

## Lepton-Nucleus Cross Section Measurements for DUNE with the LDMX Detector

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New electron-nucleus scattering data is necessary to develop accurate models of neutrino-nucleus interactions, which are essential for the DUNE physics program. Designed for multi-GeV electron beam fixed-target kinematics, the LDMX (Light Dark Matter eXperiment) detector concept consists of a small precision tracker, and electromagnetic and hadronic calorimeters, all with near  $2\pi$  azimuthal acceptance from the forward beam axis out to  $\sim 40^\circ$  angle. This detector would be capable of measuring correlations among electrons, pions, protons, and neutrons in electron-nucleus scattering at exactly the energies relevant for DUNE physics. In particular, LDMX is ideally suited for probing inelastic electron-nucleus scattering in DUNE kinematics, which is poorly constrained by existing experimental data. LDMX would provide exclusive final-state cross-section measurements with unmatched acceptance in the  $40^\circ$  forward cone. We compare the predictions of the three widely-used generators (GENIE, GIBUU, GEANT4) in the LDMX region of acceptance to illustrate the large modeling discrepancies in electron-nucleus interactions at DUNE-like kinematics that could be addressed with future LDMX data.

## I. INTRODUCTION

The discovery of neutrino masses and flavor mixing represents a breakthrough in the search for physics beyond the Standard Model. As the field of neutrino physics enters the precision era, accelerator-based neutrino oscillation experiments are taking center stage. This includes NOvA, T2K, and MicroBooNE, which are currently taking data, SBND and ICARUS detectors, which will soon be deployed at Fermilab, and the Deep Underground Neutrino Experiment (DUNE), for which the technical design is being finalized.

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 [1–3], 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  $\delta_{CP}$  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. The latter can occur through the excitation of baryonic resonances, as well as through nonresonant channels. At sufficiently high values of 4-momentum transfer,  $Q^2 = -(p_\nu - p_\mu)^2$ , and en-

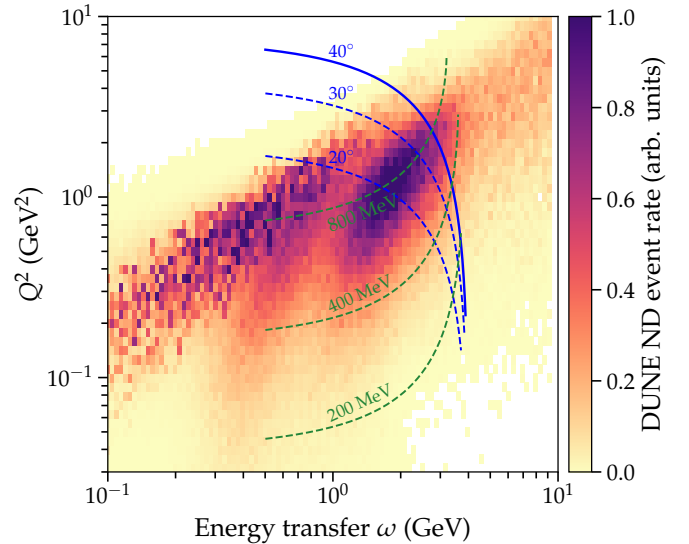


FIG. 1. Simulated event distribution for charged-current muon neutrino scattering on argon in the DUNE near detector, shown as a heat map, compared with the kinematics accessible in *inclusive* and *exclusive* electron scattering measurements at LDMX. Blue lines correspond to constant electron-scattering angles of  $40^\circ$ ,  $30^\circ$ , and  $20^\circ$ . Green lines represent contours of constant transverse electron momenta  $p_T$  of 800, 400, and 200 MeV. As currently envisioned, LDMX can probe the region with  $\theta_e < 40^\circ$  and  $p_T > 10$  MeV (below the scale of the plot).

ergy 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”.

As DUNE uses argon as a target, all this happens inside a large nucleus, adding further complexity. The

presence of the surrounding nucleons means hadrons created at the primary interaction vertex may undergo large final-state interactions (FSI) on their way out. The resulting intra-nuclear cascade can lead to energy loss or absorption of primary hadrons, production of additional hadrons, and nucleon knockout. Initial states of the interacting nucleons are also affected, by nuclear binding and motions inside a nucleus. Last but not least, multi-nucleon effects, such as meson-exchange currents (MEC), which arise from scattering on interacting nucleon pairs, likewise have to be considered.

To model this rich physics, experiments rely on event generator codes, among them GENIE [5, 6] and GIBUU [7–11], which are used as benchmarks in this paper. As we will see explicitly below, these codes are often not in agreement with each other. More importantly, they are often also not in agreement with recent high-statistics data from the MINERvA experiment, collected in the kinematic regime relevant to DUNE. For example, the default models in GENIE seem to significantly overestimate neutron production [12], mis-predict the ratio of charge-current interactions across different nuclear targets [13], and mis-model single-pion production [14]. Thus, there is direct *experimental* evidence that existing models need to be improved.

Importantly, simple phenomenological tuning of parameters within the existing models may not be sufficient. For example, Ref. [14] reports that no tune could describe all different exclusive final states in their analysis. Crucially, the paper also notes that the physical origin of the discrepancies is difficult to pinpoint, based on only the available data.

This brings us to an important question: what new data is needed to improve the physics in these generators? A priori, one might think that all that is needed is more neutrino-nucleus scattering data, with higher statistics and precision, as will be collected with the future near detectors. In reality, while better neutrino data would certainly be desirable, it is unlikely to be sufficient. To-date, neutrino experiments only have access to broadband beams, and neutrino energy reconstruction itself suffers from sizable uncertainties. In turn, the process of energy reconstruction *relies* on neutrino generators. The reason is that even today’s state-of-the-art neutrino detectors are imperfect calorimeters at several GeV energies, with event generators being used to fill in the missing information. 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, as discussed below in Sec. II. What electron scattering offers is precisely controlled kinematics (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 paper, we point out that the proposed LDMX (Light Dark Matter eXperiment) setup at SLAC [15], designed to search for sub-GeV dark matter, will have very advantageous characteristics to also pursue electron-scattering measurements relevant to the neutrino program. 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 reconstruction energy threshold. Figure 1 shows the simulated event distribution for charged-current (CC) scattering of muon neutrinos on the argon nuclei in the near detector of DUNE, presented in the  $(\omega, Q^2)$  plane. As can be immediately seen, the LDMX coverage in the relevant kinematic window is excellent. Below, we explain why this offers an important opportunity to leverage data from the proposed LDMX detector in support of lepton-nucleus cross section measurements.

## II. ELECTRON SCATTERING MEASUREMENTS AND NEUTRINO CROSS SECTIONS

Let us now define the connection between electron- and neutrino-nucleus scattering more precisely. Superficially, the mere existence of such a connection is not obvious, since the weak and electromagnetic forces have a number of important differences. The differences are immediately apparent in the elastic scattering regime: while CC neutrino interactions occur on initial-state neutrons in the nucleus, electromagnetic scattering also involves initial-state protons (neutrons couple through their magnetic moments). The situation is similar in the DIS regime, where the primary vertex is treated at the quark level: while CC neutrino (antineutrino) interactions are controlled by the distribution of initial-state down (up) quarks, electron scattering involves both up and down quarks. Additional differences come from the chiral nature of the weak interactions. While the electron-nucleon vertex is sensitive only to the electric charge distribution inside a nucleon and its magnetic moment, neutrino scattering also depends on the distribution of the axial charge. The effect of this axial coupling is not small; in fact, at 1 GeV neutrino energy, the axial part of the weak interaction provides a dominant contribution to the elastic neutrino-nucleus cross section. In short, one should not expect to blindly convert electron scattering data into predictions for neutrinos.

