Latest Results from NOvA

Jianming Bian
For the NOvA Collaboration
University of California, Irvine
07-07-2018

ICHEP2018, Seoul, Korea
\( \nu_e \) appearance + \( \nu_\mu \) disappearance

- **Mass hierarchy**: \( m_3 > m_{1,2} \) or \( m_{1,2} > m_3 \)?
- **CP phase** \( \delta_{CP} \): whether neutrinos and antineutrinos behave the same way in oscillation?
- **Octant of** \( \theta_{23} \): Is \( \nu_3 \) more strongly coupled to \( \nu_\tau \) or \( \nu_\mu \)? Is \( \theta_{23} \) exactly \( 45^\circ \)?

- **NC disappearance**
  - **Sterile neutrino search**: are there other neutrinos beyond the three known active flavors?

- Also, cross sections, exotic phenomena and non-beam physics

This talk: New results with NOvA’s first antineutrino data

\( \nu_e + \bar{\nu}_e \) appearance for MH, CP and octant
• Upgraded NuMI muon neutrino beam at Fermilab (700 kW design)
• Longest baseline in operation (810 km), large matter effect (±30%), sensitive to mass hierarchy
• Far/Near detector sited 14 mrad off-axis, narrow-band beam around oscillation maximum, small wrong sign components
Beam Performance

- **Neutrino beam** data: $8.85 \times 10^{20}$ POT, taken Feb 2014 - Feb 2017
- **First antineutrino data**: $6.9 \times 10^{20}$ POT, taken Feb 2017 - April 2018

Operating at 700 kW since Jan 2017
The NOvA Detectors

- 14-kton Far Detector
- 344,064 detector cells
- 0.3-kton functionally identical Near Detector
- 18,432 cells

Composed of PVC modules extruded to form long tube-like cells: 16m long in FD, 4m ND
Each cell is filled with liquid scintillator and has a loop of wavelength-shifting fiber (WLS) routed to an Avalanche Photodiode (APD)
Cells arranged in planes, assembled in alternating vertical and horizontal directions
Low-Z and low-density, each plane just 0.15 $X_0$. Great for $e^-$ vs $\pi^0$
NOvA Event Topologies

$\nu_\mu$ CC ($\nu_\mu$ disappearance signal)

$\nu_e$ CC ($\nu_e$ appearance signal)

NC (NC disappearance signal)
Neutrino Interaction Tuning

- QE, RES tuned to consider long-range nuclear correlations using València model via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]

- DIS at high invariant mass (W>1.7 GeV/c²) weighted up 10% based on NOvA data

- Empirical MEC (Meson Exchange Current) model for Multi-nucleon ejection (2p2h) [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)], amount tuned in 2D 3-momentum and energy transfers ($q_0 = E_\nu - E_\mu$, $|q| = |p_\nu - p_\mu|$) space to match ND data

- MEC shape systematic estimated by re-fitting using models with QE and RES related systematic shifts
Deep-Learning based PID for $\nu_e$ and $\nu_\mu$ Analyses

- CVN: a convolutional neural network (CNN), based on modern image recognition technology
- Introduce convolution filters to extract features from the hit map for the training of the neural net
- Statistical power equivalent to 30% more exposure than previous $\nu_e$ PIDs
- $\nu_e$, $\nu_\mu$ and NC analyses all use CVN as event selector

At NOvA, CVN has been extended to single particle ID, energy reconstruction, etc for future analyses
Observed NC events in Far Detector

• FD selection:
  – NC CVN selection applied
  – Additional Deep-learning based cosmic rejection

• Neutrino beam:
  – Observe 201 events, predict $188 \pm 13$ (syst.) events (38 bkg.)

• Antineutrino beam:
  – Observe 61 events, predict $69 \pm 8$ (syst.) events (16 bkg.)

• No significant suppression for NC observed, consistent with 3-flavor oscillation
Near Detector Spectrum ($\nu_\mu$ disappearance)

- Select $\nu_\mu$ ($\overline{\nu}_\mu$) CC in ND from neutrino (antineutrino) beam, wrong sign contamination 3% (11%)

- $E_\nu = E_\mu + E_{\text{had}}$, data split in 4 equal energy quantiles based on $E_{\text{had}}/E_\nu$, resolution varies from 5.8% (5.5%) to 11.7% (10.8%) for neutrino (antineutrino) beam.

