Snowmass Letter of Intent: **Snowmass Topical Groups: NF6, RF6, TF11**

Electron-Nucleon Scattering at LDMX for DUNE

Torsten Akesson[1], Artur Ankowski[2], Nikita Blinov[3], Lene Kristian Bryngemark[4], Pierfrancesco Butti[2], Caterina Doglioni[1], Craig Dukes[5], Valentina Dutta[6], Bertrand Echenard[7], Thomas Eichlersmith[8], Ralf Ehrlich[5], Andrew Furmanski[*8], Niramay Gogate[9], Mathew Graham[2], Craig Group[5], Alexander Friedland[2], David Hitlin[7], Vinay Hegde[9], Christian Herwig[3], Joseph Incandela[6], Wesley Ketchum[†3], Gordan Krnjaic[3], Amina Li[6], Shirley Li[‡2,3], Dexu Lin[7], Jeremiah Mans[8], Cristina Mantilla Suarez[3], Phillip Masterson[6], Martin Meier[8], Sophie Middleton[7], Omar Moreno[2], Geoffrey Mullier[1], Tim Nelson[2], James Oyang[7], Gianluca Petrillo[2], Ruth Pottgen[1], Stefan Prestel[1], Luis Sarmiento[1], Philip Schuster[2], Hirohisa Tanaka[2], Lauren Tompkins[4], Natalia Toro[2], Nhan Tran[§3], and Andrew Whitbeck[9]

[1]Lund University
[2]Stanford Linear Accelerator Laboratory
[3]Fermi National Accelerator Laboratory
[4]Stanford University
[5]University of Virginia
[6]University of California Santa Barbara
[7]California Institute of Technology
[8]University of Minnesota
[9]Texas Tech University

ABSTRACT

We point out that the LDMX (Light Dark Matter eXperiment) detector design, conceived to search for sub-GeV dark matter, will also have very advantageous characteristics to pursue electron-nucleus scattering measurements of direct relevance to the neutrino program at DUNE and elsewhere. These characteristics include a 4-GeV electron beam, a precision tracker, electromagnetic and hadronic calorimeters with near 2π azimuthal acceptance from the forward beam axis out to $\sim$40° angle, and low reconstruction energy threshold. LDMX thus could provide (semi)exclusive cross section measurements, with detailed information about final-state electrons, pions, protons, and neutrons. We compare the predictions of two widely used neutrino generators (GENIE, GiBUU) in the LDMX region of acceptance to illustrate the large modeling discrepancies in electron-nucleus interactions at DUNE-like kinematics. We argue that discriminating between these predictions is well within the capabilities of the LDMX detector.

Contents

*afurmans@umn.edu
†wketchum@fnal.gov
‡shirleyl@slac.stanford.edu.
§ntran@fnal.gov

1 Motivation

The primary goal of the accelerator-based neutrino program is the measurement of oscillation features in a reconstructed neutrino-energy spectrum. Performing this reconstruction accurately and consistently for both neutrinos and antineutrinos requires a detailed understanding of how (anti)neutrinos interact with nuclei—a subtlety that has already impacted past oscillation fits (1; 2; 3), despite the availability of near detectors, which can help tune cross section models and constrain other systematic effects. The situation will be even more challenging at DUNE (4), where the science goal is to measure the subtle effects of $\delta_{\rm CP}$ and mass hierarchy, requiring a much higher level of precision.

The origin of these difficulties stems from the complexity of neutrino-nucleus interactions in the relevant energy range, which for DUNE is approximately between 500 MeV and 4 GeV. At these energies, different mechanisms of interaction yield comparable contributions to the cross section. One has to model both quasielastic (QE) scattering, in which a struck nucleon remains unbroken, $\nu_\mu + n \rightarrow \mu^- + p$, and various processes in which one or more pions are produced. At sufficiently high values of four-momentum transfer, $Q^2 = -(p_\nu - p_\mu)^2$, and energy transfer, $\omega = E_\nu - E_\mu$, the deep inelastic scattering (DIS) description of the interaction becomes appropriate, in which the lepton scatters on individual quarks inside the nucleon, followed by a process of "hadronization."

