ν Oscillations in the NOνA Experiment

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Driven to Discover
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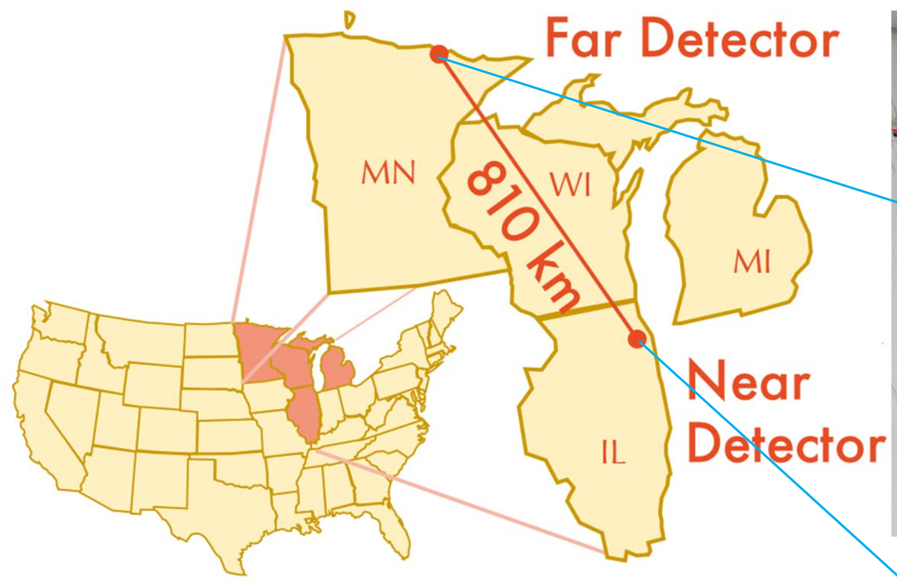
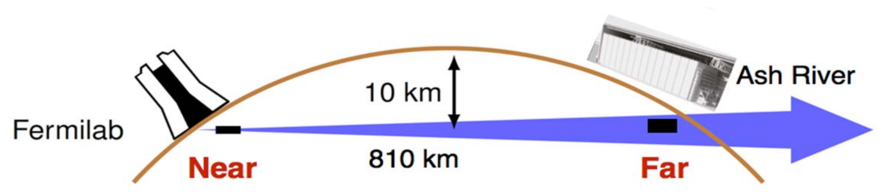
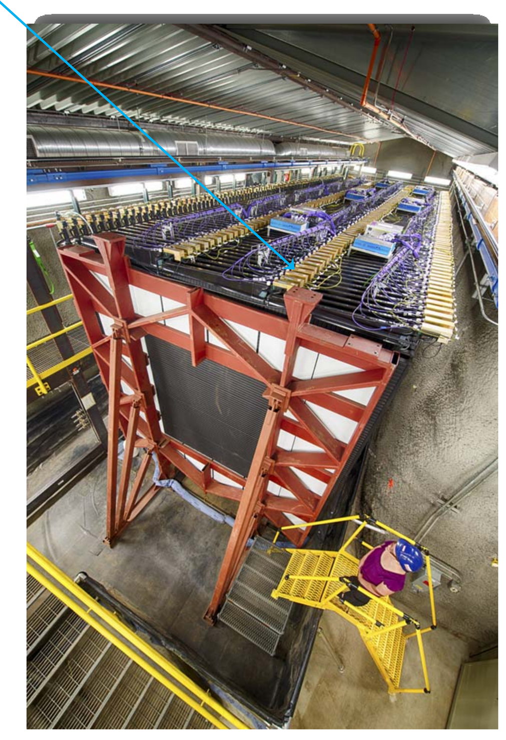
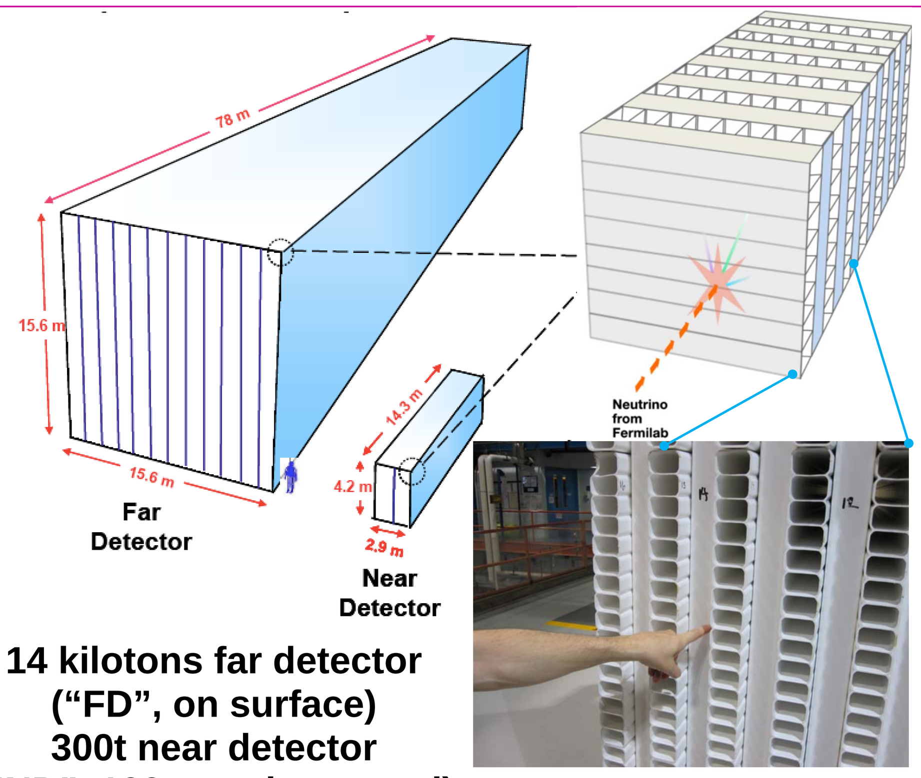
for the NOνA Collaboration





