DOE Final Technical Report

1 Grant Information

DOE Award #: DE-SC0019077

Recipient: University of California, Irvine

Project Title: Detector Instrumentation, Energy Reconstruction and Data Analysis in the DUNE and NOvA Neutrino Experiments

Principle Investigator:
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Period covered by the report: 05/01/2018 - 05/15/2019
The work supported by this grant is continuing and is currently supported by DOE grant DE-SC0009920-TaskB to the PI.

2 Personnel Involved in This Project

The core members in our group involved in this project are **Jianming Bian (PI)**, postdoctoral researcher **Ilsoo Seong (PD)**, physics Ph.D. student **Nitish Nayak (GSR1)**, and statistics Ph.D. students **Lars Hertel (GSR3)** and **Lingge Li (GSR4)**. UCI Technician **Jeff Griskevich (TC)** is working for the PI on the PrM hardware.
The PI joined UCI in 2016. He joined NOvA in 2011 and joined DUNE (LBNE) in 2013. The PI is Team Leader of the purity monitoring system at ProtoDUNE-SP, Co-convenor of the reconstruction and deep-learning group at NOvA, Co-convenor of the Liquid Argon Instrumentation group in DUNE's Cryogenics Instrumentation and Slow Control (CISC) consortium, and Co-convenor of the Neutrino Oscillation Working Group (WG1) of NuFACT2017-2019. He is a member of the Speaker Committee at DUNE, and is the IB representative of DUNE and NOvA at UCI.
Seong (PD) joined the UCI group in 2017. He has been the major contributor to the fabrication, commissioning, and DAQ of the ProtoDUNE-SP purity monitoring system. Seong is now operating the PrMs in ProtoDUNE-SP and carrying out PrM R&D for DUNE. Working with GSR3 and GSR4, Seong has been leading the effort to develop the regression CNN energy estimator at DUNE. He is also a main contributor to the ν-e scattering analysis at NOvA since early 2018.
Nayak (GSR1) joined the UCI group in 2016 and has chosen NOvA ν_e appearance measurement as his thesis topic. Before joining UCI, Nayak obtained a Master degree in Physics and a Bachelor degree in Electrical Engineering from Indian Institute of Technology. Nayak has been a leading contributor to the ν_e appearance analysis at NOvA. He is one of the four editors, along with former spokesperson Mark Messier and current spokesperson Peter Shanahan, for NOvA's first anti-neutrino oscillation paper. The paper has been published in *PRL* in 2019 [1]. Thanks to his EE

background, Nayak built the complicated front-end electronic modules of the three ProtoDUNE-SP PrMs. Nayak was involved in the ProtoDUNE cold electronics tests at BNL, NOvA calibration, and NOvA reconstruction software update and maintenance. He has given several talks in conferences and won Fermilab's NPC Award in 2017.
Herter (GSR3) and **Li (GSR4)** joined the UCI group in 2016. Their advisor in UCI's School of Information and Computer Sciences is Professor Pierre Baldi. The PI has an ongoing collaboration with Prof. Baldi in applying machine learning and statistical technologies in NOvA and DUNE. Hertel and Li are experts in deep learning and statistics tools. They have chosen the application of deep-learning and statistical technologies at NOvA and DUNE as their thesis topics. Hertel is working on designing and optimizing regression CNNs for DUNE and NOvA. Li is working on the regression CNN optimization and the Gaussian process enhanced Feldman-Cousins approach. They are also doing NOvA service work on data production and software installation and maintenance.

UG students Yiwen Xiao, Muyuan He, and Chen Wang have been working in the PI's group since 2017. They are involved in the PrM electronics and in the Gaussian process enhanced Feldman-Cousins approach. They also finished a large share of the work in refurbishing and testing photomultiplier tubes (PMT) for the upgrade of the Super-K experiment for UCI's Super-K group.

Since 2016, PD and GSRs have given several talks or posters in conferences for their work. The research plan allows them to have opportunities to acquire experience in hardware, software, and analysis and paper writing. The educational aim is to train them as well-rounded HEP physicists.

3 Unexpended Funds

The grant is fully expended.

