Snowmass2021 - Letter of Interest

The NOvA Physics Program through 2025

NF Topical Groups: (check all that apply ☐/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
☐ (NF7) Applications
☐ (TF11) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors
☐ (Other) *[Please specify frontier/topical group(s)]*

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Abstract:

The physics program of the ongoing NOvA experiment includes long-baseline neutrino oscillation measurements, searches for signatures of sterile neutrinos and other non-standard flavor change phenomena, neutrino cross-section measurements, and astrophysics and cosmic ray physics searches and measurements. A brief overview of the status of the program is presented, along with expectations for the remainder of the NOvA run and the physics opportunities it presents, to inform the community's understanding of the prospects for the state of knowledge in these topics in the coming 5 years.

1 Introduction

Many compelling questions of the P5 Science Driver, "Pursue the Physics Associated with Neutrino Mass[1]," can be examined with the study of neutrino flavor oscillations over long-baselines. The nature of the mixing of muon and tau flavor in the ν_3 mass state, parameterized by the mixing angle θ_{23}, is currently poorly constrained. It is still unknown whether the ν_3 mass state is more ν_τ ($\theta_{23} < \pi/4$ in the lower octant), more ν_μ ($\theta_{23} > \pi/4$ in the upper octant), or equal in τ and μ flavor, ($\theta_{23} = \pi/4$, or maximal mixing), potentially indicating a new mu-tau flavor symmetry. While the absolute value of the larger neutrino mass-squared splitting, $|\Delta m^2_{32}|$, is now known to nearly 1%[2], the question of the neutrino mass hierarchy, i.e. the sign of Δm^2_{32}, remains open. This question bears directly on the potential for future $0\nu\beta\beta$ experiments to determine whether the neutrino is a Majorana particle[3]. Finally, the existence of CP-violation in the lepton sector has not yet been firmly established. As the Jarlskog invariant of the neutrino sector has the potential to be up to 3 orders of magnitude larger than that of the quark sector[2;4], a measurement of significant CP-violation in neutrinos may help explain the matter-antimatter asymmetry of the universe through leptogenesis[5;6].

Each of these questions can be studied by the combined measurement, using neutrinos and antineutrinos, of long-baseline muon neutrino survival and the appearance of electron neutrinos from muon neutrinos in matter[7]. These and other measurements, such as flavor-independent survival in neutral current interactions, are potentially sensitive to phenomena beyond the unitary mixing of 3 masses and flavors in matter. All these measurements give insight to the texture of neutrino mixing and its potential connection to the origin of neutrino mass and a possible unification of quarks and leptons[8].

The NOvA experiment studies high-purity muon neutrino and antineutrino beams from the Fermilab NuMI facility. Flavor transitions are observed between a 300-ton liquid scintillator, tracking calorimeter detector at Fermilab, and a functionally identical, 14 kt detector located 809 km away in Ash River, Minnesota. The detectors provide excellent identification of electron neutrino interactions and are capable of a nearly background-free identification of muon neutrinos. Situated 14 mrad off the NuMI beam axis, the detectors see a narrow energy band neutrino beam centered at 2 GeV. In addition to pursuit of the remaining unknowns within the 3-flavor mixing paradigm, the NOvA detectors provide other unique physics opportunities including high statistics neutrino cross section measurements, searches for sterile neutrinos and other non-standard flavor-change phenomena, searches for exotic phenomena, and a host of astrophysical studies.

2 NOvA Status and Prospects

NOvA has been taking physics quality beam data since early 2014. Following upgrades to the Fermilab accelerator complex and the NuMI beamline, the proton beam power delivered to NuMI increased to the NOvA design goal of 700 kW by January 2017. When Main Injector acceleration cycles are shared among other Fermilab experiments, NuMI typically receives 620-700 kW of beam power. To-date NuMI has received a peak annual proton delivery of 5.6×10^{20} protons-on-target (POT) in FY 2018. Since the start of physics data-taking, the Far Detector has recorded data for 13.6×10^{20} POT (14 kt-equivalent, accounting for detector construction) delivered in neutrino mode and 12.5×10^{20} POT delivered in antineutrino mode.