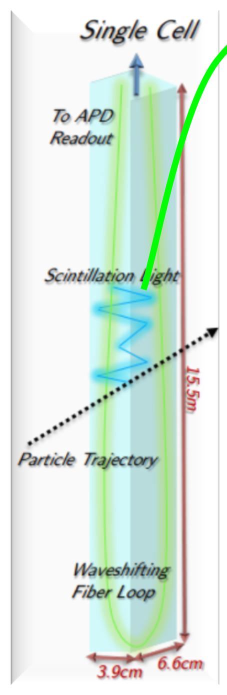


NOνA is an off-axis (14.6 mrad), long-baseline (810km), neutrino experiment using the ~2 GeV, 700 kW NuMI ν_μ beam to look for ν_e appearance and thus ν mass ordering, δ_{CP}, and θ_{23} octant. An exposure of 6.05×10^{20} protons-on-target is presented here.

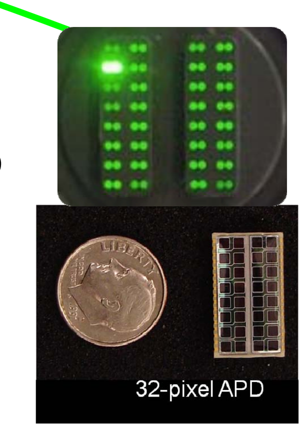


14 kilotons far detector ("FD", on surface)
300t near detector ("ND", 100m underground)

NOνA is composed of highly reflective (15% TiO_2) extruded PVC cells filled with liquid scintillator. A loop of wavelength shifting fiber is placed in each cell to pipe the scintillation light out to the readout. Alternating horizontal and vertical layers provide stereo views.