While better neutrino data would certainly be desirable to improve modeling, it is unlikely to be sufficient. To date, neutrino experiments only have access to broadband beams, extract flux-integrated cross sections (5; 6; 7; 8; 9; 10; 11; 12; 13), and neutrino-energy reconstruction itself suffers from sizable uncertainties. In turn, the process of energy reconstruction *relies* on neutrino generators. Even with a perfect calorimeter, some of the neutrino energy is lost to nuclear breakup which must be corrected for using a model. With an imperfect calorimeter, particularly missing energy carried away by neutrons, these corrections become more significant and rely on poorly understood nuclear physics. Hence, complementary probes that are free from these limitations are highly desirable for accurately validating the physical models in event generators. Precise electron-nucleus scattering data provide just such a complementary probe. While electron and neutrino interactions are different at the primary vertex, many relevant physical processes in the nucleus are the same in the two cases. What electron scattering offers is precisely controlled kinematics (both initial and final energies, and scattering angles), large statistics, *in situ* calibration of the detector response using exclusive reactions, and a prospect of easily swapping different nuclear targets. This allows one to easily zero in on specific scattering processes and to diagnose problems that are currently obscured by the quality of the neutrino scattering data.

In this letter, we point out that the proposed LDMX (Light Dark Matter eXperiment) setup at SLAC (14), designed to search for sub-GeV dark matter, will have very advantageous characteristics to also pursue electron-scattering measurements relevant to the neutrino program (15) and complementary to existing or planned electron scattering measurements. These include a 4-GeV electron beam and a detector with high acceptance of hadronic products in the $\sim 40^\circ$ forward cone and low-energy threshold. A cartoon schematic of LDMX is shown in Figure 1 (left). In Figure 1 (right), we show the (ω, Q^2) plane of charged-current (CC) events for muon neutrino scattering on argon nuclei in the near detector of DUNE, simulated with the GiBUU generator code. As can be immediately seen, the LDMX coverage in the relevant kinematic window is excellent. Below, we quantify how future LDMX data can be used to test and improve physics models in lepton-nucleus event generator codes.

2 LDMX detector

While the final detector design is still under development, we describe a coarse set of detector capabilities (motivated by the baseline design), which are particularly relevant for electron-scattering measurements (14; 15):

- *Electrons*: We estimate the electron energy resolution to be 5%–10% and the p_T resolution to be < 10 MeV (14), where p_T is the transverse momentum of the outgoing electron. The tracker acceptance is approximately 40° in the polar angle where the z-axis is defined along the beamline. Electrons can be measured down to a kinetic energy of approximately 60 MeV.

- *Charged pions and protons*: The energy and p_T resolutions, tracking acceptance, and kinetic thresholds are similar for charged pions, protons, and electrons. The recoil tracker and ECal detectors can be used to perform particle identification via mean energy loss (dE/dx) to separate charged pions and protons. Based on previous studies of similar silicon-tracking technologies at CMS (16; 17), the recoil tracker by itself has good pion/proton discrimination power for kinetic energies < 1.5 GeV.

- *Neutrons*: The nominal neutron signal is a hadronic shower in the HCal, although the shower can start in the ECal, which is roughly one hadronic-interaction mean free path in thickness. Once identified, neutrons can be efficiently distinguished from charged hadrons (protons, charged pions/kaons) at angles $< 40^\circ$ by identifying those charged tracks in the tracking and ECal detectors. Based on GEANT4 simulations for the baseline HCal sampling fraction, we estimate the HCal to

