New Oscillation Results from the NOvA Experiment

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The NOvA Experiment

- Long-baseline neutrino oscillation experiment
- NuMI beam: $\nu_\mu$ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

Take a tour in VR!
NOvA Physics

• Atmospheric sector oscillations:
  – $\Delta m^2_{32}, \sin^2\theta_{23}, \delta_{CP}$

• Key open questions in oscillations:
  – Is the neutrino mass hierarchy normal or inverted?
  – Is CP violated in the neutrino sector?
  – Is $\theta_{23}$ mixing maximal?
    • $\nu_\mu$-$\nu_\tau$ symmetry
    • If not, what is the octant of $\theta_{23}$?
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• Disentangle by measuring...
  – disappearance $P(\nu_\mu \rightarrow \nu_\mu)$ and appearance $P(\nu_\mu \rightarrow \nu_e)$
  – in neutrinos and antineutrinos
  – over long baselines to separate hierarchy and $\delta$ effects.
NOvA Physics Beyond 3-flavor

Neutrino 2020 Talks

- Cross-section measurements with NOvA
  - Linda Cremonesi

Papers since NEUTRINO 2018

- Observation of seasonal variation of atmospheric multiple-muon events in the NOvA Near Detector, Phys.Rev.D 99 (2019) 12, 122004
- Measurement of Neutrino-Induced Neutral-Current Coherent $\pi^0$ Production in the NOvA Near Detector, Accepted to PRD, arXiv: 1902.00558 [hep-ex]

Neutrino 2020 Posters

- 358. Astrophysics with NOvA, Matt Strait & Oleg Samoylov
- 550. Galactic Supernova Neutrinos, Justin Vasel, Andrey Sheshukov, Alec Habig
- 555. Event Selection and Systematics, Adam Lister & Anne Norrick
- 442. Sterile Neutrino Search via NC Disappearance with Antineutrinos, Mike Wallbank
- 431. Poisson Likelihood Covariance Technique for 3+1 Sterile Searches, Jeremy Hewes
- 541. Neutrino Tridents, Erica Smith & Kelli Michaels
- 398. Inclusive CC $\nu_\mu$, Connor Johnson
- 505. Inclusive CC $\nu_e$, Matt Judah
- 228. CC $\nu_\mu \pi^\pm$, Cathal Sweeney
Typically ~670 kW

Peaks >750 kW

50% more neutrino beam data in this analysis

Working towards 900+ kW
  - Upgrading the NuMI beamline components
  - Allows gradual increase in power up to 850 kW with faster cycle times
  - Early PIP-II upgrades allow 900+ kW
The NOvA Detectors

- Segmented liquid scintillator detectors provide 3D tracking and calorimetry
- Optimized for electron showers: ~6 samples per $X_0$ and ~60% active

![Zoom of a $\nu_e$ candidate in the FD](image)

- Good time resolution (few ns) and spatial resolution (few cm)
  - Allows clear separation of individual interactions

![Pile-up during a 10 $\mu$s ND beam spill](image)
Observe flavor change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections, and detector response.
Observe *flavor* change as a function of *energy* over a long distance while *mitigating uncertainties* on neutrino flux, cross sections, and detector response.
Observe *flavor* change as a function of *energy* over a long distance while mitigating uncertainties on neutrino flux, cross sections, and detector response.
Neutrino Interaction Model

• Constantly evolving understanding of $\nu$ interactions.
• Upgrade to GENIE 3.0.6 → freedom to choose models
• Chose the most “theory-driven” set of models plus GENIE’s re-tune of some parameters*.
• Some custom tuning is still required.
  – Substantially less than was needed with GENIE 2.12.2, which required tweaks to most models.

<table>
<thead>
<tr>
<th>Process</th>
<th>Model</th>
<th>Reference</th>
</tr>
</thead>
</table>

* We call our tune N1810j_0211a, and it is built by starting with G1810b_0211a and substituting the Z-expansion form factor for the dipole one. This combination was not available in the 3.0.6 release, but it may be available in future versions.

Neutrino Interaction Model

- 2p2h \textit{or} Meson Exchange Current \textit{or} Multi-nucleon Interactions:
  - Disagreement of models with multiple experiments well-known
  - Tuned to \textbf{NOvA ND data} with two 2D gaussians in $q_0-|\vec{q}|$ space.
  - Generous systematics covering normalization and kinematic shape

- Final State Interactions
  - Used \textbf{external \pi-scattering data} primarily to set uncertainties
  - Required adjusting central value, change in overall xsec was small.

\begin{itemize}
  \item \textbf{NOvA Preliminary}
  \item \textbf{Neutrino Beam $\nu_\mu + \bar{\nu}_\mu$ CC Selection}
  \item ND Data
  \item MEC
  \item QE
  \item RES
  \item DIS
  \item Other
\end{itemize}

67. Cross section adjustments for 2p2h
   - Maria Martinez Casales

352. Central value tuning and uncertainties for the hN FSI model in GENIE 3
   - Michael Dolce, Jeremy Wolcott, Hugh Gallagher
Selecting and Identifying Neutrinos

• Identify neutrino flavor using a convolutional neural network.
  – A deep-learning technique from computer vision

• Before main PID:
  – Events are contained in the detector
  – CC $\nu_\mu$ require a well-reconstructed $\mu$ track
  – Reject cosmic rays with BDTs

• Performance relative to preselection:
  – $\nu_\mu$: $\sim$90% efficient, 99% bkg. rejection
  – $\nu_e$: $\sim$80% efficient, 80% bkg. rejection

• Validate performance against data-driven control samples in both detectors.