4 Research Accomplishments

Neutrino oscillations are so far the only experimental observation beyond the standard model since its development four decades ago. The remaining fundamental questions that can be answered by long-baseline neutrino oscillations are (1) the CP violation (whether neutrinos and antineutrinos behave the same way in oscillation), and (2) the mass hierarchy ($m_3 > m_{1,2}$ or $m_{1,2} > m_3$), and (3) the octant of θ_{23} ($\theta_{23} > 45°, = 45°$ or $< 45°$) [2] − [18]. The PI's group at UCI focuses on long-baseline neutrino experiments DUNE [19] and NOvA [20], key components of DOE's Intensity Frontier program. NOvA is the current major U.S.-based long-baseline neutrino experiment aiming to solve the mass hierarchy and θ_{23} octant. It is taking ν and $\bar{\nu}$ data from the NuMI beam at Fermilab. DUNE is the next-generation flagship neutrino experiment in the U.S. which is designed to decisively determine neutrino CP violation, mass hierarchy and θ_{23} octant. DUNE is Fermilab's first priority, and has been established as an international collaboration. During the period covered by the report, the PI's group has been exceptionally productive, with leading contributions to DUNE argon-purity monitoring detectors, NOvA/DUNE deep-learning reconstruction, and NOvA oscillation and near detector (ND) analyses. The group also is actively involved in DUNE/NOvA detector operation, data production, calibration, software upgrade and maintenance, and ProtoDUNE cold electronic QA/QC. Specifically, we have made accomplishments in the following four research projects:

1) Purity monitor R&D and data analysis for DUNE
DUNE detectors are based on liquid argon TPC (LArTPC) technology, which offers excellent spatial resolution. A challenging part of DUNE is to make electrons drift over long distances in LAr, so

the electron lifetime which is determined by the LAr purity is an essential concern for DUNE's successful operation and physics reach. A purity monitor (PrM) is a standalone miniature TPC which measures the lifetime of photoelectrons generated by a UV-illuminated gold photocathode to measure the purity of LAr. PrMs have high sensitivity to LAr purity and are almost unaffected by cosmic-ray-induced space charge due to their small volumes. They are important to guarantee successful commissioning and operation of a LArTPC. The UCI group has built and is operating the LAr purity monitoring system at ProtoDUNE-SP, which has played a critical role in the successful protoDUNE-SP commissioning and test beam data taking.

A PrM's basic design is based on those used by the ICARUS and LAPD [21, 22]. It is a double-gridded ion chamber which measures the lifetime of photoelectrons generated by a UV-illuminated gold photocathode to monitor the purity of LAr. The UV is generated by a xenon flash lamp, and is delivered by optic fibers. The electron (e-) lifetime in LAr is inversely proportional to the electronegative impurity concentration. The fraction of electrons generated at the PrM cathode that arrive at the anode (Q_A/Q_C) after the drift time t is a measure of the e-lifetime τ: $Q_A/Q_C = e^{-t/\tau}$. The PI's group has built and is operating the LAr purity monitoring system at ProtoDUNE-SP, which has played a critical role in the successful protoDUNE-SP commissioning and test beam data taking. The fabrication of PrM hardware (PI, PD, and TC) and electronics (GSR1), and the development of PrM DAQ (PD, GSR1 and TC) were carried out in UCI's high-bay neutrino lab. The assembly and installation of ProtoDUNE-SP PrMs at CERN were led by the UCI group (PI, PD). The measured electron lifetimes in the three PrMs as a function of time are shown in Fig 1. PrMs have alerted the experiment solely to serious problems several times. The first time was for filter saturation during LAr filling, and the rest were recirculation pump stoppages, false alarms, and problems from the cryostat-level gauges. These alerts are crucial to the ProtoDUNE-SP project's success, as they prevented situations which otherwise would have continued unnoticed for some time, with severe consequences to the ability to take any data. Neither the gas analyzers nor the TPC caught these problems in time.

