

Investigating Electro-Nuclear Interactions in a New Dark Matter Search

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(Dated: 7 August 2024)

Electro-nuclear (EN) interactions are interactions in which an incident electron collides with a nucleus, scattering the electron and creating byproduct particles. Such interactions are of interest to neutrino physicists, who use EN interactions to inform model building of neutrino-nucleus interactions. The Light Dark Matter Experiment (LDMX) is a small-scale, fixed-target, electron beam experiment which seeks to probe for dark matter and mediator particle production in the sub-GeV mass region. The 8GeV LDMX electron beam will serve as an opportunity to study electro-nuclear interactions in final states in the multi-GeV region. LDMX's missing energy trigger for dark matter interactions however, will not be sufficient to efficiently capture EN interactions. An additional trigger is needed. Using simulated events, that included background and EN interactions, a trigger on momentum was developed.

I. INTRODUCTION

Neutrino physics is a main focus of many upcoming and ongoing major high energy physics experiments. Neutrino physics experiments seek to make high-precision measurements to understand phenomena such as neutrino oscillations and neutrino mass, among others. Any improvements to the precision of neutrino physics experiments are extremely significant. One of the greatest sources of systematic uncertainty in neutrino experiments comes from neutrino-nucleus interactions. Reconstructing the initial conditions and collision conditions that produce a recorded final result in neutrino-nucleus interactions is incredibly difficult¹. To improve neutrino-nucleus modelling, neutrino physicists rely on electro-nuclear (EN) interactions to inform their model building. EN interactions are much better understood and provide a useful series of boundary conditions on neutrino-nucleus interaction². Neutrino- and electron-nucleus interactions are ones in which the incident particle (electron or neutrino) collides with a nucleus and scatters off, producing a host of different particles in the interaction depending on interaction-specific details.

A. The Light Dark Matter eXperiment

The Light Dark Matter eXperiment (LDMX) provides an opportunity to study EN interactions. LDMX is a small-scale, fixed-target, electron beam accelerator experiment which seeks to probe for dark matter and mediator particle production in the sub-GeV range³. The LDMX setup can be seen in Figure 1. The interaction between the electron beam and thin target of LDMX will produce a small but substantial number of EN events, which recorded properly, will serve as data for analysis to improve neutrino-nucleus modelling. LDMX is also designed in a way which uniquely serves the study of EN interactions, by having a low-GeV electron beam and high acceptance of particles in a 40° cone of scattering from the target in the calorimeters⁴. The EM and hadronic calorimeters of LDMX will be able to accept all particles produced in EN interactions (Figure 2c).

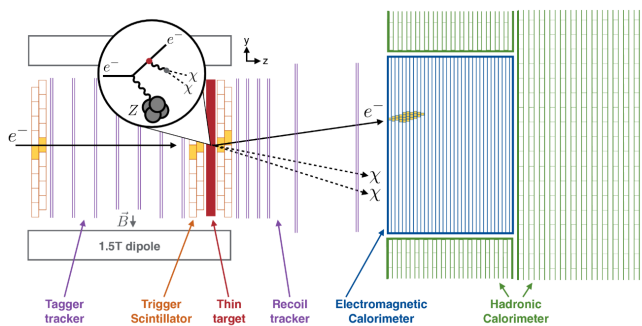


FIG. 1. Setup for the LDMX experiment. Particles travel through trackers before and after a thin target, eventually ending up in the electromagnetic and hadronic calorimeters. The particle interaction overlaid on the diagram at top left shows an electron-boson interaction that results in a scattered electron and the production of two dark matter particles. This is the main interaction sought after in LDMX.

LDMX will operate at SLAC National Accelerator Laboratory on their 8GeV electron beam. Electrons will be accelerated at a low current to allow for one electron (and byproduct particles) recorded in the EM calorimeter at a time. Electrons will arrive at 37.2 MHz, or once every 27 ns. LDMX will be aiming for an experiment total of 4e14 electrons on target (EoT) in phase 1 of the experiment and 1e16 EoT in phase 2 of the experiment⁵. Due to the high volume of events, LDMX has developed triggers to save only the events of interest. The majority of events will be uninteresting, with the electron moving through the target without interacting with any other particles, thus beginning and ending with 8 GeV of energy (Figure 2a).

The trigger for LDMX was designed for a missing energy signature to search for dark matter. Dark matter production will result in a significant energy loss (Figure 2b). While this trigger is efficient for dark matter and mediator particles, it is inefficient for collecting EN interactions. Recording EN interactions requires the development of a new trigger.

