New Results from NOvA

Giulia Brunetti on behalf of the NOvA Collaboration
Neutrinos

- Neutrino mix: flavors eigenstates are linear combinations of mass eigenstate

- Non-zero probability of detecting a different neutrino flavor than that produced at the source

  - depends on: squared mass difference, mixing angles, CP-violating phase, hierarchy....

- Mixing matrix for the three-flavor case:

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

\[
\theta_{23} \sim 45^\circ \\
\theta_{13} = 8.5^\circ \\
\theta_{12} = 33.5^\circ
\]

\[
\Delta m_{23}^2 \sim \pm 2.5 \times 10^{-3} \text{eV}^2 \\
\delta_{CP} \\
\Delta m_{21}^2 = +7.5 \times 10^{-5} \text{eV}^2
\]
Neutrinos

- Open questions:
  - Maximal mixing in the atmospheric sector? ($\theta_{23}$)
  - CP-violation? ($\delta_{CP}$, $P(\nu_\mu)$ vs $P(\bar{\nu}_\mu)$, matter/antimatter asymmetry in the universe)
  - Hierarchy? ($sign(\Delta m^2_{23})$, matter effects)
  - Majorana or Dirac? (IH & no 0νββ decays)
  - Absolute masses?

- NOvA (NuMI Off-Axis $\nu_e$ Appearance) Experiment
  - designed to answer the next generation of $\nu$ questions: tuned for $\nu_e$ appearance in an almost pure $\nu_\mu$ beam

- 200+ collaborators
- 41 institutions
- 7 countries
NOvA

NuMI Off-Axis $\nu_e$ Appearance Experiment

- NOvA is a long baseline (810 km), off-axis (14.6 mrad) neutrino oscillation experiment
- NuMI beam at Fermilab
- Energy peak @ 2 GeV
- 2 functionally identical detectors:
  - ND underground at Fermilab. 290-ton.
    Used to predict event rate at the FD
  - FD on surface in Ash River, MN. 14-kton.
    To look for oscillations
The NuMI beam

- 120 GeV protons onto a graphite target
- Secondary mesons charge-selected and focused by two magnets
- Pions decay into neutrinos/antineutrinos
- 6.05 $10^{20}$ POT in 14 kton equivalent detector
- Currently running at 560 kW, achieved 700 kW design goal in tests on June 13
NOvA Detectors

- Functionally identical, PVC cells filled with 10.2M Liters liquid scintillator
- Low-Z, 65% active volume, DAQ runs without deadtime (beam trigger, cosmic calibration samples, SNEWS, exotics)
- Read-out using WLS to APDs
- Cells organized in horizontal and vertical planes
- FD is 14 kton, ND is 0.3 kton
NOvA Physics

- **3-flavor oscillation analyses**
  - **DISAPPEARANCE:** $\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_\mu (\bar{\nu}_\mu)$
    - $\Delta m^2_{23}, \sin^2 2\theta_{23}$
  - **APPEARANCE:** $\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_\mu (\bar{\nu}_\mu)$
    - $\theta_{13}, \theta_{23}, \delta_{CP}$, mass hierarchy
    - Matter effects over 810 km $\rightarrow \pm 30\%$

- **Event Topologies**
  - **$\nu_\mu$ CC**
    - Straight track (~5m)
  - **$\nu_e$ CC**
    - Fuzzy shower
  - **NC**
    - Diffuse activity

- Good granularity
- $X_0 = 38$cm (6 cells depths, 10 cells widths)
ν_μ Disappearance

- The principle:
  - Select ν_μ CC sample: events with long tracks and distinctive dE/dx
  - Extrapolation of the ND spectrum to the FD and measurement of the deficit
  - 2-flavor oscillation approximation works well in this case:
    \[ P_{\mu \mu} \sim 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{23}^2 L}{4E} \right) \]
    \[ \theta_{23} \sim 45^\circ \rightarrow \text{at the oscillation max almost all } \nu_\mu \text{ disappear} \]
  - NC and cosmic background suppression, containment cuts to remove events with activity close to the detector walls
  - ν_μ ID: Multivariate kNN classifier using 4 variables:
    - Track length
    - dE/dx
    - Scattering along the track
    - Track only fraction of planes
  - 81% selection efficiency for signal with 95% purity
\( \nu_\mu \) Disappearance

- \( \nu_\mu \) ND events
  - Hadronic energy scale uncertainty from 14\% to 5\% with the addition of MEC events to the simulation (w.r.t. NOvA 2015 results)
  - ND reconstructed energy spectrum unfolded and extrapolated to FD using Far/Near true ratio for prediction

\[ E_N = E_\mu \text{ (L track)} + E_{\text{had}} \text{ (7\% res)} \]
Disappearance