NOvA is scheduled to run until 2025, when the Fermilab accelerator complex is scheduled to shut down to allow for final construction of PIP-II and LBNF in preparation for the start of DUNE. The Fermilab Accelerator Complex has demonstrated the ability to routinely deliver above 700 kW when NuMI is the sole user of Main Injector (MI) beam, and has achieved an hourly power record of 750 kW. Fermilab is now pursuing several modest improvements that stand to deliver power to NuMI in excess of 900 kW in the next several years. Improvements to the NuMI target system include a megawatt-capable target (installed in 2019), an upstream horn with improved cooling, and improvements to air and water handling (both scheduled for 2020). Higher beam power will require reducing losses primarily in the 8 GeV booster, relying in part on new collimators and dampers included in the scope of the PIP-II project[9] necessary for achieving the design power required for the DUNE program. Depending on the schedule with which this work and the corresponding performance improvements are realized, and the amount of NuMI running time achieved each year, NOvA could accumulate a total of 63×10^{20} POT by the end of its run.

3 Summary of NOvA's physics program

NOvA has published 11 peer reviewed papers to-date[10–20] and 37 theses. The collaboration has produced updated neutrino oscillation results each year since 2016 with increasing statistics and analysis sophistication. Among the analysis improvements made by NOvA is the pioneering first use of convolutional neural networks in a particle physics analysis, which provided an improvement in the signal-to-background of selected electron neutrino candidates equivalent to a 30% increase in detector fiducial volume[21].

The most recent NOvA result on long-baseline neutrino oscillations in the 3-flavor framework[22] presents an allowed region of the mixing parameters Δm^2_{32} and $\sin^2\theta_{23}$ that is in good agreement with world data and achieves a precision of 3% in the mass-squared splitting. On the other hand, the result does not show a strong asymmetry in the appearance probability of electron neutrinos compared to electron antineutrinos, somewhat contrary to T2K's observation[23], putting the NOvA measurement in mild tension[24] with T2K's best fit. This tension has been analyzed as a possible hint of new physics[25;26]. Other recent NOvA results include double differential measurements in lepton kinematics of the inclusive cross section for muon neutrinos[27;28] and electron neutrinos[29] - the first such measurement for electron neutrinos, limits on a sterile neutrino in long-baseline disappearance of the expected rate of neutral current interactions in an antineutrino beam, and searches for multi-messenger neutrino signals coincident with gravitational waves[19].

At the end of the 2025 run, NOvA will have collected about 2.4 times its current exposure if all beam improvements are realized. In this scenario, NOvA will achieve 95% CL a priori sensitivity for the mass hierarchy for 45-60% of the δ_{CP} range as well as 2σ sensitivity to CP violation for 20-30% of the δ_{CP} range[30]. A priori mass hierarchy sensitivity of 4-5σ is achievable for the most favorable parameter combinations. The additional exposure, on its own and in a joint fit[31], will also help clarify whether the tension with T2K is a fluctuation or a signature of the unexpected. Should the tension persist, data at the 810km baseline could prove invaluable in unraveling any new physics phenomena with a non-L/E dependence via comparison to the 1300km baseline of the DUNE experiment, and 295km baseline of T2K and HyperK. NOvA is also poised to make a broad set of cross-section measurements. The large data sample allows for up to quadruple differential measurements in fine bins of lepton and hadronic system kinematics, and good precision measurements of rare interactions[32]. Beyond the Standard Model, NOvA has power to search for sterile neutrinos and constrain other models that lead to neutrino flavor change[33]. NOvA will also search for astrophysical signals coincident with gravitational waves, magnetic monopoles in currently unexplored mass and velocity regimes, oscillations between neutrons and antineutrons, and dark matter[34]. NOvA is the largest carbon-based supernova detector currently operating, and its data will be invaluable in combination with detectors using other target material to constrain the flavor content of a galactic supernova burst.

NOvA's physics campaign has informed the future program through its experience with a high-power neutrino beam, remote detector operations, and refinements in analysis tools and techniques. For the coming 5 years, and potentially beyond if conditions in the field warrant, the NOvA will continue to realize the investment in the NuMI facility to maximally exploit the unique opportunity to understand the physics of neutrino oscillations manifest at the 810km baseline.

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