With the proper development of an EN trigger, LDMX promises to collect improved data in the multi-GeV range on

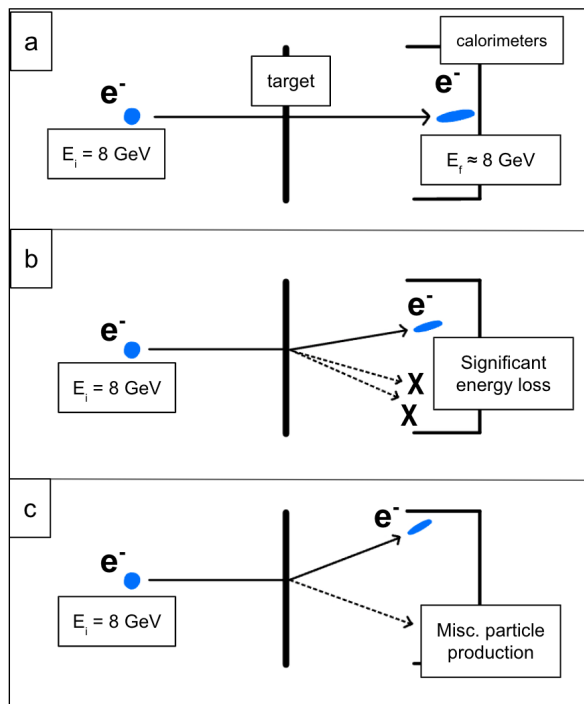


FIG. 2. These diagrams depict displacement in the y -direction. All electrons will be displaced in the x direction due to magnetic field effects of the magnet in the detector. a. Most events in LDMX will be uninteresting: the electron will move through the target and not interact with any other particles. It will begin and end with 8 GeV of energy. b. Dark matter production will result in significant energy loss from the electron interaction in the target and production of dark matter particles. c. EN interactions will cause the electron to scatter, resulting in large momentum. Other particles will also be produced in such interactions, their identity depending on the specific interaction.

final states in electron scattering.

II. METHODS

The development of the EN trigger relied on Monte Carlo simulation. We simulate 10 million events of all possible background processes from a single electron incident on the target, including EN interactions.

The LDMX experiment utilizes trackers both before and after its target to track the momentum and position of particles in the detector for the entirety of their trajectory. Ultimately, the hardware only collects data on particle position and energy, from which momentum can be inferred. Thus, a trigger can be created based upon particle energy or momentum. As discussed in the introduction, the energy trigger for LDMX is very inefficient for collecting EN interactions. This leaves a momentum trigger as a first option to collect EN interactions.

EN interactions are likely to have large transverse momentum, events in which the electron is scattered at a large angle off of a nucleus. Thus, selecting for events with large momentum can be used to record EN interactions. The rate at

which EN events can be saved must only be 1 kHz in order to satisfy detector hardware requirements. This limits where the trigger threshold can be placed, pushing it higher than desired. The EN interaction trigger must function for real LDMX data, which would contain events of multiple types resulting in large momentum. It is thus beneficial to find additional ways to collect only EN interactions, lower the EN interaction event rates, and lower the trigger threshold. This ensures that a proper range of momentum (and EN interactions) will be saved by the EN trigger.

A. Event Reconstruction Quality

The simulation data used in this study had two types of electron information: truth information and reconstructed information. Truth information is related to the true properties of particles in the detector: their position, energy, and momentum. Reconstructed information is related to the properties of particles in the detector as "measured" by detector instruments.

Comparing truth and reconstructed information reveals how well the event reconstruction algorithm is performing, and for what types of events it performs worst and best. The algorithm used to reconstruct events in the electromagnetic (EM) calorimeter of LDMX is simple. The EM calorimeter is constructed of 34 hexagonal silicon detectors placed parallel in succession. Particles leaving the target, if charged, are absorbed in the EM calorimeter. Each calorimeter layer is made up of seven smaller hexagons. Each of those smaller hexagons are made up of smaller rhombuses in turn. To reconstruct events, a clustering algorithm will register energy deposited in a EM calorimeter cell and "cluster" it with other energy deposits on surrounding cells to make a hit. Hits in the 2D calorimeter layers are then extended into the 3-dimensional layers of the calorimeter to recreate particle tracks.

Certain kinds of particle trajectories will not be reconstructed correctly by this algorithm. Checking event reconstruction quality seeks to understand which events those are and how their reconstruction can be improved.

Checking event reconstruction quality can be done using three types of visualizations.