Yet, a tight connection between electron and neutrino scattering does exist. This is most immediately seen by considering the nuclear physics of the problem. Neutrino scattering depends on the wave functions of the initial nucleons (in momentum space) and on the nuclear density profile, and these are most accurately probed with

electron scattering. The differences between proton and neutron couplings mentioned above might give one pause. However, by systematically analyzing electron data on mirror nuclei, in which neutrons in one nucleus have the same shell structure as protons in another, one can learn about both proton and neutron wave functions [16–18].

The same argument can be made about modeling final-state interactions, which dictate the subsequent evolution of the interaction products inside the nucleus [7, 19, 20]. FSI can significantly modify the properties of the hadronic system, through energy loss of propagating particles, absorption and creation of mesons, as well as nucleon knockout. It is essential to model the intranuclear transport of various hadrons using a unified framework, regardless of whether they were produced in electron or neutrino scattering. The accuracy of the treatment can then be validated by targeted studies of exclusive hadronic final states in electron scattering.

We see here that it is important for the differences between electron and neutrino interactions to be limited to the elementary scattering vertex. This is justified at typical momentum transfer values relevant to DUNE, where scattering involves predominantly a single nucleon. It can be shown that under these conditions nuclear effects become largely independent of the interaction dynamics [21].

The connections between electron and neutrino scattering, in fact, extend beyond nuclear physics models, to include many hadronic physics effects. For example, to model neutrino-quark interactions in the DIS regime, one needs accurate parton distribution functions. These can be extracted from precision electron-scattering data. The physics of the subsequent hadronization can also be treated in a common framework. Finally, it is desirable to use a unified treatment of other physics, such as hadronic resonances, two-nucleon currents, or quark-hadron duality. Of course, in doing so, one needs to include the correct treatment of the nucleon axial properties. Even there, however, comparisons to electron scattering are proving to be highly advantageous. For example, recent lattice QCD studies found it useful to simultaneously model the nucleon axial and vector form factors (e.g., Refs. [22–26]).

The importance of using the same nuclear model for neutrino and electron scattering was realized a long time ago, as illustrated, for instance, by the discussion in the seminal paper by Smith and Moniz [27]. In fact, it was argued in that paper that combining electron and neutrino scattering gives one the best tool for probing the physics of the nucleus. The same argument has also been made more recently from the experimental point of view [28]. It has since been incorporated into the mission statement of the GENIE generator. Insofar as this crucial principle is adhered to in the generator development and applications, electron-scattering data should provide an excellent validation platform.

Let us next outline the requirements from the point of view of neutrino experiments. As stated in the Introduc-

tion, the key to many modern neutrino experiments is accurate neutrino-energy reconstruction. Experiments such as NOvA and DUNE approach this problem by using the calorimetric technique, which involves adding up visible energies of all final-state particles and inferring invisible components, such as neutrons and low-energy charged hadrons, using event-generator predictions. Event generators are also used to model the composition of the final-state hadronic system, whenever that information is unavailable from the particle-identification algorithms. Knowledge of the final-state composition is needed to convert measured ionization charge, or scintillation light, to true energy loss. This is not a small effect, and existing differences among generator models consistent with available validation data can yield energy reconstruction variations as large as 20%, which has been discussed systematically in Ref. [29], together with other factors impacting the energy resolution.

Thus, to adequately constrain the underlying generator models, one needs to measure not only inclusive electron-scattering rates, but also various exclusive hadronic final states, paying attention both to the energies and multiplicities of various hadrons, as a function of  $Q^2$  and  $\omega$ . This includes charged pions, neutral pions, and protons, as well as any available information on final-state neutrons. Practically, one needs to simultaneously measure the kinematics of an energetic, often-forward electron, as well as detect charged hadrons to below 100–200 MeV momenta (see e.g. Ref. [30]) with wide and well-characterized angular acceptance.

Discrepancies between scattering data and generator predictions can indicate problems either with the nuclear model or with hadronic physics [31, 32]. Having information on exclusive hadronic final states can help diagnose the origin of the problem. To conclusively disentangle nuclear and hadronic effects may require comparative analyses of electron scattering data on various nuclear targets, including the lightest elements—helium, deuterium, and hydrogen. That such targets can be quite small in the case of electron scattering represents another tangible advantage over neutrino scattering, where concerns about fire safety make future hydrogen bubble-chamber experiments prohibitively costly.

To this end, a systematic analysis of the data collected on various nuclear targets by different experiments using the CLAS detector in Hall B at Jefferson Laboratory, while not completely addressing the requirements outlined above, would be an important advance. So far, the published studies focused on specific hadronic processes with hydrogen targets [33–40]. These should already be useful for testing generator models for certain hadronic processes, such as  $\rho$  meson production through higher resonances. The CLAS12 proposal “Electrons for Neutrinos” would make further inroads by collecting more data [41, 42]. At present, published datasets involving argon and its mirror nucleus titanium come from a separate experiment in Hall A [18, 43, 44]. While undoubtedly valuable [45–49]—for example, enabling com-

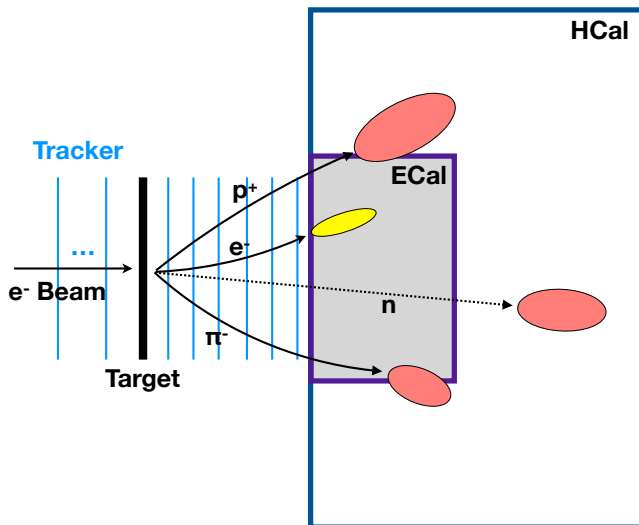


FIG. 2. Schematic of the LDMX experiment for dark matter search (not to scale). The electron beam is incident from the left and interacts in the target (which can be varied). Direct tracking and calorimetry along the beam axis provides excellent (nearly  $2\pi$  azimuthal) forward acceptance to a range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

parisons with the well-studied carbon data [31]—they are limited to the inclusive spectrum of scattered electrons measured at a single value of the beam energy (2.22 GeV) and a fixed scattering angle ( $15.54^\circ$ ).

At the moment, and over the next several years, electronuclear scattering data with excellent hadronic final-state reconstruction is sorely needed. The ideal would be reconstruction with no detection threshold, full  $4\pi$  coverage, and with excellent neutron identification. While CLAS12 can make some inroads in this direction, acceptance will be limited (especially in the forward direction), neutron energy reconstruction will be modest, and reconstruction energy thresholds of 100 MeV or more will be typical. The proposed LDMX detector concept offers a number of complementary and unique advantages that can be leveraged to provide a range of valuable electron-nucleus scattering data for the purpose of constraining neutrino-scattering models.

### III. THE LDMX DETECTOR CONCEPT AND ELECTRON-NUCLEAR SCATTERING DATA

LDMX (Light Dark Matter eXperiment) is a fixed-target experiment designed to search for sub-GeV dark matter, employing a high-repetition-rate, low-current electron beam [15] with precision tracking (in a magnetic field) and calorimetry along the beam axis to provide extremely high fidelity detection of both charged and neutral particles. Figure 2 provides a high-level illustration

of the detector layout, which is largely optimized to search for dark matter production. In candidate events for dark-matter production, most of the initial electron's energy is expected to be carried away by undetected particle(s). Therefore, identification of these processes requires an excellent hermeticity of the detector, allowing, e.g., energetic neutron-knockout events to be detected with sufficiently small uncertainty.