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Posters

182. Improvements and New Applications of Machine Learning
  – Ashley Back & Micah Groh

120. Data-Driven cross checks for $\nu_e$ selection efficiency in NOvA
  – Anna Hall & Liudmila Kolupaeva

258. Data-Driven Wrong-Sign Background Estimates
  – Abhilash Yallappa Dombara

First CNN in HEP result: A. Aurisano, et al. JINST 11 (2016) 09, P09001
Energy Reconstruction

\[ E_{\text{had}} \text{ from calorimetry, } \sim 30\% \text{ resolution} \]

\[ E_\mu \text{ from length, } \sim 4\% \text{ resolution} \]

\[ E_{\text{EM}} \text{ from calorimetry, } \sim 10\% \text{ resolution} \]
Near Detector $\nu_\mu$ Spectra

NOvA Preliminary

- Band around the MC shows the large impact of flux and cross-section uncertainties in only a single detector.
- We use this sample to predict both $\nu_\mu$ and $\nu_e$ signal spectra at the Far Detector.
  - Appearing $\nu_e$'s are still $\nu_\mu$'s at the ND
Near Detector $\nu_e$-like Spectra

- The ND $\nu_e$-like spectrum contains the **background** to the appearing $\nu_e$'s at the FD.
- Largest background is the irreducible $\nu_e/\bar{\nu}_e$ flux component.
  - 50% in neutrino-mode
  - 71% in antineutrino mode
- We use this sample to predict the background to $\nu_e$ appearance.
**ν_μ sample**

- Sensitivity depends primarily on the shape of the energy spectrum.
- Bin by *energy resolution* → bin by hadronic energy fraction

**ν_e sample**

- Sensitivity depends primarily on separating signal from background.
- Bin by *purity* → bins of low & high PID
- Peripheral sample:
  - Captures high-PID events which might not be contained close to detector edges.
  - No energy binning.
Extrapolating from Near to Far Detector

- Observe data-MC differences at the ND, use them to modify the FD MC.
  - Extrapolation performed in the analysis binning of energy + (resolution or PID).
- Significantly reduces the impact of uncertainties correlated between detectors
  - Especially effective at rate effects like the flux (7% → 0.3%).
Extrapolating Kinematics

- Containment limits the range of lepton angles more in the Near Detector than in the Far.
  - The ND is 1/5 the size of the FD.

- Mitigate by extrapolating in bins of lepton transverse momentum, $p_t$
  - Transverse to the $\nu$-beam direction $\approx$ the central axis of the detectors

- Split the ND sample into 3 bins of $p_\nu$ extrapolate each separately to the FD.
  - Effectively “rebalances” the kinematics to better match between the detectors.
  - Re-sum the $p_t$ bins before fitting.
Increased robustness also leads to a 30% reduction in cross section uncertainties.

- Reduces the size of the systematics most likely to contain “unknown unknowns”
- Slightly increase the sensitivity to well-understood systematics on lepton reconstruction.

Overall systematic reduction is 5-10%,
- The largest systematics come from the detector energy scale.
• Simultaneous fit of all samples, reactor-constrained $\sin^2 2\theta_{13} = 0.085 \pm 0.003$.

• We perform a frequentist analysis and use the Feldman-Cousins method to ensure proper coverage in all contours and intervals.
$\nu_\mu$ and $\bar{\nu}_\mu$ Data at the Far Detector

**NOvA Preliminary**

- **$\nu_\mu$ Data**
  - FD data
  - 2020 Best-fit
  - 1-\sigma syst. range
  - Background

- **$\bar{\nu}_\mu$ Data**
  - FD data
  - 2020 Best-fit
  - 1-\sigma syst. range
  - Background

211 events, 8.2 background

105 events, 2.1 background
$\nu_e$ and $\bar{\nu}_e$ Data at the Far Detector

### Table: Total Observed and Predicted Events

<table>
<thead>
<tr>
<th></th>
<th>Total Observed</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$-beam</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>$\bar{\nu}_e$-beam</td>
<td>33</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Total Prediction</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$-beam Total</td>
<td>85.8</td>
<td>52-110</td>
</tr>
<tr>
<td>Wrong-sign</td>
<td>1.0</td>
<td>0.6-1.7</td>
</tr>
<tr>
<td>Beam Bkgd.</td>
<td>22.7</td>
<td></td>
</tr>
<tr>
<td>Cosmic Bkgd.</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Total Bkgd.</td>
<td>26.8</td>
<td>26-28</td>
</tr>
</tbody>
</table>

| $\bar{\nu}_e$-beam Total | 33.2 | 25-45 |
| Wrong-sign               | 2.3  | 1.0-3.2 |
| Beam Bkgd.               | 10.2 |       |
| Cosmic Bkgd.             | 1.6  |       |
| Total Bkgd.              | 14.0 | 13-15 |

>4σ evidence of $\bar{\nu}_e$ appearance
Precision measurements of $\Delta m^2_{32}$ (3%) and $\sin^2 \theta_{23}$ (6%).