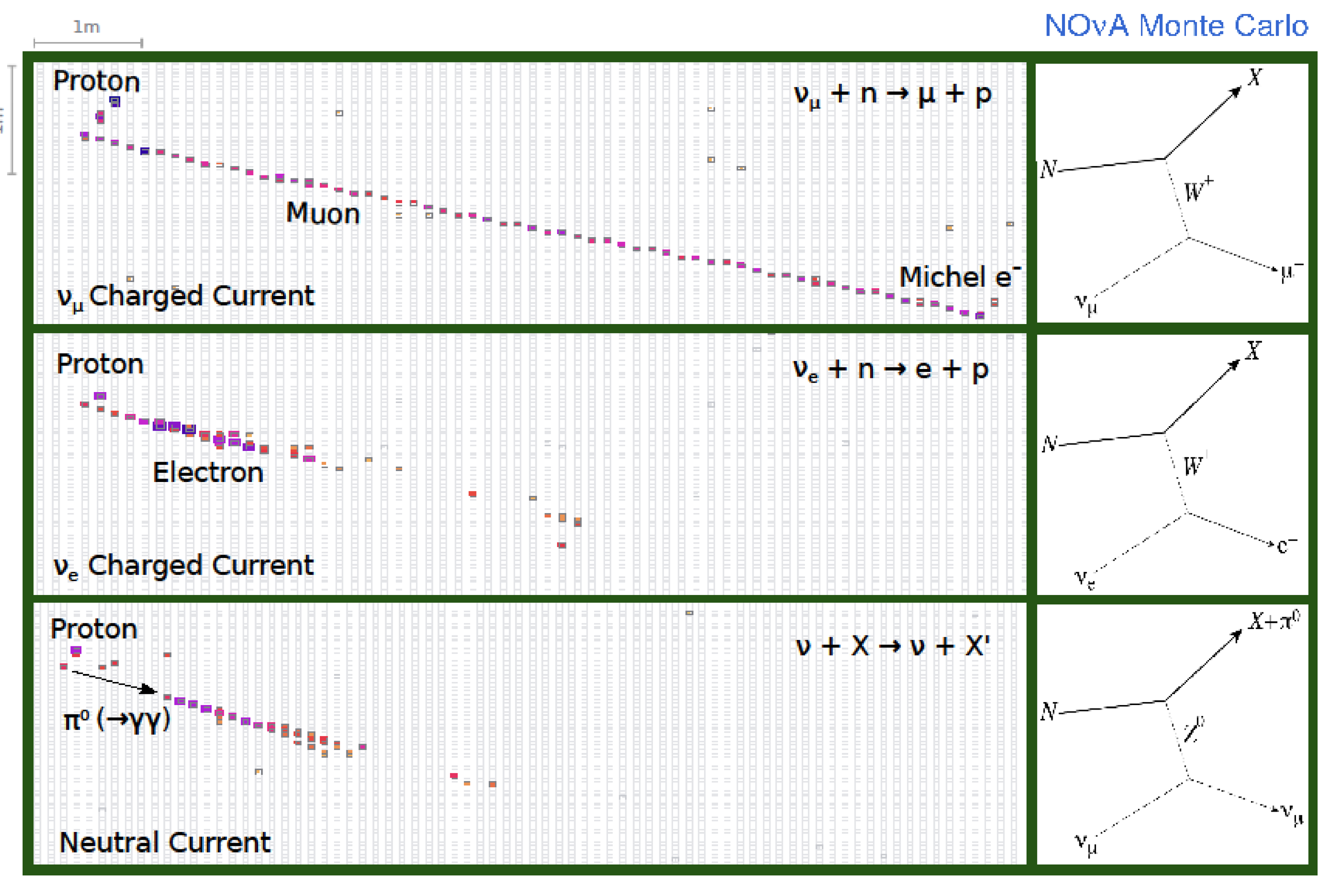
Scintillation light is piped to Avalanche Photo Diodes (APDs) to be digitized and timestamped.



ν in NOνA

10 ns timing resolution leaves few (1 in 10^5) of the 148 kHz of cosmic rays in the FD in the 10 μs NuMI beam spill window: the contained nature of a ν interaction provides a factor of 10^8 further cosmic reduction.

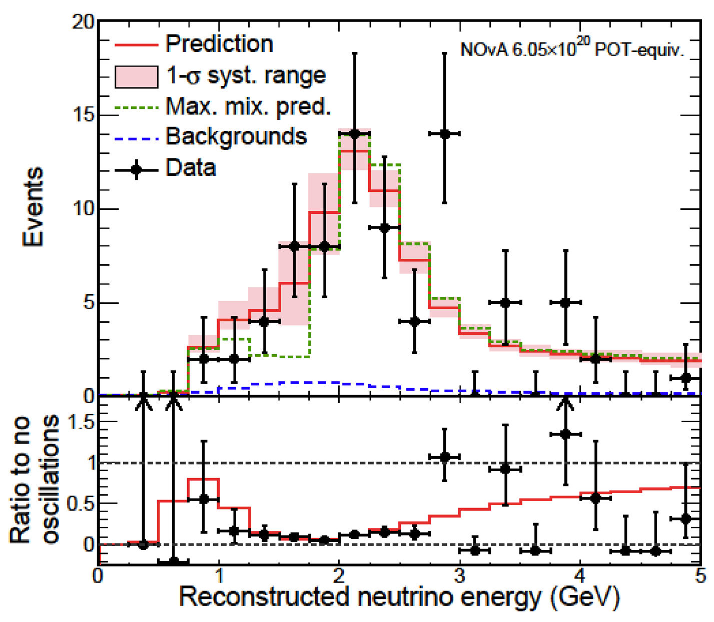
A combination of traditional reconstruction and machine learning classifies event topologies, allowing a ν interaction type to be identified with confidence (*examples below*). Each colored "pixel" in the display on the left is one cell where light was deposited: the corresponding ν interaction is on the right.