- Normalize ND MC to data in each $E_\nu$ bin, then extrapolate the 4 quantiles to FD.
Near Detector Spectrum ($\nu_e$ appearance)

- Select $\nu_e$ ($\bar{\nu}_e$) CC in ND from neutrino (antineutrino) beam
- $E_\nu = f(E_e, E_{\text{had}})$, data split into low and high particle ID (purity) range
- For neutrino beam:
  - Contained and uncontained $\nu_\mu$ events constrain the $\pi/K$ contributions to the beam $\nu_e$’s.
  - Michel electrons constrains NC/$\nu_\mu$ CC balance in each $E_\nu$ bin
- For antineutrino beam, scale all components evenly to match data
- ND $\rightarrow$ FD extrapolation: Each component propagated independently in energy and PID bins
\( \nu_\mu \) Data at Far Detector

- **FD selection:**
  - Additional BDT to reduce cosmic backgrounds
  - Estimate cosmic background rate from timing sidebands of the NuMI beam triggers and cosmic trigger data

- **Neutrino beam:**
  - Observe 113 events
  - Expect 730 \( +38/-49 \) (syst.) w/o oscillations

- **Antineutrino beam:**
  - Observe 65 events
  - Expect 266 \( +12/-14 \) (syst.) w/o oscillations
$\nu_e$ Data at Far Detector

- **FD selection:**
  - Add a one-bin peripheral with less stringent containment selection to include more signal.
  - Use location dependent BDT and tight PID cuts to recover signal events in this peripheral bin.

- **Neutrino beam:**
  - Observe 58 events, expect 15 background events.
  - Background: 11 beam, 3 cosmic and < 1 wrong sign.

- **Antineutrino beam:**
  - Observe 18 events, expect 5.3 background events.
  - Background events: 3.5 beam, <1 cosmic and 1 wrong sign.

- $> 4\sigma \bar{\nu}_e$ appearance.
Joint Appearance and Disappearance

- Statistically limited, largest systematics for $\nu_\mu$ and $\nu_e$ are calibration and cross-sections.
- Best fit:
  - Normal Hierarchy
  - $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
  - $\Delta m^2_{32} = (2.51 \pm 0.12 - 0.08) \times 10^{-3}$ eV$^2$
- Prefer Upper Octant
NOvA’s allowed 90% C.L. regions are compatible to other experiments.
Joint Appearance and Disappearance

- Statistically limited, largest systematics for $\nu_\mu$ and $\nu_e$ are calibration and cross-sections.
- Best fit:
  - Normal Hierarchy
  - $\delta_{CP} = 0.17\pi$
  - $\sin^2\theta_{23} = 0.58\pm0.03$ (UO)
  - $\Delta m^2_{32} = (2.51\pm0.12-0.08)\times10^{-3}$ eV$^2$
- Consistent with all $\delta_{CP}$ values in NH at $< 1.6\sigma$
- Exclude $\delta=\pi/2$ in IH at $> 3\sigma$
- Prefer NH at $1.8\sigma$
• Taking antineutrino data since 2017, switch back to neutrinos in 2019, run 50% neutrino, 50% anti-neutrino

• Extended running through 2024, test beam program and potential accelerator improvement to enhance ultimate reach

• If $\delta_{CP}=3\pi/2$, 3 $\sigma$ sensitivity to MH by 2020, $\sim$5 $\sigma$ by 2024

• 3 $\sigma$ to MH for 30-50% (depending on octant) of $\delta_{CP}$ range by 2024

• 2+ $\sigma$ to CP at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ by 2024

Thank you!
Backup
NuMI Off-Axis $\nu_e$ Appearance Experiment

NOvA Simulation

$\nu_\mu$ Spectrum
$\bar{\nu}_\mu$ Spectrum

Flux 1-5 GeV:
95 % $\nu_\mu$
4% $\bar{\nu}_\mu$
1% $\nu_e$

Jianming Bian - UCI
• Package to Predict the Flux (PPFX) from MINERvA.
  – Based on thin target hadron production data from NA49 and MIPP.
• Significantly reduced systematic uncertainties.
  – Central values also changed within prior systematics, but not shown here.
Systematic Error in Calibration

- Our calibration is built on dE/dx from stopping cosmic muons.
- Control samples for calibration uncertainty
  - $\pi^0$ mass peak in ND
  - Michel electrons in ND and FD

$$m^2_{\pi^0} = 2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{12})$$
**Prong/track Reconstruction**

**Vertexing:** Find lines of energy depositions with Hough transform. Then determine the vertex that all lines converge to.

**Shower Clustering:** Based on the vertex and the lines, showers are reconstructed by angular clustering.

**Tracking:** Trace particle trajectories with **Kalman filter** tracker (below). Also have a **cosmic ray tracker** that reconstructs cosmic tracks with high speed.
Because NOvA is on surface, hits in a trigger window are a combination of cosmic and beam events. First step in reconstruction is to cluster hits by space-time coincidence to separate neutrino hits and cosmic hits.
Event clustering

Event clusters that contain neutrino interactions can be correctly selected in the neutrino spill timing window.
PID efficiencies

NOvA Preliminary

<table>
<thead>
<tr>
<th>Selected</th>
<th>True</th>
<th>NC</th>
<th>Cosmic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>0.08</td>
<td>0.1</td>
<td>0.41</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>0.0058</td>
<td>0.017</td>
<td>0.25</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>0.022</td>
<td>0.86</td>
<td>0.21</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>0.89</td>
<td>0.015</td>
<td>0.13</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>0.92</td>
<td>0.005</td>
<td>0.13</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>0.0047</td>
<td>0.0002</td>
<td>0.00059</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>0.057</td>
<td>0.075</td>
<td>0.36</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>0.0082</td>
<td>0.019</td>
<td>0.29</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>0.0081</td>
<td>0.9</td>
<td>0.22</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>0.92</td>
<td>0.005</td>
<td>0.13</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>0.0047</td>
<td>0.0002</td>
<td>0.00059</td>
</tr>
</tbody>
</table>