- $\nu_\mu$ FD events: **78** events observed
  - No oscillation prediction: $473\pm30$
  - Best oscillation fit: 82 events
  - Beam BG: 3.7, Cosmics: 2.9

$\chi^2$/NDF=41.6/17

driven by fluctuations in the tail, no pull in oscillation fit
\( \nu_\mu \) Disappearance

- Fit for \( \Delta m^2 \) and \( \sin^2 \theta_{23} \)
- Dominant systematic effects included in fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scale
  - Cross section
  - Detector response and noise

Maximal mixing (\( \theta_{23} = 45° \)) excluded at 2.5\( \sigma \)

Our best fit (in NH):

\[
|\Delta m_{32}^2| = 2.67 \pm 0.12 \times 10^{-3} \text{ eV}^2
\]

\[
\sin^2 \theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})
\]
\( \nu_\mu \) Disappearance

- Our best fit (in NH):
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  \sin^2 \theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03}) \nu
  \]

- Non-maximal fit is driven by bins in oscillation dip (1-2 GeV)
- Forcing maximal mixing gives:
  \[
  |\Delta m^2_{32}| = 2.46 \cdot 10^{-3} \text{ eV}^2
  \]
Improved event selection

**CVN – Convolutional Visual Network**: new event selection technique based on ideas from computer vision and deep learning

- Calibrated hit maps are inputs to the CVN
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

**Improved sensitivity equivalent to 30% more exposure**
Improved event selection

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**Improved sensitivity equivalent to 30% more exposure**
$\nu_e$ Appearance

$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (\Delta_{31} - aL) - \Delta^2_{31}}{\Delta^2_{31}} \frac{\sin (aL) \sin (\Delta_{31} - aL) \cos \Delta_{32}}{\Delta_{31} - aL} \frac{\sin \Delta_{32}}{\Delta_{32}}$

- Depends simultaneously on $\theta_{13}$, $\theta_{23}$, $\delta_{CP}$, $\text{sign}(\Delta m^2_{31})$
- $\sin^2 2\theta_{13} = 0.095 \rightarrow$ most $\nu_\mu$ go to $\nu_\tau$
- Look for deviations due to hierarchy (matter effects) and CP-violation

- NOvA measures $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 2GeV, different dependence on $\text{sign}(\Delta m^2_{32})$ and $\delta_{CP}$
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$P \propto \sin^2 \theta_{23}$

Constrain a space region
$\nu_e$ Results

- CVN PID, loosen cut on Pid optimized to favor parameter measurement
- Separate $\nu_e$ CC interactions from backgrounds, backgrounds evaluated in ND:
  - intrinsic beam $\nu_e$, Neutral Currents, $\nu_\mu$ CC, each propagate differently
  - Use ND data to predict background in the FD
- Looking for an excess in the FD
**ν_e Results**

- Expected events depend on oscillation parameters:
  \[ \sin^2 \theta_{23} = 0.5, \pm 5\% \text{ syst.} \]

**Total Prediction** (signal+background):

<table>
<thead>
<tr>
<th>NH, 3π/2</th>
<th>IH, π/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.4</td>
<td>19.4</td>
</tr>
</tbody>
</table>

Background components (±10% syst):

<table>
<thead>
<tr>
<th>Total BG</th>
<th>NC</th>
<th>Beam ν_e</th>
<th>ν_μ CC</th>
<th>ν_τ 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>

- Each component extrapolated in bins of energy and CVN output
$\nu_e$ Results

- Total Prediction (signal+background):
  - NH, $3\pi/2$: 36.4
  - IH, $\pi/2$: 19.4

- Observed events in FD: 33
$\nu_e$ Results

- Fit for hierarchy, $\delta_{CP}$, $\sin^2\theta_{23}$
  - Constrain $\sin^2(2\theta_{13})=0.085\pm0.05$ from reactor
  - Constrain $\Delta m$ and $\sin\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, syst and other oscillation parameters not correlated

- Global best fit, preference for NH, $\Delta\chi^2=0.47$
  - $\delta_{CP} = 1.49\pi$, $\sin^2(\theta_{23}) = 0.40$
  - Both octants and hierarchies allowed at $1\sigma$
  - IH lower octant around $\delta_{CP} = \pi/2$ excluded at $3\sigma$
$\nu_e$ Results

- Fit for hierarchy, $\delta_{CP}$, $\sin^2\theta_{23}$
  - Constrain $\sin^2(2\theta_{13}) = 0.085 \pm 0.05$ from reactor
  - Constrain $\Delta m$ and $\sin\theta_{23}$ with NOvA disappearance results
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  - $\delta_{CP} = 1.49\pi$, $\sin^2(\theta_{23}) = 0.40$
  - Both octants and hierarchies allowed at 1$\sigma$
  - IH lower octant around $\delta_{CP} = \pi/2$ excluded at 3$\sigma$

- Antineutrino Run (planned for spring 2017) will help resolve degeneracies
Summary

- Early days for NOvA, our baseline program is six times our current exposure.