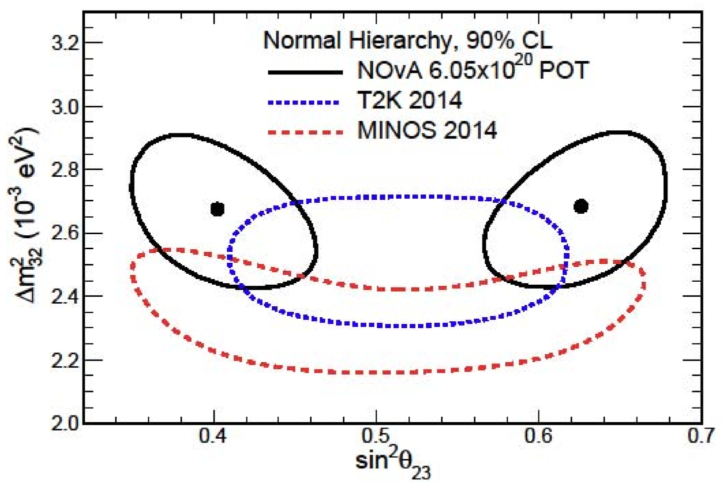
ν_μ Disappearance (*PRL 118 (2017)* ***15****, 151802*)

The neutrino spectrum observed at the ND has not had a chance to oscillate, while the FD is located at the first oscillation minimum for $\nu_\mu \rightarrow \nu_\tau$ oscillations: the amplitude of this disappearance is governed by $\sin^2\theta_{23}$.

Extrapolating the ν flux seen at the ND 810km to the FD, 473±30 ν_μ interactions would be seen if there were no oscillations: 78 candidates were observed (black dots with statistical errors). Backgrounds of 2.7 cosmics, 3.4 neutral-current ν, 0.23 ν_e and 0.27 ν_τ compose the blue dashed line in the spectrum to the right. The best fit oscillation scenario is the red line with systematic errors. Maximal mixing ($\sin^2\theta_{23}$=0.5) predicts even fewer ν_μ between 1-2 GeV (the green line).



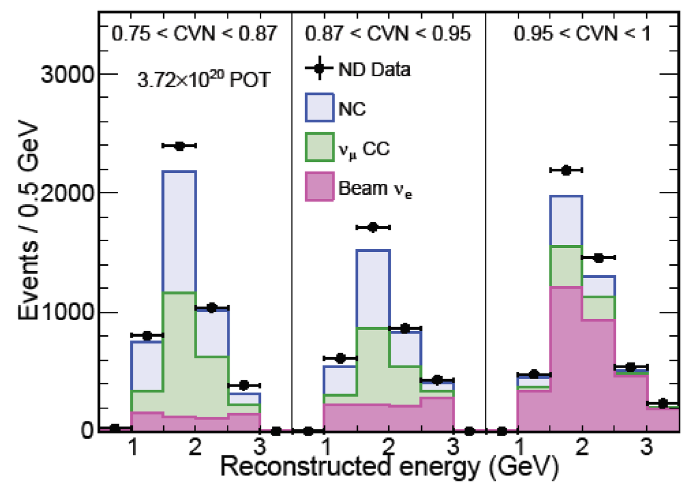
The best fit oscillation parameters are (*at 68% c.l.*)
Δm^2_{32}=(+2.67±0.11)x10-3 eV^2 and two degenerate points $\sin^2\theta_{23}$=$0.404^{+0.030}_{-0.022}$ and $0.624^{+0.022}_{-0.030}$ for the normal mass hierarchy. This analysis is mostly insensitive to δ_{CP}, so its possible values are included in the systematic errors. In the case of the inverted hierarchy, the best fit is Δm^2_{32}=(-2.72±0.11)x10-3 eV^2 and $\sin^2\theta_{23}$=$0.398^{+0.030}_{-0.022}$ and $0.618^{+0.022}_{-0.030}$



