LATEST OSCILLATION RESULTS FROM THE NOVA EXPERIMENT

Bruno Zamorano
EPS - Venice - 6th July 2017
**The NOvA experiment**

- **NuMI Off-Axis $\nu_e$ Appearance**, the leading neutrino oscillation experiment in the NuMI beam
  - Two totally active scintillator detectors:
    - Far Detector: 14 kT, on surface
    - Near Detector: 300 T, 105 m underground
  - 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, $L/E \sim 405$ km/GeV

- $\nu_\mu$ disappearance channel: $\theta_{23}, \Delta m^2_{32}$

- $\nu_e$ appearance channel: mass hierarchy, $\delta_{CP}, \theta_{13}, \theta_{23}$ and octant degeneracy
• NuMI Off-Axis $\nu_{e}$ Appearance, the leading neutrino oscillation experiment in the NuMI beam

• Two highly active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground

• 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, L/E ~ 405 km/GeV

• $\nu_{\mu}$ disappearance channel: $\theta_{23}$, $\Delta m^{2}_{32}$

• $\nu_{e}$ appearance channel: mass hierarchy, $\delta_{CP}$, $\theta_{13}$, $\theta_{23}$ and octant degeneracy
The NOvA experiment

- NuMI Off-Axis $\nu_e$ Appearance, the leading neutrino oscillation experiment in the NuMI beam
- Two highly active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground
- 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, L/E ~ 405 km/GeV
- $\nu_\mu$ disappearance channel: $\theta_{23}, \Delta m_{32}^2$
- $\nu_e$ appearance channel: mass hierarchy, $\delta_{CP}, \theta_{13}, \theta_{23}$ and octant degeneracy

Also: neutrino cross sections at the ND, sterile neutrinos, supernovae…
The NOvA experiment

- Superb granularity for a detector this scale
- Outstanding event identification capability

I radiation length = 38 cm
(6 cell depths, 10 cell widths)
Signal selection: $\nu_\mu$ CC

- First: basic containment cuts: require a buffer of no activity around the event
- Muon ID: 4-variable k-nearest neighbours algorithm to identify muons
  - Track length
  - $dE/dx$ along track
  - Scattering along track
  - Track-only plane fraction
- Keep events with muon-ID > 0.75
Energy estimation

- Muon track: \textbf{length} \Rightarrow E_\mu \text{ (Res: } \sim 4\%\text{)}
- Highly active detector: calorimetric measurement of E_{\text{had}}
- Hadronic system: \textbf{\Sigma Total visible E} \Rightarrow E_{\text{had}} \text{ (Res: } \sim 20\%\text{)}
- Reconstructed neutrino energy is the sum of them: E_\nu = E_\mu + E_{\text{had}}
- Neutrino energy resolution: 7%
- Narrow energy and identical detectors reduces impact of cross sections & FSI
• 78 events in the FD for 473 w/o osc.
• 82 (3.9 beam bkg, 2.7 cosmic) at best fit
• $X^2/NDF = 41.6/17$ driven by tail
• Systematics included in the fit have negligible pull terms ($< 0.5$)

$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.404^{+0.030}_{-0.022}$$

$$= 0.624^{+0.022}_{-0.030}$$

Maximal mixing disfavoured at $2.6\sigma$
Comparison with other experiments

Maximal mixing disfavoured at $2.6\sigma$

Event selection

- Event selection based on ideas from computer vision and deep learning
- Calibrated hit maps are inputs to Convolutional Visual Network (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
- **Improvement in sensitivity from CVN equivalent to 30% more exposure**

A. Aurisano et al., arXiv:1604.01444

Posters P1.028 by A. Radovic, P1.032 by F. Psihas and A. Himmel for more detail

P. Vahle, Neutrino 2016

A. Aurisano et al., JINST 11 P09001 (2016)
• Selection optimised for parameter measurement (increased signal efficiency by including lower purity bins)

• Constrained beam backgrounds with dedicated decompositions: beam $\nu_e$ from $\nu_\mu$ CC and these from the distribution of Michel electrons

• Analysis uses four bins of energy and three bins of CVN
Far detector selected events

- **Observed 33 events in the FD** (background $8.2 \pm 0.8$)

Selectors from 2015 analysis show consistent results

- LID: 34 events, $12.2 \pm 1.2$ bkg
- LEM: 33 events, $10.3 \pm 1.0$ bkg
• Full joint-analysis including disappearance constraints
• Best fit to NH, $\delta_{CP} = 1.49\pi$ and $\sin^2(\theta_{23}) = 0.40$
• But best fit IH-NH has $\Delta \chi^2 = 0.47$
• Both octants and hierarchies allowed at $1\sigma$
• $3\sigma$ exclusion of IH, lower octant around $\delta_{CP} = \pi/2$
• Antineutrino data will resolve degeneracies

NC disappearance

- Search for active-sterile oscillation by measuring NC spectrum in both detectors
- 95 events observed for $83.5 \pm 9.7$ (stat.) $\pm 9.4$ (syst.) expected
- No evidence of oscillations involving sterile neutrinos
- Promising future sensitivities
• Search for active-sterile oscillation by measuring NC spectrum in both detectors
• 95 events observed for $83.5 \pm 9.7$ (stat.) $\pm 9.4$ (syst.) expected
• No evidence of oscillations involving sterile neutrinos
• Promising future sensitivities

arXiv: 1706.04592
(submitted to PRD)
Conclusions

- Indubitable observation of neutrino disappearance (78 obs, 473 exp.)
- Best fit for $\theta_{23}$ is non-maximal. Maximal mixing disfavoured at $2.6\sigma$
- Small preference for normal hierarchy. Region in inverted hierarchy, lower octant and around $\delta_{CP} = \pi/2$ excluded at $3\sigma$
- Neutral current event rate shows no evidence of sterile neutrinos
- Currently taking antineutrino data
THANK YOU FOR YOUR ATTENTION

www-nova.fnal.gov
BACKUP
ND measurements

• Uniquely sensitive to QE, RES and DIS (almost equally across the three)
• Absolute cross section or yield measurements will be limited to ~10% due to flux uncertainties
• Ability to measure a huge number of FSI channels

• $\nu_\mu$CC inclusive and channels (0-$\pi$, 2p2h, Coh, $\pi^0$, …)
• $\nu_e$CC inclusive and channels (0-$\pi$, $\pi^0$, …)
• NC inclusive and channels ($\pi^0$, 2p2h, …)
• $\nu_\mu$ on $\nu_e$ scattering (flux constraint)

And all of the above with antineutrinos