  NOvA collected $6.05 \times 10^{20}$ POT, oscillation results:
  - $\nu_\mu$ disappear, maximal mixing is excluded at 2.5$\sigma$.
  - $\nu_e$ appear:
    - slight preference for NH
    - IH lower octant around $\delta_{CP} = \pi/2$ is excluded ($>3 \, \sigma$)

- Antineutrino run in spring 2017

- Many other interesting NOvA analyses!
  - sterile neutrinos, cross section measurements, supernovae…
Thank you!
Back up
NuMI beam

- Beam performance
- 14mrad Off-Axis:
  - Neutrino energy spectrum peaked at 2GeV, width ~20%

\[ E_\nu = \frac{1 - \frac{m_\mu^2}{m_\nu^2}}{1 + \gamma^2 \theta^2} E_{\nu,K} \]

\[ \theta = 0 \]

\[ \theta = 7 \text{ mrad} \]

\[ \theta = 14 \text{ mrad} \]

\[ \theta = 21 \text{ mrad} \]
Reconstruction

**Vertexing:** Find lines of energy depositions w/ Hough transform CC events: 11 cm resolution

**Clustering:** Find clusters in angular space around vertex. Merge views via topology and prong dE/dx

**Tracking:** Trace particle trajectories with Kalman filter tracker. Also, cosmic ray tracker: lightweight, fast, and for large calibration samples, online monitoring.
Calibration and energy scale: Cosmic ray muons are the standard candle

- Cells individually corrected for
  - Light attenuation along cell length
  - Shadowing due to detector bulk
  - Threshold effects far from readout

Energy scale set by $dE/dx$ near the end of stopping muons

- Cross-check including $\pi^0$ mass peak, Michel-$e^-$, beam muon $dE/dx$
- Take 5% absolute and relative errors
**νμ Disappearance**

- Calibration and energy scale: Cosmic ray muons are the standard candle
- Cells individually corrected for
  - Light attenuation along cell length
  - Shadowing due to detector bulk
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- Energy scale set by dE/dx near the end of stopping muons
  - Cross-check including π0 mass peak, Michel-\(e^-\), beam muon dE/dx
  - Take 5% absolute and relative errors
νμ Disappearance

Cosmic rejection

- 10μs spill window gives $10^5$ rejection
- Cosmic ray data in data are measured in time window adjacent to the spill
- Event topology+BDT provide additional $O(10^7)$ reduction
  - BDT inputs: track direction, track start and end point, track length, energy, number of hits
νμ Disappearance

ND data suggest unsimulated process between QE and Δ production (Minerva experiment reported similar excess)

1. Leptonic model (Dytman model)
2. Hadronic model (Nucleon cluster model)
3. FSI model (hA model)
\( \nu_\mu \) Disappearance

ND data suggest unsimulated process between QE and \( \Delta \) production (Minerva experiment reported similar excess)

- enable GENIE empirical MEC (50% systematic on MEC component)
- reweight the model to match observation as a function of \( p \) transfer

Reduction of largest systematics
- Hadronic energy scale
- QE cross section modeling

Reduction of single non-RES pion production by 50%
\( \nu_\mu \) Disappearance

Near-Far Extrapolation – 3 step process

1) Convert ND reconstructed energy to true energy
2) Use Near/Far ratio to convert to FD true energy spectrum
3) Translate back to reconstructed energy
**ν_μ** Disappearance

Systematic uncertainties

<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>± 1.0%</td>
<td>± 0.2 %</td>
</tr>
<tr>
<td>Muon E scale</td>
<td>± 2.2%</td>
<td>± 0.8 %</td>
</tr>
<tr>
<td>Calibration</td>
<td>± 2.0 %</td>
<td>± 0.2 %</td>
</tr>
<tr>
<td>Relative E scale</td>
<td>± 2.0 %</td>
<td>± 0.9 %</td>
</tr>
<tr>
<td>Cross sections + FSI</td>
<td>± 0.6 %</td>
<td>± 0.5 %</td>
</tr>
<tr>
<td>Osc. parameters</td>
<td>± 0.7 %</td>
<td>± 1.5 %</td>
</tr>
<tr>
<td>Beam backgrounds</td>
<td>± 0.9 %</td>
<td>± 0.5 %</td>
</tr>
<tr>
<td>Scintillation model</td>
<td>± 0.7 %</td>
<td>± 0.1 %</td>
</tr>
<tr>
<td>All systematics</td>
<td>± 3.4 %</td>
<td>± 2.4 %</td>
</tr>
<tr>
<td>Stat. Uncertainty</td>
<td>± 4.1 %</td>
<td>± 3.5 %</td>
</tr>
</tbody>
</table>