In fact, the primary purpose of the downstream calorimetry in LDMX is to provide a fast, radiation hard, and highly granular veto against photo-nuclear and electro-nuclear reactions in the target area that might generate difficult-to-detect final states, and hence a potential background to dark matter reactions. In the nominal design, the vast majority of triggered data would be comprised of these photo/electro-nuclear reactions, and rejected offline. The key result of this paper is that this vetoed data will itself be of great value in service of neutrino-interaction modeling, as was described above.

To see why this is the case, we start with a more detailed description of the detector layout. The tracking system upstream of the target and the target itself are housed inside of a 1.5 T dipole magnet while the downstream (recoil) tracker is in the fringe magnetic field. The target is currently envisioned to be titanium, and we assume it to be  $0.1 X_0$  (0.356 cm) thick,  $X_0$  being the radiation length. However, different target materials (such as liquid argon) and thicknesses are possible, as discussed further in Sec. VII. The two tracking systems provide robust measurements of incoming and outgoing electron momentum. The ECal (Electromagnetic Calorimeter) is surrounded by the HCal (Hadronic Calorimeter) to provide large angular coverage downstream of the target area, in order to efficiently detect interactions products. The ECal is a silicon-tungsten high-granularity sampling calorimeter based on a similar detector developed for the high-luminosity Large Hadron Collider upgrade of the endcap calorimeter of the Compact Muon Solenoid (CMS) detector. The ECal is radiation tolerant with fast readout, and the high-granularity provides good energy resolution and shower discrimination for electromagnetic and hadronic interactions. The HCal is a scintillator-steel sampling calorimeter that has wide angular coverage and is very deep, in order to provide excellent efficiency for detecting minimum ionizing particles and neutral hadrons.

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 [15]:

- **Electrons:** We estimate the electron energy resolution to be 5–10% and the  $p_T$  resolution to be  $< 10$  MeV [15], where  $p_T$  is the transverse momentum of the outgoing electron. The tracker acceptance is approximately  $40^\circ$  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.

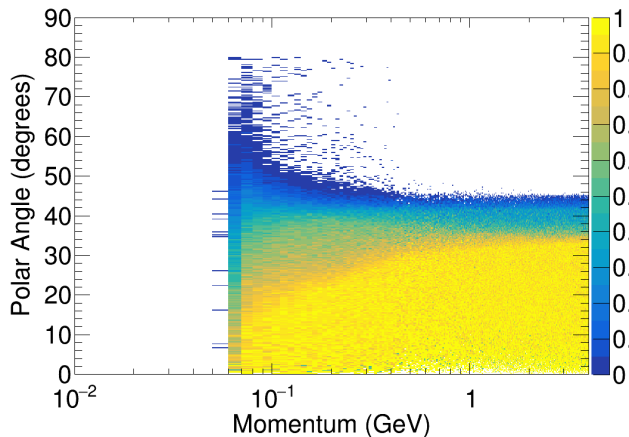


FIG. 3. The acceptance of a charged particle (pion) track as a function of its momentum and polar angle. The acceptance is defined as a charged particle that leaves 4 hits in the recoil tracking system.

- **Charged pions and protons:** The energy and  $p_T$  resolutions, tracking acceptance, and kinetic thresholds are similar for charged pions, protons, and electrons. The estimate of tracking angular and energy acceptance is shown in Fig. 3. 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 [50, 51], the recoil tracker by itself has good pion/proton discrimination power for kinetic energies  $< 1.5$  GeV.
- **Neutrons:** Based on GEANT4 simulations for the baseline HCal sampling fraction, we estimate the HCal to have an energy resolution of  $5\% \oplus 40\%/\sqrt{E/\text{GeV}}$  and a polar angular acceptance of  $65^\circ$ . However, because we have tracking acceptance out to  $\sim 40^\circ$ , our studies assume that we have good pion/proton/neutron discrimination out to only  $\sim 40^\circ$  [15]. We leave it to future studies to understand additional separation power between 40 and  $65^\circ$ .
- **Readout rate:** The total data acquisition (DAQ) rate of the detector is approximately 5 kHz. A significant fraction of the DAQ bandwidth targets high energy-transfer reactions. Thus, for this study, we focus on electron energy transfer  $\omega > 1$  GeV. This energy-transfer threshold is still below the nominal threshold for the dark-matter search, but could be achieved by prescaling the trigger or by using a combination of ECal and HCal online selections. Even smaller values of  $\omega$  may be possible, but we leave such studies to future work.

For the studies described below, we assume a 4 GeV incoming electron beam and a dataset of  $1 \times 10^{14}$  EoT

(electrons on target), corresponding to approximately 6 months of data collecting during an envisioned first phase of low-luminosity running. The beam repetition rate is assumed to be 46 MHz and the beam is tuned to have on average 1 electron per bucket.

With the beam and detector configurations described above, we will next explore the potential for LDMX to perform measurements of both inclusive (Sec. V) and exclusive (Sec. VI) electron-nucleus scattering processes.

#### IV. MONTE CARLO GENERATORS

We study the modeling of electron-titanium interactions using the Monte Carlo generators GENIE (versions 2.12.8 and 3.0.6) [5, 6] and GiBUU (versions 2017 and 2019) [7, 11]. As both GENIE and GiBUU had major updates, we show results obtained using both the versions before and after these changes. In the context of the inclusive cross sections, we also present the results obtained using GEANT4 (version 4.10.p3) [52], for reference.

GENIE [5, 6] is the generator most widely used in neutrino experiments and the default code employed in DUNE studies. In this analysis, we use its default configurations (“DefaultPlusMECWithNC” for version 2.12 and “EMPlusMEC.G18.02a.00.000” for version 3.0). Nuclear effects are described in GENIE within the global relativistic Fermi gas model of Bodek and Ritchie [53]. This approach treats the nucleus as a fragment of noninteracting nuclear matter of constant density, bound in a constant potential. The effect of short-range correlations between nucleons is added in an *ad hoc* manner, by extending the step-function momentum distribution above the Fermi momentum,  $p_F \simeq 240$ –250 MeV, with a high-momentum tail. The binding energy is taken to be independent of momentum, and fixed to a value  $\sim 30$  MeV. As a consequence, nucleons in the high-momentum tail of the Bodek–Ritchie model are typically unbound.

Pion production through excitation of nucleon resonances is described in GENIE 2.12 using the framework of the Rein–Sehgal model [54]. While the original work included 18 resonances and accounted for interference between them, its implementation in GENIE disregards the effect of interference, and is limited to 16 resonances, which are described using up-to-date parameters. In GENIE 3.0 the default model for resonance excitation is the approach of Berger and Sehgal [55].

