NOvA Disappearance Analysis

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NOνA Overview

- Source: NuMI $\nu_\mu$ beam (FNAL)
- Far Det (FD) (810 km @ Ash River, MN)
- Near Detector (ND) (1km @ FNAL)
- 15 mrad off axis (tight energy peak @2 GeV)
- Appearance and disappearance oscillation physics (parallel analyses)
- Beam upgrading to 700 kW (currently 500)
- Beam pulse: 10 $\mu$s every 1.33 s
• **FD (at Ash River, MN, 810 km baseline):**
  – 16m x 16m x 60m, 14kton, on surface
  – ~2/3 LS by mass, ~344,000 cells, 28x32 planes
  – 99.5% of channels operational

• **ND (@ FNAL, 1km from NuMI target):**
  – 4m x 4m x 16m, 0.3kton, underground
  – ~20,000 cells, design similar to FD
  – main differences: size and ND muon catcher

• High resolution tracking calorimeters
• Radiation length = 38 cm = 6-10 cells
• Cells filled with liquid scintillator, wavelength shifting optical fiber
• Fiber traps light, channels it to an Avalanche Photo Diode (APD)
νμ Disappearance

• Start with a νμ beam (NUMI @ FNAL)
• νμ ’s oscillate to other flavors
• Survival probability:
  \[ P(ν_μ \rightarrow ν_μ) \approx 1 - \sin^2(2θ_{23})\sin^2(1.27Δm^2_{32}L/E) \]
• Direct measurement of θ_{23} (maximal?), Δm^2_{23}
• Backgrounds for disappearance:
  – NC neutrino events
  – Cosmic ray background
• Signature is high E muon, possible vertex hadronic activity
550 $\mu$s exposure of the Far Detector

Diagram showing the layout of the detector with labels for '+' side, '-' side, top, and bottom sides, as well as the beam direction.
Time-zoom on 10 $\mu$s interval during NuMI beam pulse
Lots of pieces I don’t have time to go into detail on!

- **Calibration:**
  - Stopping $\mu$s $\rightarrow$ Absolute E scale
  - $\pi^0$, Michels, $\mu$ dE/dx ...
  - WLS fiber attenuation corrections

- **Simulation:**
  - **FLUKA/FLUGG:** Beam hadron neutrino flux
  - **GENIE:** Neutrino interactions and FSI
  - **GEANT4:** Detector simulation

- **Reconstruction:**
  - Cluster in space and time (event)
  - Kalman filter based tracking
Energy Reconstruction:

• 2-part energy estimation:
  – 1) muon E from track length
  – 2) hadronic E from non-muon hit calorimetry
  – \( E_\nu = E_\mu + E_{\text{HAD}} \)

• \( \sim 7\% \) FD energy resolution

• Estimators trained on MC

Hadronic E modeling:

• Simulation (GENIE) hadronics inaccurate

• Not unexpected; limited data in this regime, no GENIE 2p2h

• Too many hadronic hits in MC, and thus too large of a reconstructed neutrino E

• To fix this we apply a 21\% correction to hadronic E (6\% \( E_\nu \))

• This fixes the neutrino E distribution, studies ongoing for deeper understanding

• This 21\% is a recalibration applied to data to account for MC being off
Event Selection

- **Step 1: basic quality**
  - remove unusable data
  - require good tracks

- **Step 2: containment**
  - veto events with activity in outer 2 cells
  - look at track projections to wall, veto if too few unhit cells to wall (≤ 10 in FD)

- **Step 3: select muons**
  - use 4 parameter kNN
  - includes track length, dE/dx, scattering information
  - primary NC rejection
Event Selection

- Step 4: cosmic rejection
  - FD only (ND underground)
  - need $\sim 10^7$ cosmic reduction!
  - 11 variable BDT
  - main handles:
    - track directions
    - hadronic activity
    - nearness to detector top
  - BDT combined with hard cuts
**Extrapolation and Systematics**

- The next talk is just about this! *(L. Suter, Extrapolation Techniques...)*
- Basically a far/near extrapolation
- 16 systematics, 4 oscillation parameters marginalized over in fit
- Dominant systematic is 100% on $E_{\text{HAD}}$ correction
- full 3-flavor fit

**Data set**

- Data taken as detector built; thus multiple FD detector configurations
- Simulations mirror this accurately
- FD: $3.466 \times 10^{20}$ POT
- ND: $1.66 \times 10^{20}$ POT
- Quote POT as 14 kton equiv. POT
- Allows easy comparison as we accumulate more data
- **First results public as of yesterday!**
Main timing window

2\textsuperscript{nd} window needed for some early data due to understood timing shift.
Example final sample event

+ side
- side
top
bottom
beam direction
Example final sample event
Example final sample event
Real data: 33 events (0-5 GeV)
Unoscillated prediction: 201 events
1.4 $\pm$ 0.2 of which are cosmics (cosmic estimation: out of time data)
2.0 of which are other background (from simulation, mostly NC)

Clear oscillation deficit
\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32} L/E) \]

\( \theta_{23} \) controls normalization  
\( \Delta m^2_{32} \) controls position of dip
Best fit: $12.64 / 16$ d.o.f.

systematics pull fit due to deficit of data in high $E$ tail
$1\text{-D 68\% limits:}$

$\Delta m^2_{32} = 2.37 \pm 0.16 \times 10^{-3} \text{ eV}^2$

$\sin^2(\theta_{23}) = 0.51 \pm 0.10$

NOvA Preliminary

Normal Hierarchy

(Feldman-Cousins contours will be used for paper)

NOvA 2.74$\times$10$^{20}$ POT-equiv.

- 90\% CL
- 68\% CL
Agreement with T2K and MINOS
This is only 7.6% of NOvA total planned exposure!
with 1 more year data, and the hadronic E better understood
Conclusions

• NOvA detector complete, beam partially upgraded, more upgrades underway
• NOvA first results public (as of just yesterday!)
• Disappearance analysis sees clear oscillations
• Contours agree with T2K, MINOS
• Less than 8% of final exposure so far!
• Look for more soon!
Thanks!

~40 Institutions, > 220 members, 6 countries
Backups
Very close agreement with MC estimated sensitivity!
1-D $\chi^2$ profiles
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