_e$ CC**
- **NC**
Analysis Improvements
Convolutional Neural Networks

• Take advantage of recent advances in machine learning/computer vision
• Deep networks extract increasingly complex features from input data, GPUs greatly improve training time
• Inputs to the network are pixels in image
• Apply convolutional kernels to pull out event features
**Convolutional Neural Networks**

- Architecture adapted from GoogLeNet
  - C. Szegedy et al., arXiv:1409.4842
  - Input is 80 cell x 200 plane detector pixel map
  - Each event view processed separately and then merged

- Network implemented and trained in the Caffe Framework (Y. Jia et al., arXiv:1408.5093)
- Trained on 4.7 million simulated events on Fermilab GPU cluster

- Output classifies neutrino interaction type \((\nu_\mu, \nu_\tau, \nu_e, NC)\)
- Used in appearance analysis.
  - Performance gain over previous classifiers equivalent to adding 30% more detector mass

A. Aurisano and A. Radovic and D. Rocco et. al, JINST 11 P09001 (2016)
Convolutional Neural Networks

• Showing a muon neutrino interaction and the first layer of feature maps extracted from the convolutional kernels
Convolutional Neural Networks

- Showing a electron neutrino interaction and the first layer of feature maps extracted from the convolutional kernels
- The strong features extracted are the shower as opposed to the muon track
Nuclear Model Corrections

Near Detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production

Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Solution: 2-particle, 2-hole (2p2h) events where neutrino is scattering off a nucleon-nucleon pair
Nuclear Model Corrections

- Enable GENIE’s empirical Meson Exchange Current model\(^1\)
- Reweight to matched observed excess as a function of momentum transfer
- Weight single non-resonant pion production down by effectively 50\(^%\)\(^2\)

\(^1\)S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57
\(^2\)P.A. Rodrigues et al., arXiv:1601.01888
Nuclear Model Corrections

- Take 50% systematic uncertainty on MEC component
- Reduces hadronic energy scale and quasi-elastic cross section systematic uncertainties

1. S. Dytman, based on J. W. Lightbody, J. S. OConnell, Comp. in Phys. 2 (1988) 57
2. P.A. Rodrigues et al., arXiv:1601.01888
Muon Neutrino Disappearance Analysis
$\nu_\mu \rightarrow \nu_\mu$ Disappearance channel

- Illustrate measurement with two flavor approximation:

$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$

- Measure shape of $\nu_\mu$ CC spectrum in energy region of the oscillation dip

- Requires good energy resolution
Muon Neutrino Selection

- Separate $\nu_\mu$ CC interactions from NC and cosmic-ray backgrounds

- Containment cuts remove activity near walls

- Four variable kNN to select muons
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction

- Selection is 81% efficient and 91% pure
Energy Estimation

- Muon dE/dx used in length-to-energy conversion
- Hadronic energy estimated calorimetrically from off-track hits
- ~7% resolution on neutrino energy

\[ E_V = E_\mu (L_\mu) + E_h \]

*With MEC events*
Energy Estimation

- Muon dE/dx used in length-to-energy conversion
- Hadronic energy estimated calorimetrically from off-track hits
- ~7% resolution on neutrino energy

\[ E_V = E_{\mu} (L_\mu) + E_h \]

NOvA Preliminary

![Graph showing reconstructed neutrino energy distribution](image)
Cosmic Rejection

- Far Detector sees 150 kHz of cosmic induced events

- 10 μs beam window at a rate of ~0.8 Hz reduces background by $10^5$
  - The two year data period amounts to ~5 minutes of neutrino beam

- Additional factor of $10^7$ rejection achieved from event topology and a boosted decision tree (BDT) based on:
  - track direction
  - start/end points of track
  - track length
  - energy
  - number of hits
Extrapolation

- Use high statistics ND data/MC to adjust prediction at FD
  - Translate ND data/MC observation to true energy
  - Oscillate ratio to the FD
  - Smear back into reconstructed energy
  - Reduces systematic uncertainties
Systematic Uncertainties

- Various sources of systematic uncertainty considered
- Propagate the effect of each though the extrapolation with specially modified MC samples
- Include as pull terms in fit
- Table shows increase in quadrature of measurement uncertainty