**Best Fit**
- Normal hierarchy
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV$^2$
- $\sin^2 \theta_{23} = 0.57^{+0.04}_{-0.03}$

Prefer non-maximal mixing by 1.1\sigma.
Best Fit
Normal hierarchy
\[ \Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} = 0.57^{+0.04}_{-0.03} \]
\[ \delta = 0.82 \pi \]
• We see no strong asymmetry in the rates of appearance of $\nu_e$ and $\bar{\nu}_e$
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Disfavor hierarchy-$\delta$ combinations which would produce that asymmetry

Exclude IH $\delta = \pi/2$ at >3$\sigma$
Disfavor NH $\delta = 3\pi/2$ at ~2$\sigma$
• We see no strong asymmetry in the rates of appearance of $\nu_e$ and $\bar{\nu}_e$
• Disfavor hierarchy-$\delta$ combinations which would produce that asymmetry
• Consistent with hierarchy-octant-$\delta$ combinations which include some “cancellation.”
  – Since such options exist for both octants and hierarchies, results show no strong preferences.

Exclude IH $\delta = \pi/2$ at $>3\sigma$
Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Prefer...
Normal Hierarchy at $1.0\sigma$
Upper Octant at $1.2\sigma$
Comparison to T2K

- Clear tension with T2K’s preferred region.
- Quantifying consistency requires a joint fit of the data from the two experiments, which is already in the works.
  - Semi-annual workshops, regular joint group meetings, and a signed joint agreement.
Comparison to T2K

T2K, Nature 580: ■ BF ≤ 90% CL - - - ≤ 68% CL
NOvA: ★ BF ≤ 90% CL - - - ≤ 68% CL

NOvA Preliminary

Normal Hierarchy

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

\[ \delta_{CP} \]

NOvA-T2K Workshop, Fermilab, February 2019
Conclusions

- We present an updated neutrino oscillation analysis with:
  - 50% more neutrino beam data,
  - updated simulation and reconstruction, including a new GENIE 3 cross-section model,
  - updated extrapolation which mitigates differing detector acceptances.

- New 3-flavor oscillation results:
  - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV$^2$
  - $\sin^2 \theta_{23} = 0.57^{+0.04}_{-0.03}$
  - exclude IH, $\delta = \pi/2$ at $> 3\sigma$,
  - disfavor NH, $\delta = 3\pi/2$ at $\sim 2\sigma$.

- Looking ahead:
  - We can reach $3\sigma$ hierarchy sensitivity for 30-50% of $\delta$ values, with the full dataset and an upgraded beam.
  - Plan to reduce our largest systematics, those related to detector energy scale, with the results of our test beam experiment.
Questions?
Reconstructed neutrino energy (GeV) vs. Events / 0.1 GeV for different quartiles:

- **Quartile 1** (best resolution): 2020 Best-fit (purple line) with 1-σ syst. range (purple shaded region).
- **Quartile 2**: Background (gray shaded region).
- **Quartile 3**: FD data (black points with error bars).
- **Quartile 4** (worst resolution): 2020 Best-fit (purple line) with 1-σ syst. range (purple shaded region).

The plot includes a symbol representing the antineutrino ($\bar{\nu}_\mu$).
Largest pulls also correspond to some of our known most important systematics:

- Detector light model and energy scale (calibration)
- Multi-nucleon cross section

We see examples where a pull comes primarily from the neutrino or antineutrino beam, but generally do not see *contradictory* pulls.
Spectra with NOvA and T2K Best Fits

- Both best fits also include minimization of our systematic uncertainties.
2020 vs. 2017 Cross Section Model

- The QE central value is quite similar, but the expanded uncertainty due to the Z-expansion is apparent.

- In resonance, the uncertainty remains similar, but the central value has changed.

- New model, Berger-Seghal, plus the global retune to scattering data.
hN2018 FSI tuning

• New FSI model in GENIE 3.0.6: semi-classical cascade, “hN”
  – Propagates hadrons through nucleus in finite steps
  – Simulates interactions according to probabilities derived from Oset et al. quantum model*
  – Tuned using external pion scattering data, which is related to intranuclear probabilities using amplitudes from Oset model

• Old model (“hA”) simply assumes hadron scattering data applies directly to FSI

Selection: Validating Performance

- Examine PID efficiency relative to pre-selection.
  - Specifically target the behavior of the PID.
- ND: mixed data-MC sample
  - Mix simulated electrons and real hadronic showers
- FD: decay-in-flight electrons
  - Real electron showers from cosmic muons which decay

120. Data-Driven cross checks for $\nu_e$ selection efficiency in NOvA
  - Anna Hall

258. Data-Driven Wrong-Sign Background Estimates
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- Create 3 energy spectra, one for each $p_t$ bin.
- Each spectra gets its own extrapolation.
- Predictions are summed before fitting.