All mechanisms of pion production on nucleons that do not involve resonance excitation are referred to in GENIE as DIS processes. They are modeled following the effective approach of Bodek and Yang [56, 57]. Relying on leading-order parton-distribution functions [58], this model applies higher-order corrections to the effective masses of the target and the final state, in order to extend the applicability of the parton model to the low- $Q^2$  region. While DIS is the only mechanism of interaction in GENIE for the invariant hadronic masses  $W \geq 1.7$  GeV, it is also employed to produce nonresonant background of



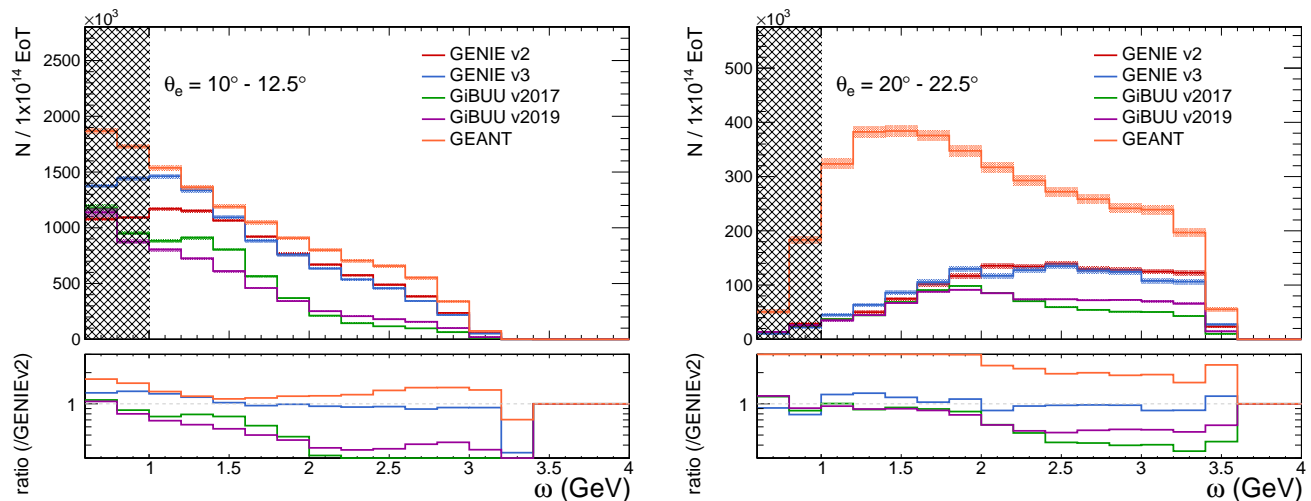


FIG. 4. Event distribution as a function of electron energy transfer for the scattering angles of  $10^\circ \leq \theta_e \leq 12.5^\circ$  (left panel) and  $20^\circ \leq \theta_e \leq 22.5^\circ$  (right panel). Our nominal analyses only consider events that pass our trigger selection,  $\omega \geq 1$  GeV.

events involving one or two pions in the resonance region, corresponding to  $W < 1.7$  GeV.

GiBUU [7, 11] is a Monte Carlo code based on the transport theory, originally developed to describe heavy ion collisions. Its nuclear model accounts for the nuclear density profile determined in electron scattering according to Ref. [59], treating the nucleus as a local relativistic Fermi gas, bound by a potential exhibiting momentum dependence [46].

Implementation of both resonance-excitation processes and single-pion nonresonant background in GiBUU makes use of the MAID analysis [60], including 13 resonances of the invariant mass  $W \leq 2.0$  GeV and accounting for the interference between them, as well as for the interference between the resonant and nonresonant contributions. The two-pion background is estimated by generalizing the model [61] for photoproduction, by assuming the dependence on the transverse polarization of the photon and  $Q^2$  deduced from the total cross section [62].

To describe DIS processes, GiBUU relies on a modification of the PYTHIA code [63], extending its applicability down to the invariant hadronic mass 2.0 GeV. In this manner, leading order processes are implemented in the primary interaction vertex.

GEANT4 simulations describe electron-nucleus interactions using the equivalent-photon approximation, relying on the Bertini cascade model [64] with improvements discussed in Ref. [15]. Here GEANT4 results are presented for comparison with those obtained using other generators.

In order to eliminate trivial differences between the considered Monte Carlo generators, we apply the kinematic selection  $Q^2 > 0.03$  GeV<sup>2</sup>, needed to define a phase space where all the generators are physically valid [65]. This selection has no visible effect on the presented cross sections, as it removes only the tails of the distributions

corresponding to the highest values of the energy transfer, where the cross section is negligible.

## V. INCLUSIVE MEASUREMENTS

In the baseline detector configuration, we study the potential for LDMX to make measurements of electron-nucleus processes, the results of which can be used to improve Monte Carlo generators. In this section, we focus on the simplest inclusive measurements LDMX can perform, namely, on the distribution of the scattered electrons on the  $(\theta_e, \omega)$  plane,  $\theta_e$  and  $\omega$  being the scattering angle and the energy transferred to the nucleus, respectively. Until Sec. VI, we do not consider any information on the composition or kinematics of the final-state hadrons. Here we argue that LDMX will complement the existing knowledge of the inclusive cross sections from the very forward direction to larger scattering angles by providing results for large energy transfers, where they are not available yet [66], see Appendix A.

Our analysis is focused on the fiducial region of the scattered electron's phase space defined by  $\omega > 1$  GeV and  $p_T > 0.2$  GeV. The first selection is synergistic to the LDMX dark-matter phase space, while the second highlights a region of typical DUNE kinematics. Before performing these kinematic selections, we apply parametric angular and momentum/energy smearing of electrons, charged hadrons, and neutral hadrons, according to the expected detector resolutions described above. We also apply angular acceptance criteria according to the detector acceptance described in Sec. III. Efficiency effects due to detector reconstruction identification algorithms are *not* applied and require further study. However, we expect them to be very uniform, well measured, and near unity.

Figure 4 illustrates the distribution of energy transferred by electron to the nucleus for two different selections on its scattering angle  $\theta_e$ , following the common kinematic selections and energy smearing described above. In this energy range, all kinematic features in the simulation are broader than the energy resolution. The presented results correspond to the expected number of events for  $1 \times 10^{14}$  EoT. In the figure, the bands represent statistical uncertainties of the generated Monte Carlo event samples; experimental statistical uncertainties are much smaller than the indicated bands.

The event distributions obtained using the three generators differ sizably both in the overall rate and in shape. While at 4 GeV, GiBUU and GENIE predict a consistent value of the total  $e$ -Ti cross section (integrated over all scattering angles, with the  $Q^2 > 0.03$  GeV<sup>2</sup> cut),  $1.9 \times 10^{-28}$  cm<sup>2</sup>, they yield different angular distributions. Exhibiting stronger angular dependence, GiBUU predicts fewer events at large scattering angles than expected according to GENIE.

This behavior is shown in Fig. 4. In the left panel, corresponding to scattering angles  $10^\circ \leq \theta_e \leq 12.5^\circ$ , the prediction of GiBUU is smaller by 30% than that of GENIE. In the right panel, for scattering angles  $20^\circ \leq \theta_e \leq 22.5^\circ$ , this difference increases to 50%. While the GENIE cross section is dominated by the DIS channel, this is not the case for the GiBUU results, in which resonance excitation is the main mechanism of interaction for energy transfers below 2 GeV, and DIS dominates only at  $\omega > 2$  GeV. The largest discrepancies occur at higher energy transfers ( $\omega \gtrsim 2$  GeV,  $W^2 \gtrsim 4.4$  GeV<sup>2</sup>), where events are predominately populated by DIS. Notably, there are visible differences between the results obtained using different versions of the generators GiBUU and GENIE. Nevertheless, they are much less significant than the differences between the predictions of different generators.

In the  $20^\circ \leq \theta_e \leq 22.5^\circ$  slice, both the GiBUU and GENIE cross sections result entirely from DIS interactions, and agree at a factor of 2 level. GEANT4, however, deviates significantly from GENIE and GiBUU, and the deviation is even larger at higher scattering angles. This is expected as GEANT4 uses the equivalent photon approximation to simulate electron-nucleus interactions. At higher  $Q^2$ , the exchanged photon becomes highly virtual and this approximation is not valid. Because of this issue, we do not show GEANT4 predictions in later comparisons. Comparably large disagreements across generators are seen in all angular bins, as illustrated in Appendix B.