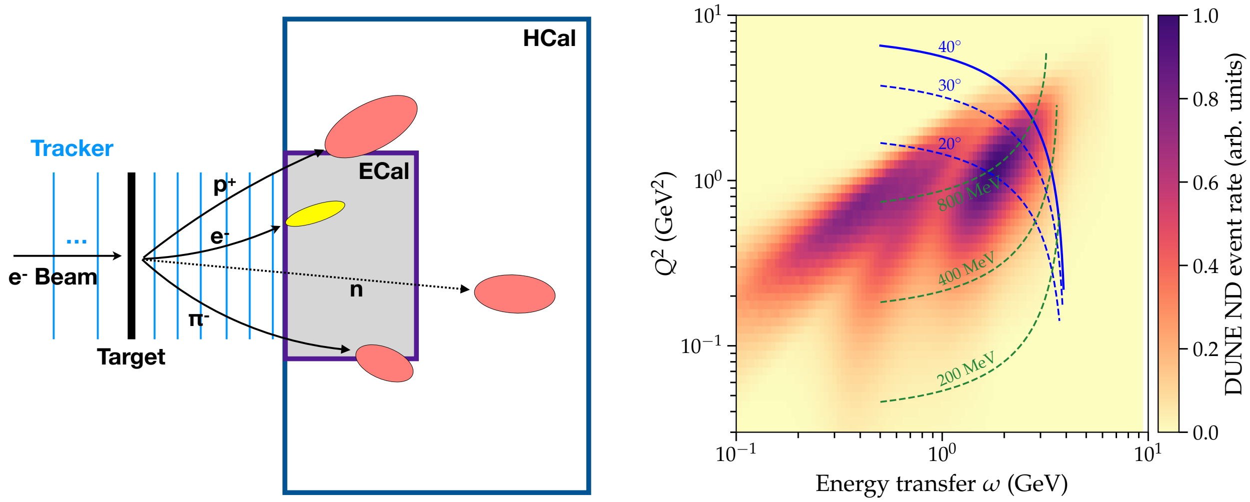

Figure 1. Schematic of the LDMX experiment for dark-matter search (not to scale). The electron beam is incident from the left and interacts in the target (which can be varied). Direct tracking and calorimetry along the beam axis provides excellent (nearly 2π azimuthal) forward acceptance to a range of final-state particles, including the recoiling electron, protons, pions, and neutrons. Figures are reproduced from Ref. (15).

have an energy resolution for neutrons of $5\% \oplus 40\%/\sqrt{E/\mathrm{GeV}}$ and a polar angular acceptance of $65°$. However, because we have tracking acceptance out to $\sim 40°$, our studies assume that we have good pion/proton/neutron discrimination out to only $\sim 40°$ (14). We have also assumed that the angular resolution of the neutrons are conservatively $10°$ based on position resolution measurements.

3 Outlook & Plans

Our goal for the Snowmass white paper is to further mature the physics case and detector design to measure electron nucleon scattering processes. In this section we list a number of desired physics studies or discussion points that we plan to address in the white paper.

- Experimental LDMX capabilities:
  - Study of the LDMX trigger system to record inclusive high pT electron topologies
  - Explore the potential precision with which LDMX can measure neutron final states by simulating and reconstructing neutron signatures
  - Detail the performance of the tracker acceptance and resolution as well as potential for particle ID using dE/dX for pion/proton separation
- Studies of LDMX capability to make precise unfolded cross section measurements such as:
  - Complete inclusive cross sections in electron energy and angle, including radiative corrections
  - Semi-exclusive cross sections with proton and/or charged and neutral pion final states, including cross sections in electron and hadron kinematics.
  - Measurements of composition of hadronic final states
  - Measurements of transverse imbalance
- Experimental/phenomenological neutrino studies:
  - Work with existing neutrino event generators to tune models directly to LDMX data
  - Studies of the differences between electron-nucleus and neutrino-nucleus scattering
  - Incorporate LDMX data to reduce uncertainties on oscillation measurements in DUNE
- Additional nuclear physics measurements, such as pentaquarks, secondary kaon processes, etc.

References

1. Adamson, P. *et al.* First measurement of muon-neutrino disappearance in NOvA. *Phys. Rev.* **D93**, 051104, DOI: 10.1103/PhysRevD.93.051104 (2016). 1601.05037.