The UCI group developed the technique to operate purity monitors with various high voltages and to correct for the effect of low transparency, which allows the ProtoDUNE purity monitors to measure e-lifetime from 35 μs to about 10 ms. Signal strength is an issue that has limited the precision and measuring ranges of purity monitors in previous LArTPC experiments. At ProtoDUNE, we used 8 fibers through an 8-channel feedthrough to deliver UV light for each PrM to increase signal strength. Signal magnitudes are 6 times larger than 1 fiber without penalty in timing resolution, thereby solving the long-existing signal strength problem. High-precision electron lifetime measurements from purity monitors are also valuable to the electron lifetime calibration for ProtoDUNE. Specifically, because the purity monitors have much smaller volumes compared with the TPC, electron lifetime measurements from purity monitors are much less affected by the space charge caused by cosmic rays.

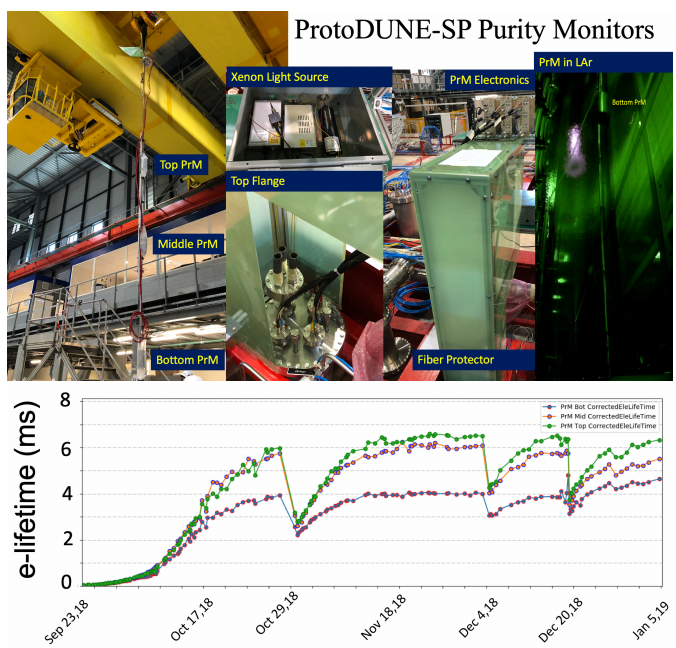

Figure 1: PrMs in ProtoDUNE-SP and e-lifetimes in PrMs at three heights

In 2018, the PI wrote the PrM section in DUNE's TDR. The UCI group is preparing the fabrication and installation of PrMs into DUNE FD. Current purity monitor designs pose several issues for long-term (20 years) operation in DUNE's large FD, and we will perform R&D and data analysis to improve PrMs for DUNE.

2) Deep-learning-based energy reconstruction at NOvA and DUNE

Convolutional Neural Network (CNN) [23] is a deep-learning method that can automatically extract features from raw pixel inputs. Deep learning and CNNs have demonstrated success in **classification** problems such as event identification in neutrino experiments, including NOvA and MicroBooNE [24–27]. At DUNE, a classification CNN was developed to identify neutrinos (CVN). The PI's group has been focusing on using CNNs to solve **regression** problems (solves continuous variables), reconstructing neutrino and lepton energy from complicated final states, which haven't yet been developed in the neutrino community. The only relevant work we aware of is the energy reconstruction of point-like charge deposition events at EXO-200 [28]. MINERvA treats the vertex identification problem as a classification problem instead of a regression problem, using a CNN-based plane classifier to identify the plane where the interaction occurred [29].