It is important to stress that electron scattering is crucial for exploring these differences between generators, as present-day neutrino data may not have the necessary discriminating power. For example, consider pion production induced by charged-current neutrino interactions in the MINERvA experiment, at the kinematics similar to that of DUNE. The shape of the single differential  $d\sigma/dQ^2$  cross sections from Ref. [67] is reproduced reasonably well by both GENIE [67] and GiBUU [9]. We see that large differences present in double-differential cross

sections can be obscured in more inclusive quantities. We can further confirm this upon calculating the cross sections for electron scattering integrated over all scattering angles (imposing the same  $Q^2 > 0.03$  GeV<sup>2</sup> cut as before). Using a 4 GeV beam energy, we find a good agreement between GENIE and GiBUU. We conclude that the double differential cross sections, which can be efficiently explored with electron scattering, provide much more detailed insight into the nuclear and hadronic physics underlying interaction dynamics. This insight is required for accurate neutrino energy reconstruction.

LDMX will measure inclusive electron-nucleus scattering rates for energy transfers  $1 \lesssim \omega \lesssim 4$  GeV and scattering angles  $5^\circ \lesssim \theta_e \lesssim 40^\circ$ . With expected  $> 10^5$  events per bin, the experimental statistical errors will be at sub-percent-level. Instrumental systematic uncertainties are difficult to assess precisely prior to data-taking, but the scales of many effects can be estimated by comparison to detailed performance studies of other similar collider and fixed-target experiments. LDMX's luminosity can be precisely measured by counting incident electrons in the tagging tracker and measuring the target thickness. Electron-reconstruction performance can be quantified precisely using standard candle reactions, such as Møller scattering. Efficiency uncertainties should be smaller and more uniform than the  $\sim 4\%$  level achieved by the less hermetic CLAS detector (see e.g. Ref. [40]). Momentum resolution uncertainties should be comparable to the  $\sim 3\%$  achieved at HPS [68], which has a similar detector geometry and beam. Such resolution would lead to negligible systematic effects on the distributions in Fig. 4, which vary over much larger energy scales.

Based on these considerations, both statistical and systematic uncertainties are expected to be small, compared with the current theoretical uncertainties. These features will enable LDMX to discern between GiBUU, GENIE, and GEANT4 predictions with high precision, and to perform measurements of the inclusive cross sections for electron scattering on nuclear targets, such as titanium, over a broad kinematics, previously unexplored. Availability of such results is essential for future development and tuning of Monte Carlo generators employed in the long-baseline neutrino-oscillation program.

## VI. EXCLUSIVE MEASUREMENTS

As explained in Sec. II, Monte Carlo generators play a fundamental role in neutrino energy reconstruction, relating the visible energy—deposited in the detector by the observed particles—with the actual neutrino energy. In order to do so, the contribution of undetected energy—carried away by undetected particles, absorbed in nuclear breakups, etc. [29]—is estimated based on the measured event composition and kinematics. The accuracy of the energy reconstruction relies on the accuracy of the particle multiplicities and spectra predicted by the Monte Carlo simulation. Therefore, availability of precise infor-

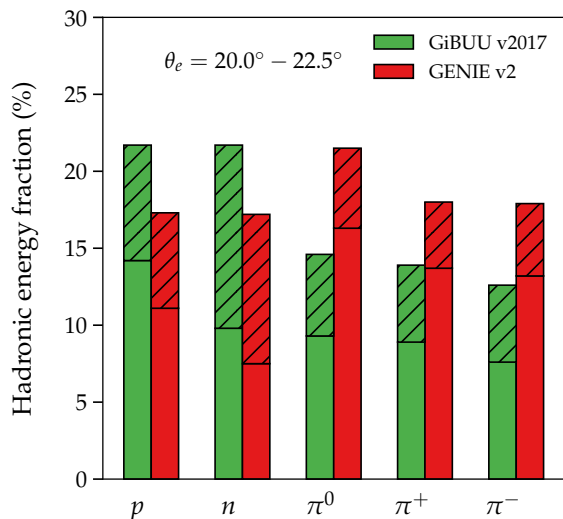


FIG. 5. Energy fractions carried by various hadrons in the final state in events with  $\omega > 1$  GeV, according to GiBUU and GENIE. The shaded regions illustrate the fractions outside of LDMX acceptance: below detection thresholds or outside the  $40^\circ$  cone. Different compositions of the final hadronic system result from different physics underlying generators.

mation on the hadronic final states is essential to validate the models underlying the generators and to estimate their contribution to the systematic uncertainty of energy reconstruction.

Here, we present spectra obtained for coincidence measurements in LDMX of electrons, pions (with particle ID), and neutrons. We argue that thanks to the angular coverage of LDMX, the measurements can be performed with high efficiency across a broad range of energy and angle.

As an example, in Fig. 5 we show the energy fraction that goes into different hadronic particles when the electron scattering angle is between  $20^\circ$  and  $22.5^\circ$  and the energy transfer exceeds 1 GeV (corresponding to the right panel of Fig. 4). The shaded areas in Fig. 5 illustrate the energy fractions that are outside LDMX acceptance, predominantly due to the angular coverage. We observe that most of the final-state particles are within LDMX acceptance. The neutron acceptance is slightly lower also due to the high threshold, the kinetic energy of 500 MeV. Even then, LDMX can detect  $\sim 50\%$  neutrons.

The hadronic energy fractions predicted by a generator depend on the interaction channel dominating its total cross section. While nucleons in the final-state carry more energy in the resonance-excitation channel than in DIS, for pions this situation is reversed. Yielding a larger resonance contribution to the total cross section than GENIE, GiBUU predicts  $\sim 40\%$  less energy carried by electromagnetic showers initiated by neutral pions, and more energy carried by neutrons. The latter issue is of partic-

ular importance because neutrons are particularly difficult to measure in neutrino detectors. If left unresolved, such large discrepancies would result in large uncertainties on the inferred neutrino energy [29]. By measuring these hadronic energy fractions within its geometric acceptance, LDMX will provide a good handle on the relative rate of neutron emission.

More specifically, the capability of LDMX to measure in coincidence the kinematics of the scattered electron and of the hadronic interaction products is illustrated by the distributions shown in Figs. 6 and 7.

Figure 6 presents the pion kinetic energy distributions expected in LDMX when the corresponding electron kinematics is selected in a similar manner as in the previous section:  $\omega > 1$  GeV,  $p_T > 200$  MeV, and  $20^\circ \leq \theta_e \leq 22.5^\circ$ . We expect approximately  $1 \times 10^8$  electrons with that particular kinematic selection for  $1 \times 10^{14}$  electrons incident on the target. After accounting for the acceptance and energy resolution of the tracker, LDMX can measure the charged-pion kinetic energy down to  $\sim 60$  MeV. We present the distribution up to 1 GeV, where LDMX is expected to have good pion/proton discrimination.

The distributions in Fig. 6 are normalized per electron meeting the selection criteria, in order to remove the generator differences for inclusive electron scattering discussed in Sec. V. We see that GENIE predicts more pions, about a factor of 2 more in the forward region, while GiBUU yields a slightly harder pion spectrum.

Similarly to the electron case, the pion energy resolution is sufficiently small that its effect is invisible in the figure, and features in pion spectra predicted by generators, e.g., the peak towards lowest pion energies due to final-state interactions, are preserved. We also observe a sensitivity to the difference between the pion spectra for  $0^\circ \leq \theta_\pi \leq 20^\circ$  and for  $20^\circ \leq \theta_\pi \leq 40^\circ$ , illustrating the advantage of having fine-grained tracking detector for all charged particles.

In Fig. 7, the angular distributions of all neutrons in an event within the acceptance of the tracker and calorimeter and with (smeared) kinetic energies greater than 500 MeV are shown. Again, this is with the same selection on the electron as in the pion result. The distributions show large overall rate differences between the generators, but even within the shape of the distributions, there are differences at the 30–40% level.