Jianming Bian - UCI
Analysis Strategy

- Separate $\nu_\mu/\nu_e$ CC interactions from beam backgrounds
- Extrapolate observed ND spectrum to FD, reject cosmic rays in FD, make FD unoscillated prediction
- Measure shapes and yields of $\nu_\mu/\nu_e$ in energy/PID bins in the FD to determine oscillation parameters

ND $\rightarrow$ FD extrapolation for $\nu_\mu$ disappearance
FD $\nu_{\mu}$ Events in 4 Quartiles

- Neutrinos
  - Quartile 1: best resolution
  - Quartile 2
  - Quartile 3
  - Quartile 4: worst resolution

- Antineutrinos
  - Quartile 1: best resolution
  - Quartile 2
  - Quartile 3
  - Quartile 4: worst resolution
2017/2018 RHC $\nu_e$ FD Data

66 FD data events in 2017 analysis

58 FD data events in 2017 analysis

Change in data events after retraining of PID, new training improved bkg rejection
Systematic Uncertainties ($\nu_\mu$)

- Largest systematics for $\nu_\mu$ and $\nu_e$ are calibration and cross-sections.
- Both analyses are statistically limited.
## Systematic Uncertainties (Joint Fit)

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$\sin^2 \theta_{23} \times 10^{-3}$</th>
<th>$\delta_{CP}/\pi$</th>
<th>$\Delta m_{32}^2 \times 10^{-3} \text{ eV}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Flux</td>
<td>+0.42 / -0.48</td>
<td>+0.0088 / -0.0048</td>
<td>+0.0016 / -0.0015</td>
</tr>
<tr>
<td>Detector Calibration</td>
<td>+6.9 / -6.1</td>
<td>+0.15 / -0.023</td>
<td>+0.024 / -0.029</td>
</tr>
<tr>
<td>Detector Response</td>
<td>+1.9 / -0.99</td>
<td>+0.055 / -0.054</td>
<td>+0.0027 / -0.0034</td>
</tr>
<tr>
<td>Muon Energy Scale</td>
<td>+2.6 / -2.1</td>
<td>+0.015 / -0.0026</td>
<td>+0.01 / -0.012</td>
</tr>
<tr>
<td>Near-Far Differences</td>
<td>+0.56 / -1.1</td>
<td>+0.11 / -0.064</td>
<td>+0.0033 / -0.0013</td>
</tr>
<tr>
<td>Neutrino Cross Sections</td>
<td>+4.2 / -3.5</td>
<td>+0.085 / -0.072</td>
<td>+0.015 / -0.014</td>
</tr>
<tr>
<td>Neutron Uncertainty</td>
<td>+6.4 / -7.9</td>
<td>+0.002 / -0.0052</td>
<td>+0.0028 / -0.01</td>
</tr>
<tr>
<td>Normalization</td>
<td>+1.4 / -1.5</td>
<td>+0.031 / -0.024</td>
<td>+0.0029 / -0.0027</td>
</tr>
<tr>
<td>Systematic Uncertainty</td>
<td>+9.6 / -11</td>
<td>+0.21 / -0.11</td>
<td>+0.032 / -0.035</td>
</tr>
<tr>
<td>Statistical Uncertainty</td>
<td>+22 / -29</td>
<td>+0.9 / -0.27</td>
<td>+0.064 / -0.059</td>
</tr>
</tbody>
</table>
\( \nu_\mu \) appearance fit

- The combined data of neutrino and antineutrino beams are fitted assuming CPT invariance.
- We observe 113 events and expect 126 at this combined best fit for the neutrino beam mode and observe 65 events and expect 52 at the best fit in antineutrino beam mode.
- If fit separately, the antineutrino beam mode prefers a more non-maximal solution than the neutrino beam mode. However the \( \chi^2 \)'s are consistent with the combined fit oscillation parameters with p > 4%.
Looking Forward

NOvA Simulation

- Neutrino beam
- Antineutrino beam

Total events - neutrino beam
Total events - antineutrino beam

\[ \sin^2 2\theta_{13} = 0.082 \]

\[ \sin^2 \theta_{23} = 0.46 \]

\[ \Delta m^2_{32} = -2.55 \times 10^{-3} \text{eV}^2 \]

\[ \Delta m^2_{32} = +2.50 \times 10^{-3} \text{eV}^2 \]

\[ \delta_{CP} = 0 \quad \delta_{CP} = \pi/2 \]

\[ \delta_{CP} = \pi \quad \delta_{CP} = 3\pi/2 \quad 2018 \text{ best fit} \]

Jianming Bian - UCI