In the past funding cycle, the UCI group has developed the first **regression** CNN-based algorithms to reconstruct ν_e and electron energy for NOvA and DUNE. To solve regression problems with CNN, we modified output activation functions, defined new loss functions to optimize energy resolution and reduce impacts from outliers. We utilized the hyperparameter optimization software SHERPA [30] to automatically optimize architecture and training parameters, significantly speeding up the computationally expensive regression CNN optimization. Regularization and dropout techniques [31, 32] were also explored to increase the robustness against noises and systematic uncertainties in inputs. A hybrid architecture in the fully connected layer is invented to consider the location dependence. To minimize the energy dependence of E_{reco}/E_{true}, flat neutrino fluxes were used in the training. Compared with kinematics-based energy reconstruction, our regression CNNs achieves significantly better energy resolutions, providing improvements of 16% and 12% for ν_e CC and electrons at NOvA and 38% for ν_e CC at DUNE (Fig 2). At NOvA, we found that the regression CNN has smaller systematic uncertainties from those of the neutrino interaction simulations. It also shows comparable or less dependence on true energy, hadronic energy fractions, and calibration. The regression CNN can be extended to solve other regression problems in HEP, taking over kinematics-based reconstruction tasks. UCI's NOvA regression CNN energy reconstruction paper was published by *PRD* [33]. Both NOvA and DUNE regression CNNs have been reported in conferences and in collaboration meetings by the UCI group [34–37]. The PI is leading the reconstruction and deep-learning group at NOvA, coordinating the group efforts using deep-learning methods to take over traditional reconstruction tasks. Based on their machine-learning backgrounds, Hertel (GSR3) and Li (GSR4) have advised other groups on neural network design and training. Working with Fermilab postdoc Pengfei Ding, Hertel had installed SHERPA on Fermilab's new HPC with GPUs for collaborators' use and HPC performance tests.

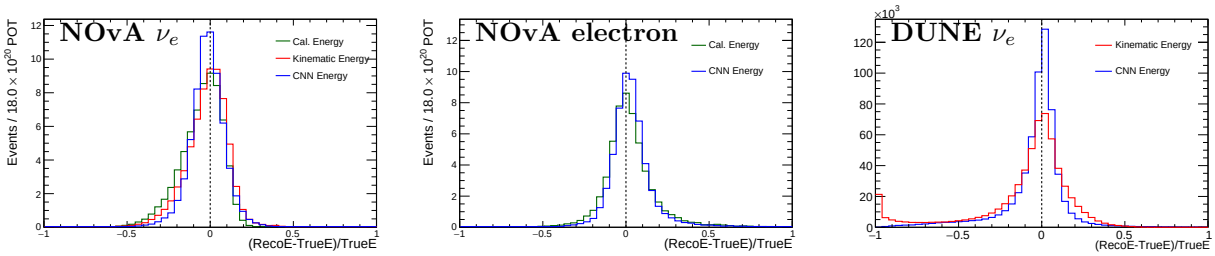

Figure 2: Energy resolution of Regression CNNs, kinematic methods, and calorimetric energy

3) Oscillation analysis at NOvA

The UCI group has played key roles in NOvA's ν_e appearance measurements. For the 2017 [38] and 2018 [1] analyses, the UCI group:

(a) implemented flux systematics from PPFX framework in oscillation analyses, which evaluates beam uncertainties with external data such as NA49 [39], (b) took correlations between the uncertainties across different neutrino energies into account with use a Principal Component Analysis (PCA)-based technique [40], (c) developed a timing- and location-based cosmic rejection method at the FD to remove the ν_e-like delayed bremsstrahlung showers (also replicated in the sterile analysis), (d) developed a BDT based wrong-sign neutrino identifier and analyzed wrong-sign neutrino backgrounds (major background in $\bar{\nu}_e$ appearance). Nayak (GSR1) is one of the main analyzers of the first joint ν+$\bar{\nu}$ oscillation measurement in 2018. The analysis observed 18 $\bar{\nu}_e$ candidate events (Fig 3), with a significance of $\bar{\nu}_e$ appearance more than 4σ, which is the first strong evidence of $\bar{\nu}_e$ appearance. The normal hierarchy is preferred at 1.8σ. Nayak served as one of the four editors, along with former spokesperson Mark Messier and current spokesperson Peter Shanahan of this paper. The paper was published in *PRL* in 2019 [1]. In addition, the UCI group has developed a new technique using a Gaussian process to speed up the computationally expensive Feldman-Cousins (FC) approach in oscillation parameter extraction [41, 42]. FC Contours produced by our method is 10 times faster than the standard FC algorithm while keeping the accuracy at 99%. In the next three years, NOvA will accumulate more ν and $\bar{\nu}$ beam data, and the significance of the mass hierarchy from the joint $\nu_e(\bar{\nu}_e)$ appearance and $\nu_\mu(\bar{\nu}_\mu)$ disappearance analysis could reach 4σ [43].