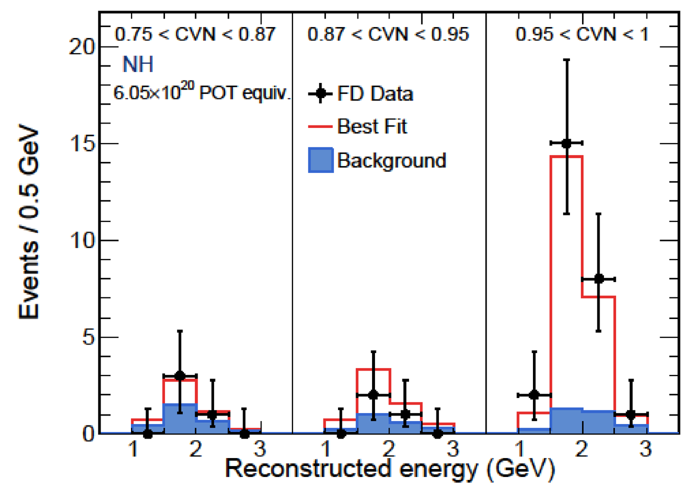
As can be seen in the 90% c.l. allowed regions, the NOνA fit (black) disfavors maximal mixing by 2.6σ.

ν_e Appearance (*PRL 118 (2017)* ***23****, 231801*)

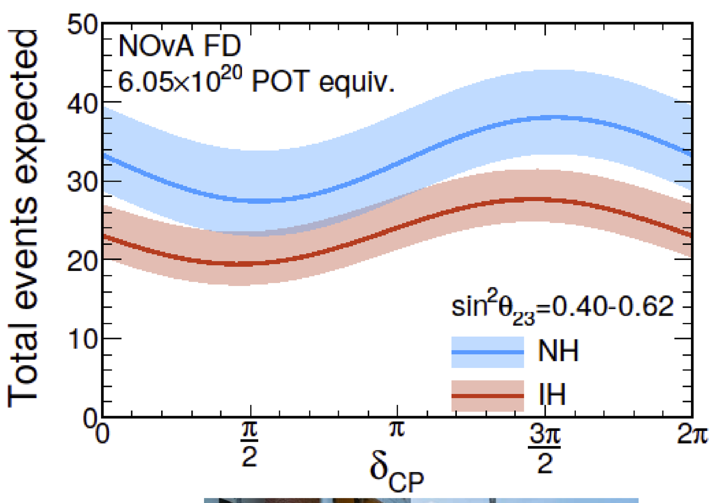
The neutrino spectrum observed at the ND has not had a chance to oscillate, so any ν_e-like interactions there must be backgrounds to a ν_e appearance search. The NuMI beam is composed of 97.5% (97.8%) ν_μ, 1.8% (1/6%) numubar, and 0.7% (0.6%) ν_e+ν_e-bar (parenthetical numbers are at the ND, which has slightly different kinematic phase space than the FD). Beam ν_e compose an irreducible background, while high-y nm events or neutral current interactions are determined using a Convolutional Visual Network ("CVN"), resulting in a 73.5% efficient and 75.5% pure sample of ν_e. Thousands of ν_e candidates are observed in the high flux present at the ND, presented as spectra in three different purity bins (black dots). Background estimations from Monte Carlo are the colored histograms.



33 ν_e candidates are found in the FD data (black dots with statistical errors), compared to an expected backgrounds of 8.2±0.8 (*syst*) (blue histograms). A best-fit ν_e oscillation appearance prediction is the red line.