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Effect on $\sin^2(\theta_{23})$</th>
<th>Effect on $\Delta m^2_{32}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalisation</td>
<td>$\pm 1.0%$</td>
<td>$\pm 0.2%$</td>
</tr>
<tr>
<td>Muon E scale</td>
<td>$\pm 2.2%$</td>
<td>$\pm 0.8%$</td>
</tr>
<tr>
<td>Calibration</td>
<td>$\pm 2.0%$</td>
<td>$\pm 0.2%$</td>
</tr>
<tr>
<td>Relative E scale</td>
<td>$\pm 2.0%$</td>
<td>$\pm 0.9%$</td>
</tr>
<tr>
<td>Cross sections + FSI</td>
<td>$\pm 0.6%$</td>
<td>$\pm 0.5%$</td>
</tr>
<tr>
<td>Osc. parameters</td>
<td>$\pm 0.7%$</td>
<td>$\pm 1.5%$</td>
</tr>
<tr>
<td>Beam backgrounds</td>
<td>$\pm 0.9%$</td>
<td>$\pm 0.5%$</td>
</tr>
<tr>
<td>Scintillation model</td>
<td>$\pm 0.7%$</td>
<td>$\pm 0.1%$</td>
</tr>
<tr>
<td><strong>All systematics</strong></td>
<td><strong>$\pm 3.4%$</strong></td>
<td><strong>$\pm 2.4%$</strong></td>
</tr>
<tr>
<td><strong>Stat. Uncertainty</strong></td>
<td><strong>$\pm 4.1%$</strong></td>
<td><strong>$\pm 3.5%$</strong></td>
</tr>
</tbody>
</table>
$\nu_\mu \rightarrow \nu_\mu$ Oscillation Results

- 473 +/- 30 events predicted in the absence of oscillations
- Observed 78 events
- 82 events predicted at the best fit point including 3.7 beam background and 2.9 cosmic induced events
$\nu_\mu \rightarrow \nu_\mu$ Oscillation Results

**Best fit (in NH):**

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Excludes maximal mixing at 2.5 $\sigma$
νμ \rightarrow νμ Oscillation Results

- Best fit χ²/DOF = 41.5/17 is driven by the high energy tail
- There is no pull in the oscillation fit from the tail
$\nu_\mu \rightarrow \nu_\mu$ Oscillation Results

- Non-maximal best fit driven by bins in oscillation dip
  - $\Delta m^2_{32} = 2.46 \times 10^{-3}$ eV$^2$
  - $\Delta \chi^2 = 6.4$ above non-maximal fit
Electron Neutrino Appearance Analysis
\[ \nu_\mu \rightarrow \nu_e \text{ Appearance channel} \]

\[
P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{sol}} \right|^2 = P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)
\]

\[
\sqrt{P_{atm}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \Delta_{31}
\]

Depends on relative sign of “a” and \(\Delta_{31}\)

\[
\sqrt{P_{sol}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}
\]

\(~1\%\) effect at the NOvA baseline

\[
a = \frac{G_F N_e}{\sqrt{2}} \approx \frac{1}{3500 km}
\]

aL=0.08 for L=295km T2K baseline
aL=0.23 for L=810km NOvA baseline

Oscillation probability is sensitive to: mass ordering, CP violating phase, and \(\theta_{23}\) octant.
$\nu_\mu \rightarrow \nu_e$ Appearance channel

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{sol}} \right|^2$$

$$= P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

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Oscillation probability is sensitive to: mass ordering, CP violating phase, and $\theta_{23}$ octant.

Electron Neutrino Selection

- 73% $\nu_e$ CC selection efficiency, 76% purity with CVN classifier
- Loose CVN cut optimized for $S/\sqrt{S+B}$
- Bin analysis in four bins of energy and three of CVN
- Good ND Data/MC agreement
- CVN provides better cosmic rejection and similar systematics to other classifiers
Evaluating Signal Efficiency

- Remove cosmic ray muon from FD events in data and simulation
- Apply selection to remaining bremsstrahlung shower to benchmark simulation of electron selection

- EM showers should be well modeled, check if selection efficiency differences come from hadronic side
- Remove reconstructed muons from selected $\nu_\mu$ events, replace with simulated electron (MRE)
  - better than 1% agreement between efficiency for selecting data MRE events and efficiency for selecting MC MRE events
ND Data Decomposition

- $\nu_e$ CC selection in the ND picks out FD backgrounds
- beam $\nu_e$ CC
- $\nu_\mu$ CC
- NC
- $\sim$10% excess of data over MC in the ND
- Extrapolate data/MC differences to adjust FD prediction
- Each component oscillates differently
- Must decompose the data into constituent components
ND Data Decomposition: Beam $\nu_e$ CC