2. Adamson, P. *et al.* Measurement of the neutrino mixing angle θ_{23} in NOvA. *Phys. Rev. Lett.* **118**, 151802, DOI: 10.1103/PhysRevLett.118.151802 (2017). 1701.05891.

3. Acero, M. A. *et al.* New constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in the NOvA experiment. *Phys. Rev.* **D98**, 032012, DOI: 10.1103/PhysRevD.98.032012 (2018). 1806.00096.

4. Ankowski, A. M., Coloma, P., Huber, P., Mariani, C. & Vagnoni, E. Missing energy and the measurement of the CP-violating phase in neutrino oscillations. *Phys. Rev.* **D92**, 091301, DOI: 10.1103/PhysRevD.92.091301 (2015). 1507.08561.

5. Aguilar-Arevalo, A. A. *et al.* First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section. *Phys. Rev. D* **81**, 092005, DOI: 10.1103/PhysRevD.81.092005 (2010).

6. Rodrigues, P. A. *et al.* Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer. *Phys. Rev. Lett.* **116**, 071802, DOI: 10.1103/PhysRevLett.121.209902,10.1103/PhysRevLett.116.071802 (2016). Erratum: Phys. Rev. Lett. **121**, 209902 (2018).

7. Patrick, C. E. *et al.* Measurement of the Muon Antineutrino Double-Differential Cross Section for Quasielastic-like Scattering on Hydrocarbon at $E_\nu \sim 3.5$GeV. *Phys. Rev. D* **97**, 052002, DOI: 10.1103/PhysRevD.97.052002 (2018).

8. Gran, R. *et al.* Antineutrino Charged-Current Reactions on Hydrocarbon with Low Momentum Transfer. *Phys. Rev. Lett.* **120**, 221805, DOI: 10.1103/PhysRevLett.120.221805 (2018).

9. Ruterbories, D. *et al.* Measurement of Quasielastic-Like Neutrino Scattering at $\langle E_\nu \rangle \sim 3.5$ GeV on a Hydrocarbon Target. *Phys. Rev. D* **99**, 012004, DOI: 10.1103/PhysRevD.99.012004 (2019).

10. Carneiro, M. F. *et al.* High-Statistics Measurement of Neutrino Quasielastic-Like Scattering at $\langle E_\nu \rangle \sim 6$ GeV on a Hydrocarbon Target. (2019). 1912.09890.

11. Abratenko, P. *et al.* First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at $E_\nu \sim 0.8$ GeV with the MicroBooNE Detector. *Phys. Rev. Lett.* **123**, 131801, DOI: 10.1103/PhysRevLett.123.131801 (2019).

12. Abe, K. *et al.* First Measurement of the Charged Current $\overline{\nu}_\mu$ Double Differential Cross Section on a Water Target without Pions in the final state. (2019). 1908.10249.

13. Abe, K. *et al.* Measurement of inclusive double-differential ν_μ charged-current cross section with improved acceptance in the T2K off-axis near detector. *Phys. Rev. D* **98**, 012004, DOI: 10.1103/PhysRevD.98.012004 (2018).

14. Åkesson, T. *et al.* Light Dark Matter eXperiment (LDMX) (2018). 1808.05219.

15. Ankowski, A. M. *et al.* Lepton-Nucleus Cross Section Measurements for DUNE with the LDMX Detector. *Phys. Rev. D* **101**, 053004, DOI: 10.1103/PhysRevD.101.053004 (2020). 1912.06140.

16. Khachatryan, V. *et al.* CMS Tracking Performance Results from Early LHC Operation. *Eur. Phys. C J.* **70**, 1165–1192, DOI: 10.1140/epjc/s10052-010-1491-3 (2010).

17. Giammanco, A. Particle identification by ionization energy loss in the CMS silicon strip tracker. *Int. J. Mod. Phys. E* **20**, 1646–1650, DOI: 10.1142/S0218301311020022 (2011).