Snowmass2021 - Letter of Interest

The NOvA Near Detector Physics Program

NF Topical Groups:

☐ (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
■ (NF8) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
☐ (Other) *[Please specify frontier/topical group(s)]*

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Table 1: List of NOvA Near Detector Cross-Section Analyses and Deliverables

	Current			Future		
Signal	Particle Kinematics	Bins	Avg. Stat. Err. Per Bin	Particle Kinematics	Bins	Avg. Stat. Err. Per Bin
ν_μ ($\bar{\nu}_\mu$) CC inclusive	μ	172	3%	μ, hadron	11k	4%
ν_e ($\bar{\nu}_\mathrm{e}$) CC inclusive	e	17	4%	e, hadron	100	5%
ν ($\bar{\nu}$)-electron	e	20	14%	e	36	10%
ν_μ ($\bar{\nu}_\mu$) CC 0 π	μ, hadron	1.5k	5%	μ, hadron	10k	7%
ν_μ ($\bar{\nu}_\mu$) CC $\pi^{+/-}$	μ, $\pi^{+/-}$, hadron	25	1%	μ, $\pi^{+/-}$, hadron	500	2%
ν_μ ($\bar{\nu}_\mu$) CC π^0	μ, π^0, hadron	15	1%	μ, π^0, hadron	100	1%
ν_μ ($\bar{\nu}_\mu$) CC COH π^+	μ, π, hadron	25	5%	μ, π, hadron	250	8%
ν_e ($\bar{\nu}_\mathrm{e}$) CC 0 π	e, hadron	10	10%	e, hadron	50	11%
ν_e ($\bar{\nu}_\mathrm{e}$) CC $\pi^{+/-}$	e, π, hadron	10	10%	e, π, hadron	50	11%
ν ($\bar{\nu}$) NC π^0	π^0	20	4%	π^0	100	4%
ν ($\bar{\nu}$) NC $\pi^{+/-}$	$\pi^{+/-}$	20	5%	$\pi^{+/-}$	100	5%
ν ($\bar{\nu}$) NC COH π^0	π^0	1	3%	π^0	10	5%

1 Introduction

NOvA is an off-axis, 810 km long-baseline neutrino oscillation experiment with detectors exposed to the NuMI beam from Fermilab[1]. The NuMI flux at the NOvA ND is composed of 95.3% muon neutrinos. The electron neutrino and antineutrino component is 0.9%. This component will allow for electron neutrino measurements in a sparsely probed energy region relevant for DUNE. In antineutrino mode, the beam is 92.5% pure in $\bar{\nu}_\mu$, and 0.9% ν_e and $\bar{\nu}_\mathrm{e}$.

The NOvA ND sits 1 km downstream from the beam target. It is a $\sim$300 t (193 t active mass) tracking calorimeter, with 100 m rock overburden. The detector is composed of extruded PVC, filled with liquid scintillator, and is composed of 77% CH_2, 17% chlorine and 6% TiO_2 by mass. The downstream end of the detector contains scintillator interleaved with 10 cm thick steel for muon containment up to $\sim$2.5 GeV.

In this LoI we explore the physics potentials of the rich, high statistics (anti)neutrino interaction samples collected with NOvA ND, using an exposure of 63×10^{20} POT split between neutrino and antineutrino mode, assuming beam improvements and operations until 2025.

2 NOvA Near Detector Cross-Section Analyses

Neutrino-nucleus (ν-A) scattering at the $\sim$GeV scale is an interesting and challenging topic, as it involves both electro-weak and QCD physics, and existing measurements are limited in number and have 10-20% uncertainties. As such ν-A models are one of the larger systematic uncertainties in long-baseline neutrino oscillation experiments. The planned DUNE experiment aims to reduce these uncertainties to near negligible levels by using the Near/Far detector approach, as implemented by experiments such as MINOS, NOvA and T2K, along with measurements of the neutrino energy spectra at different off-axis angles (the DUNE-PRISM concept). It will take significant time to develop and tune models using these techniques. Therefore, it is imperative to have robust interaction models in hand before DUNE begins collecting data to enable its early physics capabilities. Measurements from currently operating experiments such as NOvA will provide constraints on the models that could be in place on this time scale. Measurements on nuclei different from argon are also critical, as discrepancies between a model and, eg, ν-C or ν-H versus ν-Ar data could indicate a missing model feature and reveal associated systematic uncertainties.