From the representative distributions we have shown for the electron and hadron kinematics, it is clear that there are large deviations in the predictions of electron-nucleus interactions from various state-of-the-art generators. LDMX will provide good measurements of these correlated, multi-body final states. Figures 6 and 7 show the pion kinematic energies and neutron angular distributions *per incoming electron within a narrow angular slice*, but as is noted above, we expect approximately  $1 \times 10^8$  electrons with that kinematic selection. Therefore, the per-bin statistical uncertainties on these measurements will be at the percent level or smaller.



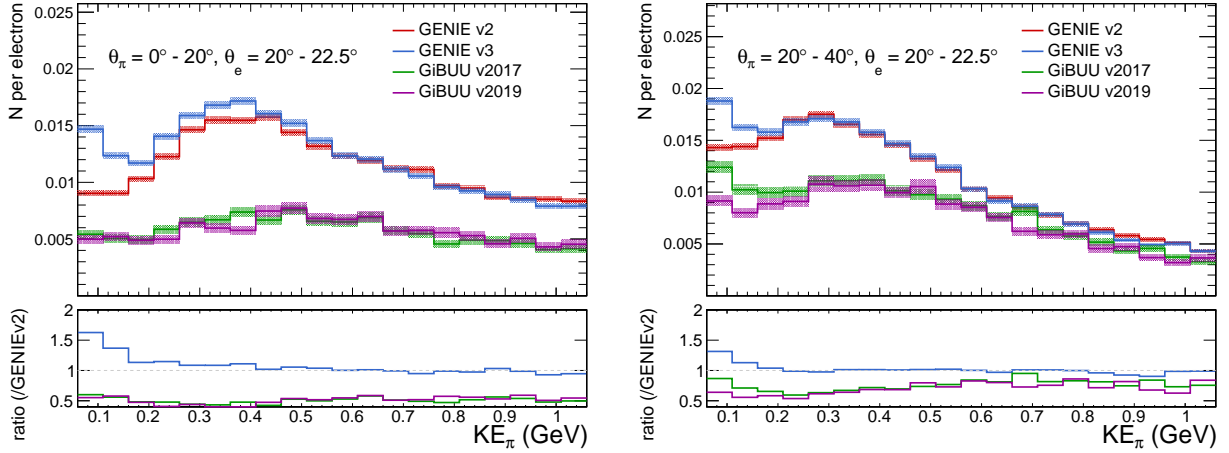


FIG. 6. Charged pion kinetic energy distribution after energy/angular resolution smearing with a scattering angle of  $0^\circ \leq \theta_\pi \leq 20^\circ$  (left panel) and  $20^\circ \leq \theta_\pi \leq 40^\circ$  (right panel). There is an additional selection on the recoiling electron of  $\omega > 1$  GeV,  $p_T > 200$  MeV, and  $20^\circ \leq \theta_e \leq 22.5^\circ$ . The pion distributions are presented *per electron* within the above electron kinematic selection. There are approximately  $1 \times 10^8$  electrons passing the  $\omega$ ,  $p_T$ , and  $\theta_e$  selections for  $1 \times 10^{14}$  electrons on target.

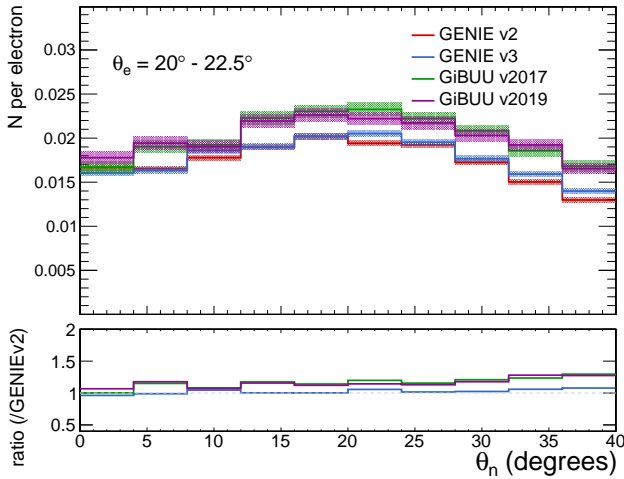


FIG. 7. Neutron polar angle distribution after energy/angular resolution smearing. There is an additional selection on the recoiling electron of  $\omega > 1$  GeV,  $p_T > 200$  MeV, and  $20^\circ \leq \theta_e \leq 22.5^\circ$ . The neutron distributions are presented *per electron* within the above electron kinematic selection. There are approximately  $1 \times 10^8$  electrons passing the  $\omega$ ,  $p_T$ , and  $\theta_e$  selections for  $1 \times 10^{14}$  electrons on target.

The systematic uncertainties discussed in the context of inclusive measurements translate directly to the case of exclusive measurements. The main new systematic in this case is the efficiency and cross-contamination of hadron particle identification using  $dE/dx$ . For 1 GeV and below, the rate of cross-contamination for charged pions and protons is likely to be similar to the several percent-level observed at CMS [50, 51]; this sets the scale

for a conservative estimate of the systematic uncertainties as well. Contamination from kaons, due to their much lower absolute rate, is expected to be even less than from protons and pions. For neutron identification, the detector technology chosen, scintillator-based sampling calorimetry, is quite mature. While the readout technology and geometry is different, the CMS experiment measures neutral hadrons down to the GeV-scale and the uncertainties on energy measurements are at the  $\sim 10$ – $20\%$  level [69].

To summarize, similarly to the inclusive case, the expected statistical and systematic errors will be sufficiently small to enable precise measurements of exclusive electron-nucleus cross sections, by detecting final-state hadrons in coincidence with scattered electron. This data will be vital to understanding neutrino-nucleus interactions and event reconstruction at DUNE. Furthermore, it is important to note that there is very little existing data for exclusive measurements of neutron knockout induced by electron-nucleus scattering, and thus, any such measurements will be important to constrain Monte Carlo models.

## VII. FUTURE POTENTIAL

In the baseline dark-matter configuration and nominal running, LDMX can be expected to perform valuable measurements of both inclusive and exclusive electron scattering on nuclear targets of interest for DUNE. Here we enumerate potential ways, some more challenging to realize than others, to extend the physics program beyond the nominal one:

- The nominal physics selections can be extended

to smaller energy transfers to fully cover the regions in which resonance-production and meson-exchange currents provide important contributions to the cross section. However, there are challenges with triggering on this topology (prescaling is a possibility) and eventually also issues of detector resolution. More study is left for future work to understand the impact of such measurements.

- In this analysis we assume a 4-GeV electron beam, but there is potential for extending measurements to higher energies. In particular, an 8-GeV electron beam from LCLS-II will move the LDMX acceptance contours to the right in Fig. 1. This would allow to cover more of the DIS phase space with relatively little change in the detector configuration.
- Varying the target material would provide more data for nuclear modeling, allowing for deeper understanding of the cross-sections' dependence on the atomic number. While a dedicated study is necessary to make a conclusive statement, it may be possible to employ a gaseous argon target, which would directly address the needs of the neutrino community. Measurements for helium, deuterium, and hydrogen are also of great importance, as they would provide a handle on the effect of nuclear transparency on the exclusive cross sections and cleanly separate hadronic and nuclear effects. A scintillator target could also be considered. As in these cases there is some potential conflict with the dark-matter program, they may require dedicated beam time.
- In order to improve energy acceptance for low-energy charged particles, the dipole magnetic field can be reduced. The effect of a reduced magnetic field on the reconstruction of higher-energy particles is left to study in future work.
- Although all the generator differences discussed here are manifest (at least in part) in the forward region, it would be ideal to simultaneously constrain the hadronic energy covering also wider angles. At a distribution level, this could be achieved by the combination of LDMX data and e4nu CLAS data. It is also possible to install a wide-angle detector in front of LDMX, to record both types of information at an event-by-event level.
- Additional detector systems such as improved silicon tracking or high-angle scintillating detectors could improve the angular acceptance of LDMX for electron-nucleus measurements. Their benefits and potential costs, including the effect on the dark-matter program, will require further study.