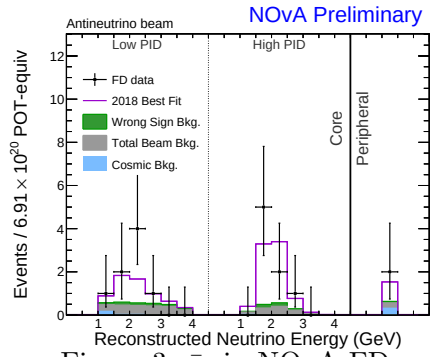

Figure 3: $\bar{\nu}_e$ in NOvA FD

4) ν-e elastic scattering analysis at NOvA

The neutrino flux has a large uncertainty that affects both near detector (ND) cross-section measurements and FD oscillation analyses in NOvA. Neutrino-electron (ν-e) elastic scattering is a purely leptonic process which can be calculated accurately, so it can be used to absolutely constrain the flux. This work will demonstrate a flux constraint method for DUNE's oscillation ND analyses.

The UCI group is leading the ν-e elastic scattering analysis based on NOvA ND data. In this measurement, the PI has developed major analytic tools, including a ν-e elastic scattering PID, an e/π^0 PID, event selection, and the analysis framework for this project, and is coordinating and first-authoring the analysis note under the collaboration review. The PI reported the status of the analysis on DPF2017 [44]. In 2018, PD joined this analysis and we updated the analysis note and extended it from 3.7×10^{20} to 8.3×10^{20} POT ND ν beam data (Fig 4). We used a more precise radiative correction in this update. The flux-shape-related uncertainty was renewed with the PPFX framework.

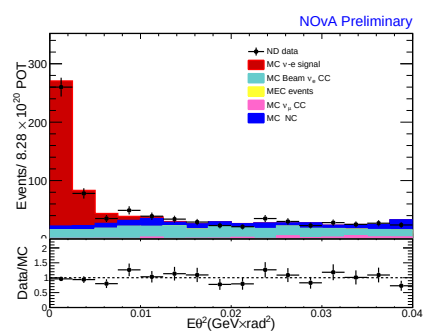

Figure 4: Data and MC of reconstructed $E_e\theta_e^2$ in ν-e scattering

5 Publications

The following are PI's publications during the report period 05/01/2018 - 05/15/2019.

[1] M. A. Acero *et al.* [NOvA Collaboration], "First Measurement of Neutrino Oscillation Parameters using Neutrinos and Antineutrinos by NOvA," Phys. Rev. Lett. **123**, 151803 (2019) doi.org/10.1103/PhysRevLett.123.151803 arXiv:1906.04907 [hep-ex].

[2] B. Bhandari *et al.* [CAPTAIN Collaboration], "First Measurement of the Total Neutron Cross Section on Argon Between 100 and 800 MeV," Phys. Rev. Lett. **123**, no. 4, 042502 (2019) doi:10.1103/PhysRevLett.123.042502 [arXiv:1903.05276 [hep-ex]].

[3] M. A. Acero *et al.* [NOvA Collaboration], "Measurement of Neutrino-Induced Neutral-Current Coherent π^0 Production in the NOvA Near Detector," submitted to Phys. Rev. D, arXiv:1902.00558 [hep-ex].

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[6] J. Bian, "Results and Prospects from NOvA," Proceedings of the 20th International Workshop on Neutrinos from Accelerators (NuFACT2018), arXiv:1812.09585 [hep-ex].

[7] P. Baldi, J. Bian, L. Hertel and L. Li, "Improved Energy Reconstruction in NOvA with Regression Convolutional Neural Networks," Phys. Rev. D **99**, no. 1, 012011 (2019) doi:10.1103/PhysRevD.99.012011 [arXiv:1811.04557 [physics.ins-det]].