The NOvA ND measures neutrino cross sections by identifying long tracks from muons in ν_μ charged-current (CC) interactions, and EM showers observed in many interaction types (e.g., ν_e CC, neutral current (NC) π^0 and ν_μ CC π^0). Table 1 lists ND measurements being pursued by the NOvA collaboration. These analyses can be done using both neutrino and antineutrino data, and ratios of many of the measurements are anticipated. In the CC analyses, final state kinematics of the lepton will be reported, and in some cases the kinematics of the leading hadrons or the total hadronic energy will also be reported[5–7]. The energy and angular resolution for muons is excellent, enabling 10-20 measurement bins in each. The energy and angular resolution for electrons and hadrons allows 5-10 measurement bins in each kinematic observable.

Currently, one of the dominant systematic uncertainties for cross-section measurements in NOvA is a $\sim 10\%$ uncertainty on the flux. This is primarily a normalisation uncertainty, and it is expected that the in-situ $\nu - e$ scattering measurements and new external hadron production measurements[2–4] will reduce this uncertainty to a few percent within the next few years. Other uncertainties include detector response and energy scale, ν-A and Final State Interactions (FSI) modeling, secondary hadronic interaction modeling, and an overall normalisation uncertainty. These contribute at least a few percent of uncertainty to measured cross sections. Ultimately, we expect at least a 5% total uncertainty on any cross-section measurement.

3 Future Improvements and Measurements

Higher statistics available with beam improvements and operations until 2025 will enhance the output of the analyses (see Table 1) to unprecedented levels. Muon-neutrino analyses will have the statistics to perform quadruple differential cross-section measurements in both the muon kinematics and the hadron system kinematics (q_0, q_3), with $\sim$10k total bins. Similarly electron-neutrino analyses will perform quadruple differential measurements, with the total number of bins (≈ 100) limited by the resolution of the electron kinematic variables. CC analyses where a pion (charged or neutral) is selected, will report quadruple differential measurements of the lepton and pion kinematics, probing the resonant and soft inelastic scattering region. Measurements of rare processes, like CC (NC) coherent scattering, will report double (single) differential results in the pion kinematics. Finally, double differential (anti)neutrino electron scattering measurements will reduce the flux normalization uncertainty from 10% to a few percent. In the event that NOvA data taking continues with the recent average performance of the NuMI beam, corresponding to an exposure of 46×10^{20} POT for both neutrino and antineutrino running, our analyses will suffer increased statistical uncertainties by 1-3% per bin, and a reduced scope in the triple and quadruple differential measurements.

4 Conclusion

NOvA is poised to produce a broad set of neutrino interaction cross-section measurements. Larger datasets would allow our measurements to be reported with finer binning and higher-dimensionality, adding information about more than one final state particle. All measurements under all scenarios will have systematic uncertainties of at least 5%. The full NOvA run with beam improvements until 2025 will significantly decrease the statistical uncertainty for NOvA near detector cross-section analyses, in particular those that are rare either because of small cross sections or small fluxes. These NOvA measurements will provide valuable constraints to the interaction models including nuclear effects and meson exchange models that are a vital part of improving precision for current and future neutrino oscillation experiments.

References

[1] P. Shanahan and P. Vahle (NOvA), *Snowmass 2021 - Letter of Interest: The NOvA Physics Program through 2025*.

[2] The NA61/SHINE Collaboration, Phys. Rev. D 100, 112001 (2019).

[3] The NA61/SHINE Collaboration, Phys. Rev. D 100, 112004 (2019).

[4] T. Akaishi, et al, *EMPHATIC: A proposed experiment to measure hadron scattering and production cross sections for improved neutrino flux predictions*, https://arxiv.org/abs/1912.08841

[5] L. Cremonesi, *Cross-section measurements in the NOvA Near Detector* (Neutrino 2020)

[6] J. Paley, *Double-differential muon-neutrino inclusive cross section measurement using the NOvA near detector* (Fermilab Joint Experimental-Theoretical Physics Seminar)

[7] M. Judah, *Double-differential electron-neutrino inclusive cross section measurement using the NOvA near detector* (Fermilab Joint Experimental-Theoretical Physics Seminar)