In each case:
- The effect is propagated through the extrapolation
- We include those effects as pull terms in the fit
- The increase (in quadrature) of the parameter measurement error is recorded
$\nu_\mu$ Disappearance

- Best Fit $\chi^2$/DOF = 41.5/17 is driven by the tail
- There is no significant pull in the oscillation fit from bins in the tail
νμ Disappearance

- Fit-checks: best fit oscillation prediction matches other distributions well.
ν<sub>μ</sub> Disappearance

- Muon Selection
- Muon Neutrino FD data
\( \nu_\mu \) Disappearance

- 1-D profiles

\[
|\Delta m_{32}^2| = 2.67 \pm 0.12 \times 10^{-3} \text{eV}^2
\]

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

1-\( \sigma \) range: 2.553-2.791

1-\( \sigma \) ranges:

- 0.379-0.431
- 0.597-0.648
Neutral Current Results

- NC events in the ND with CVN classification, extrapolate to the FD → prediction
- Count NC events in FD, compare to prediction
- For $\Delta m^2_{41} = 0.5 \text{eV}^2$ rapid oscillations in FD, minimal in ND

- Normalization agrees well
- Data shifted to lower energy relative to MC
  - No MEC model for NC events
  - Large uncertainties on NC cross section
Neutral Current Results

- Predicted events in the FD for 3-flavour mixing: \textbf{83.7} (60.6 NC, 4.8 $\nu_\mu$ CC, 3.6 beam $\nu_e$, 14.3 cosmics)
- Observed NC-like events in the FD: \textbf{95}

No evidence of oscillations involving steriles, consistent within 1\(\sigma\)

For \(0.05 \text{ eV}^2 < \Delta m^2_{41} < 0.5 \text{ eV}^2\) \(\theta_{34} < 35^\circ\), \(\theta_{24} < 21^\circ\) (90\% CL)

Excellent NC efficiency (50\%) and purity (72\%) promise strong future limits on $\theta_{34}$
$\nu_e$ Results

- CVN: 73% $\nu_e$ signal efficiency, 76% purity
- Use ND data to predict FD background, every component propagate differently:
  - Beam $\nu_e$ CC
  - low-E $\nu_e$ and $\nu_\mu$ trace back to the same $\pi^+$ ancestor
  - Use selected $\nu_\mu$ CC events to constrain beam $\nu_e$: reweight Kaon and Pion component to match the $\nu_\mu$ CC energy spectrum in the data
  - Overall effect is a 4% increase $\rightarrow$ Fix $\nu_e$ CC to flux-reweighted in the ND
- $\nu_\mu$ CC: use Michel-electron distribution to constrain
  - Michel-$e^-$ are produced also in $\nu_e$ CC and NC by pions but $\nu_\mu$ has ~1 more
  - Fit observed $N_{\text{michel}}$ in each bin
  - Data excess assigned between NC(+10%) and $\nu_\mu$ CC (+10%)
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\( \nu_e \) Results

Checking Signal Efficiency

- Far detector: Remove muon track in cosmic rays to select Brem. Showers \( \rightarrow \) simulation of EM showers matches well

- Near Detector: replace muon tracks from \( \nu_\mu \) CC data with simulated electron showers \( \rightarrow \) data/MC difference < 1%
$\nu_e$ Results

FD data
$\nu_e$ Results

FD data

CVN = 0.991
$E_\nu = 1.63$ GeV
$\nu_e$ Results

Systematics

- Statistical error
- Total syst. error
- Beam
- Calibration
- Cross Sections
- Detector Response
- Normalization

Signal uncertainty (%)

20 - 10 - 0  10  20

Background uncertainty (%)

40 - 20 - 0  20  40

Statistical error

Total syst. error

Beam

Normalization

Cross Sections

Detector Response

Calibration
$\nu_e$ Results

Selection

**Signal MC**
- LID: 1.8\%
- LEM: 1.1\%
- CVNe: 8.3\%
- Data: 95.1\%
- Selection rates:
  - LID: 86.4\%
  - LEM: 82.5\%

**BG MC**
- LID: 68.8\%
- LEM: 56.5\%
- CVNe: 13.6\%
- Selection rates:
  - LID: 23.0\%
  - LEM: 13.3\%

**Data**
- LID: 34
- LEM: 33
- CVNe: 33
- Selection rates:
  - LID: 5
  - LEM: 3
  - CVNe: 27