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[10] M. Ablikim *et al.* [BESIII Collaboration], "Measurement of $e^+e^- \to D\bar{D}$ cross sections at the $\psi(3770)$ resonance," Chin. Phys. C **42**, no. 8, 083001 (2018) doi:10.1088/1674-1137/42/8/083001 [arXiv:1803.06293 [hep-ex]].

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[12] M. Ablikim *et al.* [BESIII Collaboration], "Precision Study of $\eta' \to \gamma\pi^+\pi^-$ Decay Dynamics," Phys. Rev. Lett. **120**, no. 24, 242003 (2018) doi:10.1103/PhysRevLett.120.242003 [arXiv:1712.01525 [hep-ex]].

6 Presentations

Conference & Workshop

[1] Speaker, Results and Prospects with NOvA, **"Prospects of Neutrino Physics,"**, April 8-12, 2019, Kavli IPMU, Kashiwa, Japan

[2] Presentation Co-author, Efficient Neutrino Oscillation Parameter Inference with Gaussian Process (co-author), **"PHYSTAT-nu 2019",** January 22-25, 2019, CERN, Switzerland

[3] Presentation Co-author, Efficient Neutrino Oscillation Parameter Inference with Gaussian Process (poster, co-author), **"The 33th AAAI Conference on Artificial Intelligence (AAAI-19),"** Jan 27 - Feb 1, 2018, Honolulu, Hawaii

[4] Speaker, DUNE Energy Reconstruction: Kinematics-based and Deep-learning, **"Workshop on Calibration and Reconstruction for LArTPC Detectors"**, December 10-11, 2018, Fermilab, IL

[5] Poster Presenter, Energy Reconstruction in NOvA with Regression Convolutional Neural Networks (poster), **"The International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN18)"**, Nov 1-3, 2018, Vancouver, Canada

[6] Poster Presenter, Constraint of the Integrated Neutrino Flux from Neutrino-Electron Elastic Scattering in the NOvA Near Detector (poster) **"12th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt18)"**, Oct 15-19, 2018, Gran Sasso Science Institute (GSSI), Italy

[7] Speaker, WG1 - Neutrino Oscillations Summary, **"The 2018 International Workshop on Neutrinos from Accelerators (NuFACT2018)"**, August 12-18, 2018, Blacksburg, VA

[8] Speaker, Results and Prospects from NOvA, **"The 2018 International Workshop on Neutrinos from Accelerators (NuFACT2018)"**, August 12-18, 2018, Blacksburg, VA

[9] Speaker, Status of DUNE Experiment, **"The 39th International Conference on High Energy Physics (ICHEP2018)"**, July 4-11, 2018, Seoul, Korea

[10] Speaker, Latest Results from NOvA, **"The 39th International Conference on High Energy Physics (ICHEP2018)"**, July 4-11, 2018, Seoul, Korea

[11] Speaker, Overview of the DUNE Experiment, **"Thirteenth Conference on the Intersections of Particle and Nuclear Physics (CIPANP2018)"** May 29 - June 3, 2018 Palm Springs, CA

Seminar & Colloquium

[1] Results and Prospects with NOvA, **"DayaBay Analysis Workshop"**, May 8, 2019, Irvine, CA

[2] Neutrino Oscillation at NOvA and DUNE **"Pizza Seminars at University of California, Irvine"**, Jan 18, 2019, Irvine, CA

[3] Recent Results from the NOvA experiment **"Elementary Particle Physics Seminar at Institute of High Energy Physics, Chinese Academy of Sciences"**, Sep 10, 2018, Beijing, China

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[1] M. A. Acero *et al.* [NOvA Collaboration], "First Measurement of Neutrino Oscillation Parameters using Neutrinos and Antineutrinos by NOvA," Phys. Rev. Lett. **123** (2019) no.15, 151803 doi:10.1103/PhysRevLett.123.151803 [arXiv:1906.04907 [hep-ex]].

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[4] M. H. Ahn *et al.* [K2K Collaboration], "Measurement of Neutrino Oscillation by the K2K Experiment," Phys. Rev. D **74**, 072003 (2006) doi:10.1103/PhysRevD.74.072003 [hep-ex/0606032].

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