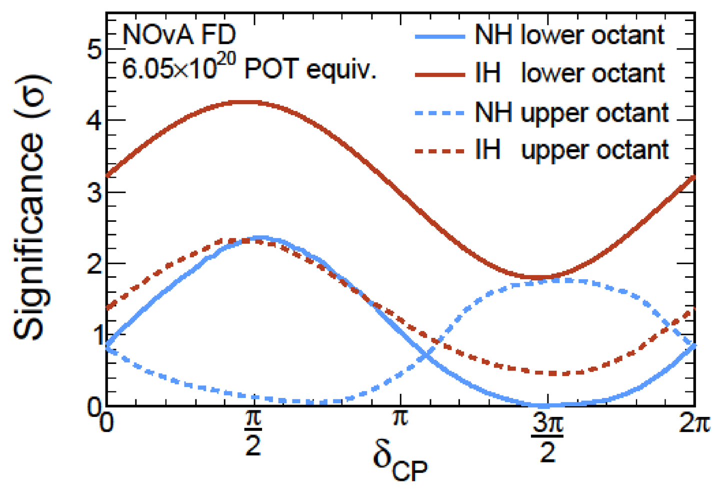


While θ_{13} itself is now well measured by reactor experiments, the passage of neutrinos through matter enhances ν_e appearance oscillations via coherent forward scattering from electrons if the neutrino mass hierarchy is "normal", and the CP-violating phase δ_{CP} enhances (suppresses) ν_e appearance at values of 3π/2 (π/2). A plot of predicted ν_e appearance as a function of δ_{CP} for both hierarchies is shown for the range of allowed θ_{23}.

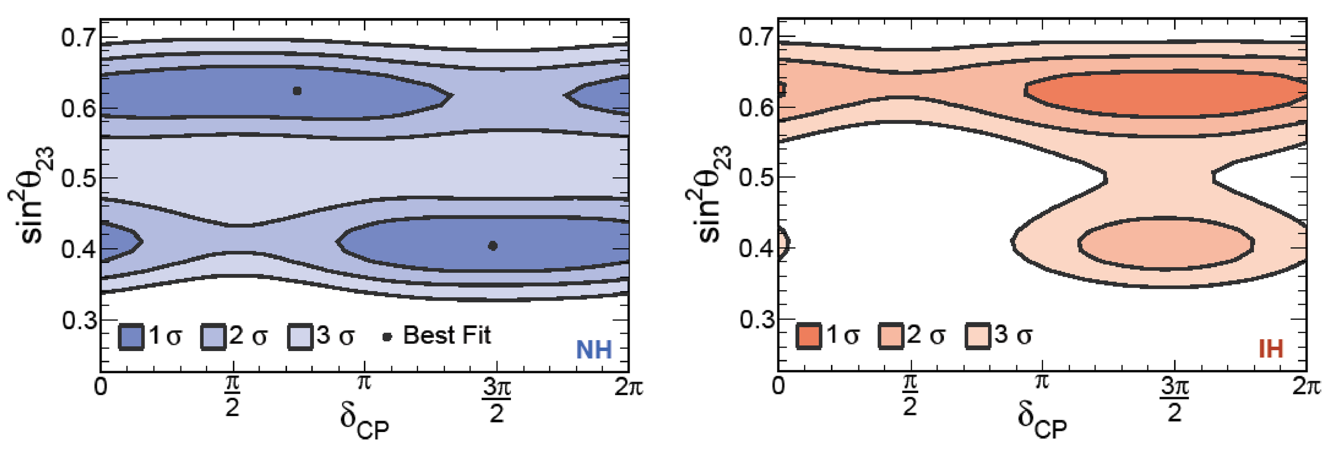


Oscillation Fits

The ν_μ disappearance fits produce degenerate allowed areas. The addition of ν_e appearance adds sensitivity to the octant of θ_{23}. Of the four permutations of hierarchy and octant, the combination of inverted hierarchy and upper octant produces too few ν_e appearances at all values, being disfavored by at least 93% c.l. The significance of disfavoring other combinations of parameters is shown here.



Comparing all possible combinations of $\sin^2\theta_{23}$ and δ_{CP} for the normal (left, blue) and inverted (right, red) hierarchies, the degree to which the data fit the parameter combination is colored by how many sigma the fit at each point in parameter space is away from the data.



Where to Next?

NOνA is currently taking data in a primarily ν_μ-bar beam. By next summer a comparable exposure as presented here in antineutrinos, along with 50% more ν_μ data, will greatly enhance these results. Also, comparisons to T2K's complementary (*different L and E*) results will add sensitivity beyond the two experiments' individual reaches.

The NOνA collaboration celebrating Fermilab's 50th birthday

www-nova.fnal.gov

The NuMI Off-axis ν_e Appearance collaboration is 241 Scientists and Engineers from 47 Institutions in 7 countries.

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