## VIII. SUMMARY AND CONCLUSIONS

Modern neutrino experiments depend on the ability of event generator codes to accurately model scattering of neutrinos of several-GeV energies on nuclear targets. This includes predicting both inclusive cross sections and the properties of the final-state hadronic system. This is a very challenging problem, as both non-perturbative hadronic and nuclear effects operate in this energy range and must be simultaneously accounted for. No *ab initio* treatment encompassing all this physics is presently available. The task of building a reliable event generator is thus an art as much as a science, combining a number of models in ways that fairly reflect the underlying physics and pass a battery of experimental tests.

Given this state of affairs, direct data comparisons are absolutely essential for validating and improving today's generators. In such comparisons, electron scattering experiments have a very important role to play. They complement what might be learned from neutrino detectors in several important ways, among which are high event rates and precisely known kinematics. This point has been recognized in the neutrino community [28] and modern event generators are built to model neutrino-nucleus and electron-nucleus interactions using common physics frameworks.

There exists another reason why electron-scattering experiments are of interest to modern particle physics: they offer a laboratory for testing theoretical ideas about dark sectors. The LDMX experiment, in particular, has been conceived for just such a purpose and its design has been optimized for searching for sub-GeV dark matter with unprecedented reach. It turns out, as we argue in this paper, that the two seemingly unrelated tasks are in reality highly synergistic and LDMX will provide invaluable data on electron-nucleus scattering processes that can be very helpful for the neutrino-oscillation program. With a 4-GeV electron beam, LDMX would be able to probe a region of DUNE's scattering phase space where the event density is high (cf. Fig. 10 in Appendix C), the theoretical description is challenging, and the existing data coverage is very limited (cf. Fig. 8 in Appendix A).

To quantify this statement, we compared predictions of GENIE and GiBUU, two of the leading event generators on the market. We argued that both statistical and systematic errors achievable at LDMX are expected to be significantly smaller than the differences between the predictions of these generators (cf. Fig. 9 in Appendix B). This applies not only to inclusive cross sections, but also to measurements of specific hadronic final states. In fact, LDMX will be able to perform high-resolution studies of spectra and angular distributions for a variety of interaction products—making use of its capability of measuring electrons, photons, neutrons, pions, and protons—over a large geometrical acceptance with high efficiency. These measurements will improve our understanding of hadronic physics in the theoretically challenging region of transition from resonance excitations

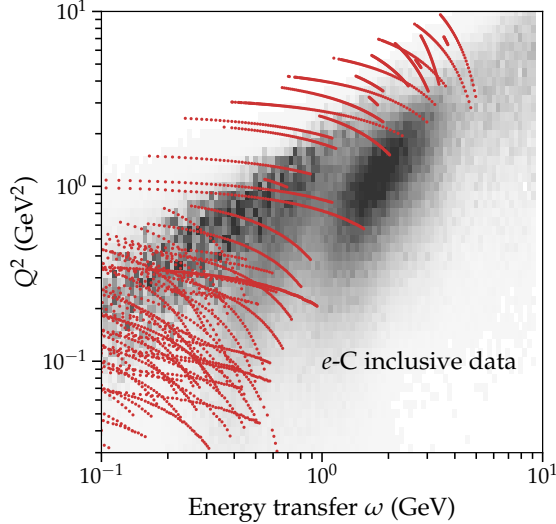


FIG. 8. Existing data for inclusive electron scattering on carbon [44, 70–81], overlaid on the simulated distribution of charged-current  $\nu_\mu$  events in the DUNE near detector.

to deep-inelastic scattering. Moreover, LDMX has also good acceptance and resolution of neutrons, which are a crucial source of missing energy in neutrino detectors. LDMX can thus serve as an important tool in constraining the neutrino-nucleus cross-section uncertainties that plague the neutrino-oscillation program.

For all of these reasons, we strongly encourage the LDMX Collaboration to pursue detailed modeling studies of the scattering processes outlined in this paper and to include the corresponding measurements in future data taking.

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## Appendix A: Current data coverage

The most extensive data coverage for inclusive electron scattering is currently available for the carbon nucleus [66]. Figure 8 shows the inclusive  $(\omega, Q^2)$  kinematic parameters covered by these data, compiled from Refs. [44, 70–81]. The grey-scale heat map in the background represents the expected event distribution in the DUNE near detector, reproduced from Fig. 1. Each colored curve represents a single data set, taken at a fixed electron-beam energy and scattering angle.

Figure 8 demonstrates that—even at the inclusive level and for carbon—there is poor data coverage where the DUNE event density is the highest. As we will see below, in Fig. 10, much of this region is dominated by resonance-excitation and DIS processes, where hadronic physics is highly complex. For improving generator models, it is essential to have not only inclusive cross sections, but also exclusive measurements that record multiple final-state hadrons. Such measurements are at present not available.

Lastly, it is important to note that, even in the context of the inclusive cross section, the phase space is three-dimensional,  $(\omega, Q^2, \theta_e)$ . Therefore, it is highly desirable to perform measurements of the cross section for different scattering angles  $\theta_e$  and beam energies.

## Appendix B: Inclusive electron distributions

Figure 9 presents simulations of the inclusive  $e$ -Ti cross section for additional scattering angles  $\theta_e$ , extending the results of Fig. 4. We see that there is general disagreement between GENIE and GiBUU predictions, at all values of  $\theta_e$ .

## Appendix C: DUNE event distributions

In Fig. 10, we break down the DUNE event sample simulated with GiBUU according to the individual channels modeled by the generator: quasielastic (QE), meson-exchange current (MEC), resonance production (RES), and deep-inelastic scattering (DIS). The color scale is consistent in all four panels, i.e., the same color indicates the same event density. The blue and green lines show constant values of electron scattering angles  $\theta_e$  and transverse momenta  $p_T$ .

When  $Q^2 \simeq 2M\omega$ ,  $M$  being the nucleon mass, the main mechanism of interaction is quasielastic scattering,  $\nu_\mu + n \rightarrow \mu^- + p$ , on individual nucleons inside the nucleus. Accordingly, we see a linear shape in the top left panel in Fig. 10. At  $Q^2 \simeq 2M\omega + M_{\text{res}}^2 - M^2$ , the energy transferred to the struck nucleon is sufficient to excite a baryon resonance state  $B_{\text{res}}$  with mass  $M_{\text{res}}$ , i.e.,  $\nu_\mu + n \rightarrow \mu^- + B_{\text{res}}$ . When the energy transfer increases further, production of higher hadronic resonances gradu-