- Low energy $\nu_\mu$ and $\nu_e$ trace back to the same $\pi$ ancestors
- Use $\nu_\mu$ at lower energy to reweight decaying pions in ($p_T$, $p_z$) space
- Decreases $\nu_e$ with $\pi^+$ parent 3-4%
- Weight $\nu_e$ with $K^+$ parents up 17% based on $\nu_\mu$ high-E tail
- Overall effect is 1% increase in 1-3 GeV range in intrinsic beam $\nu_e$ CC events

**True $\nu_e$ CC events**

**True $\nu_\mu$ CC events**
ND Data Decomposition: Michel Electrons

• $\nu_\mu$ CC events contain Michel electron from muon decay
• $\sim$1 more Michel in $\nu_\mu$ events than $\nu_e$ or NC
• Fit observed number of Michels in each bin of energy and PID by adjusting $\nu_\mu$/NC ratio
• Data excess assigned between NC (+17%) and $\nu_\mu$ CC (+10%)
Systematic Uncertainties

- Multiple sources of systematic error considered
- Extrapolate FD predictions with special MC samples for each effect.
- Uncertainty quoted as difference between shifted and nominal predictions
- Fit nuisance parameters as pull terms
- Statistical uncertainties dominate
\( \nu_\mu \rightarrow \nu_e \) Oscillation Prediction

- Prediction dependent on oscillation parameters

**Signal events**

\[ (\pm 5\% \text{ systematic uncertainty}) : \]

<table>
<thead>
<tr>
<th>NH, 3( \pi/2 )</th>
<th>IH, ( \pi/2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.2</td>
<td>11.2</td>
</tr>
</tbody>
</table>

**Background by component**

\[ (\pm 10\% \text{ systematic uncertainty}) : \]

<table>
<thead>
<tr>
<th>Total BG</th>
<th>NC</th>
<th>Beam ( \nu_e )</th>
<th>( \nu_\mu ) CC</th>
<th>( \nu_\tau ) CC</th>
<th>Cosmics</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>3.7</td>
<td>3.1</td>
<td>0.7</td>
<td>0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>
$\nu_\mu \rightarrow \nu_e$ Oscillation Results

- Observe 33 events on background of 8.2 +/- 0.8 events
- > 8 $\sigma$ significance of $\nu_e$ appearance

![Graph showing oscillation results and data points.]

Events / 0.5 GeV Bin

Reconstructed neutrino energy (GeV)

$0 < CVN < 0.75$
$0.75 < CVN < 0.87$
$0.87 < CVN < 0.95$
$0.95 < CVN < 1.0$

Total Background

Cosmic Background

FD Data

Best Fit Prediction

NOvA Preliminary

$\sin^2 \theta_{23} = 0.4 - 0.6$

$\Delta m^2_{31} = 2.5 \times 10^{-3}$

NOvA FD

$6.05 \times 10^{20}$ POT equiv.
$\nu_\mu \rightarrow \nu_e$ Oscillation Results

- Fit for hierarchy, $\delta_{\text{CP}}$, $\sin^2 \theta_{23}$
  - Constrain $\sin^2 (2\theta_{13}) = 0.085 \pm 0.05$
- Constrain $\Delta m^2 = 2.44 \pm 0.06 \times 10^{-3}$ eV$^2$, NH
  - $(-2.49 \pm 0.06 \times 10^{-3}$ eV$^2$, IH)

- Systematic effects included as nuisance parameters
  (normalization, flux, calibration, cross section, and detector response effects)
$\nu_\mu \rightarrow \nu_e$ Oscillation Results

- Fit for hierarchy, $\delta_{\text{CP}}$, $\sin^2 \theta_{23}$
  - Constrain $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ from reactor experiments
  - Constrain $\Delta m^2$ and $\sin^2 \theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated

- Global best fit Normal Hierarchy
  $$\delta_{CP} = 1.49\pi$$
  $$\sin^2 (\theta_{23}) = 0.40$$
  - best fit IH-NH, $\Delta \chi^2 = 0.47$
  - both octants and hierarchies allowed at 1\sigma
  - 3\sigma exclusion in IH, lower octant around $\delta_{\text{CP}} = \pi/2$
Conclusions

• Presented an analysis of $6.05 \times 10^{20}$ POT (1 nominal year)

• Muon neutrinos disappear
  • Best fit is a non-maximal value of $\theta_{23}$
  • Maximal mixing excluded at 2.5σ

• Electron neutrinos appear, > 8 σ significance
  • Weak preference for normal hierarchy
  • Region in IH, lower octant around $\delta_{\text{CP}}=\pi/2$ is excluded

• Planned switch to anti-neutrino running in the spring of 2017

• Thank you!