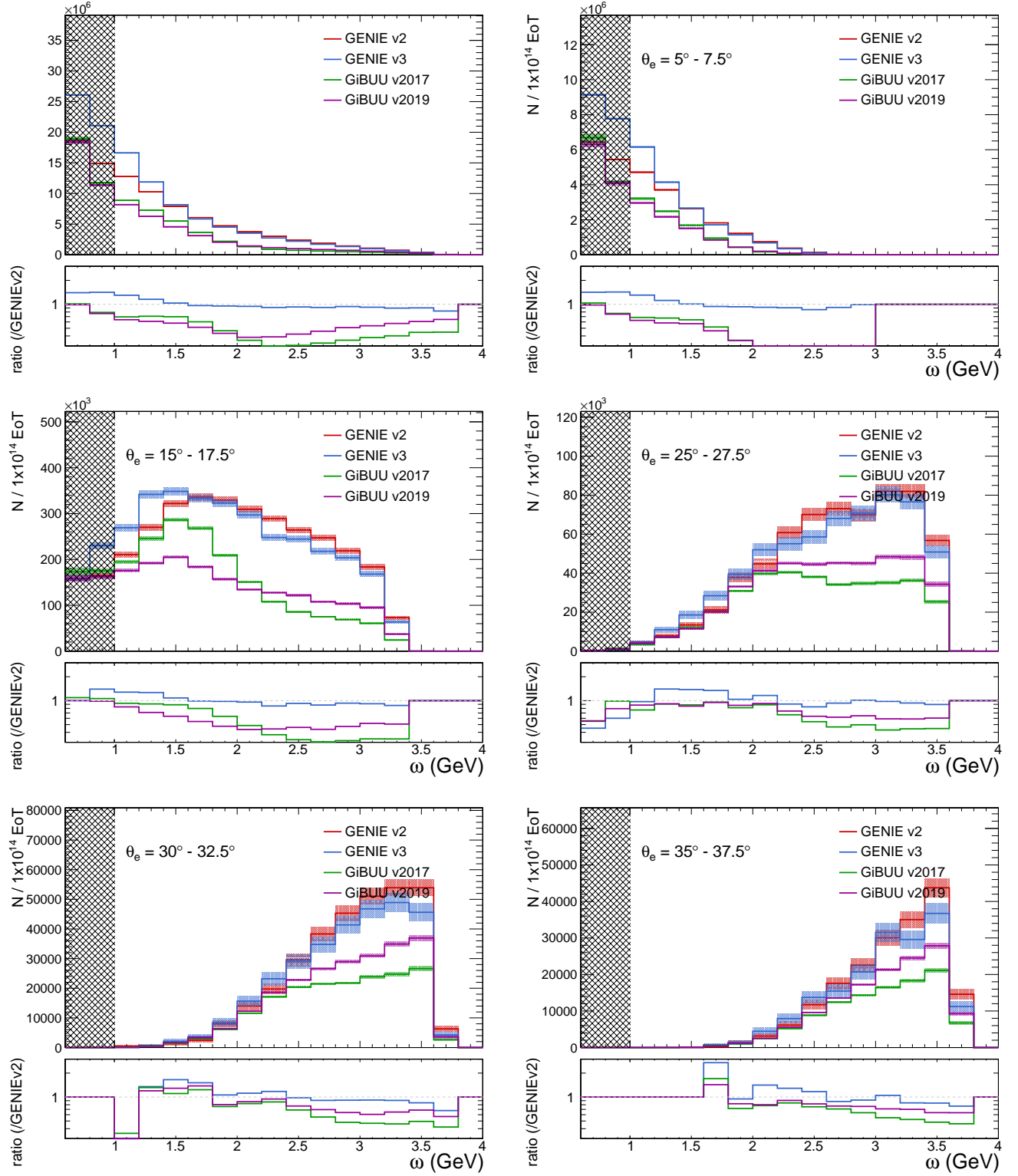


FIG. 9. Electron energy transfer ( $\omega$ ) for an electron angle of  $0^\circ$ - $40^\circ$  (top left),  $5^\circ$ - $7.5^\circ$  (top right),  $15^\circ$ - $17.5^\circ$  (middle left),  $25^\circ$ - $27.5^\circ$  (middle right),  $30^\circ$ - $32.5^\circ$  (bottom left), and  $35^\circ$ - $37.5^\circ$  (bottom right).

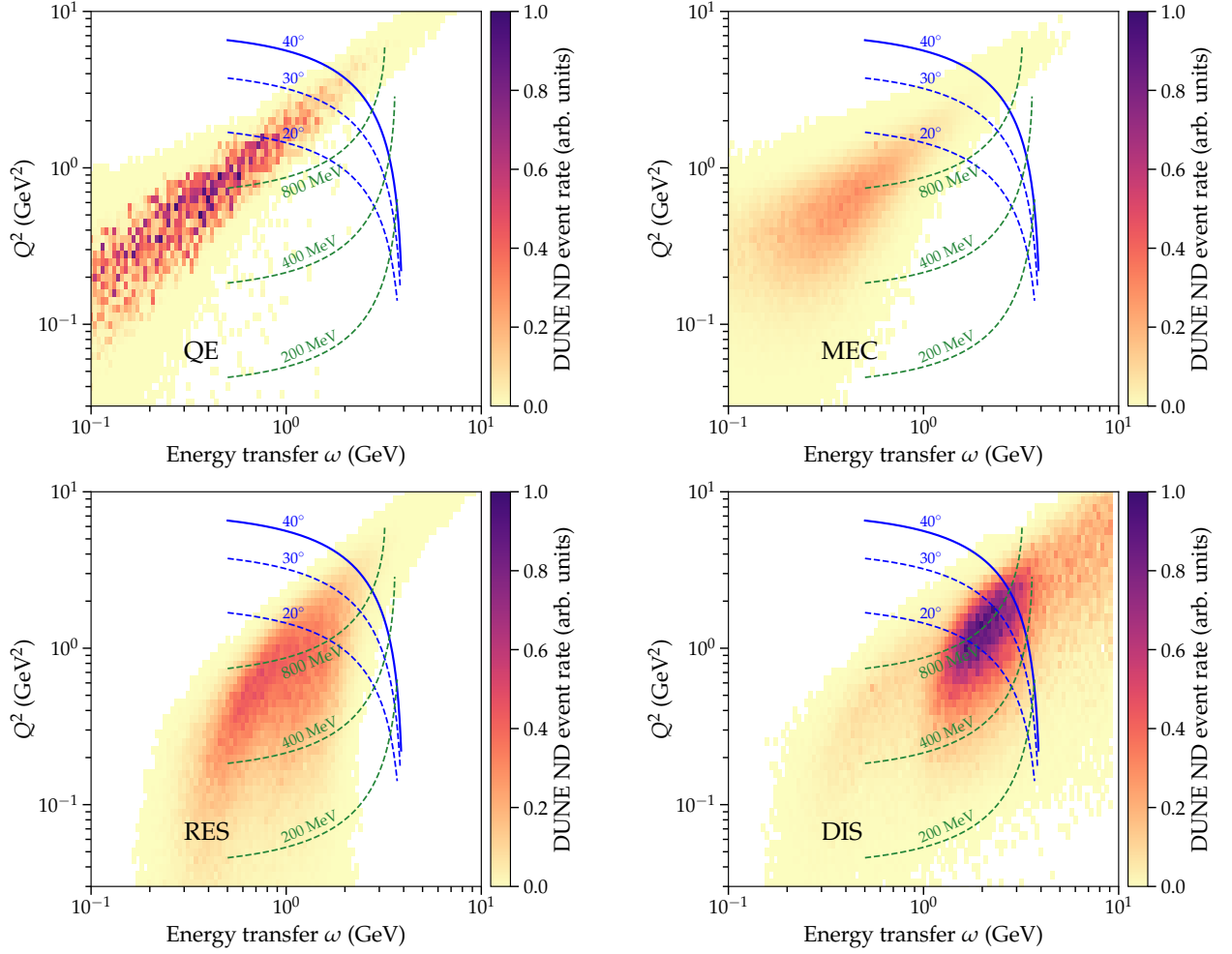


FIG. 10. Event distributions in the DUNE near detector according to GiBUU, broken into individual interaction channels: QE, MEC, RES, and DIS.



ally transitions to the DIS regime, in which interactions are treated at the quark level.

According to GiBUU, DUNE near detector events are dominated by DIS and QE events, closely followed by res-

onance production events. There is large kinematic overlap between DIS and resonance production events, making the physical distinction between them vague. The same holds true for the QE and MEC events.

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