1. Range

The distributions of truth and reconstruction can be shown overlaid on one another to visually compare their similarity. An example range comparison plot can be seen in Figure 3a.

2. Reconstruction Residuals

In a residual comparison, the distribution of truth will be subtracted from the distribution of reconstruction. Such a plot is useful for distance property comparisons. In a high quality reconstruction, the residual distribution will be centered on

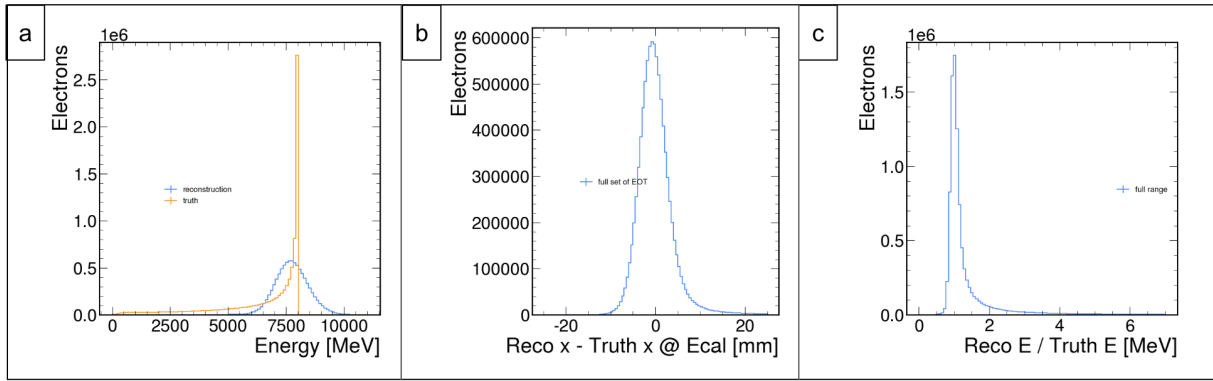


FIG. 3. a. Range comparison for the energy of the full set of electrons on target. From this plot, it is apparent that the reconstructed particle energy has a much higher upper bound than the truth particle energy. b. Reconstruction residual for particle final position in x in the EM calorimeter. The distribution is centered at 0, but has long tails, signifying a somewhat successful reconstruction of x position at the EM calorimeter for the full set of electrons. c. Reconstruction ratio for particle energy. The distribution is centered at 1, and has only a moderate tail, signifying a successful reconstruction of energy for the full set of electrons.

zero, with small distribution width. An example residual plot is shown in Figure 3b.

3. Reconstruction Ratios

In a ratio comparison, the distribution of reconstruction will be divided by the distribution of truth. Such a plot is useful for comparisons of properties with a large range. In high quality reconstructions, the ratio distribution will be centered on one, with a small distribution width. An example ratio plot is shown in Figure 3c.

B. Event Displays

Event displays place all of the particles reconstructed in one event onto a 2D position plot. They provide 3D information when labelled with information such as energy, depth, and z-position in the EM calorimeter. Event displays also include the truth position of the first particle in each event at the target and the final position in the calorimeter. A sample event display is shown in Figure 4.

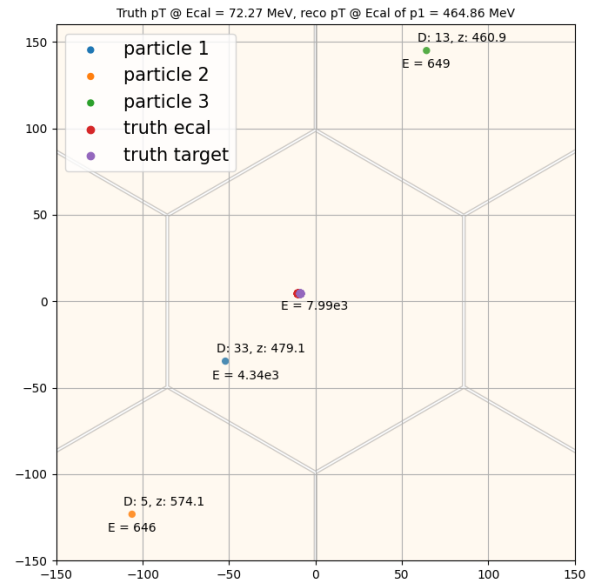


FIG. 4. This sample event display is overlaid by the EM calorimeter, allowing the placement of particles in the calorimeter to be seen. Reconstructed particles are labelled with their energy (E) in units of MeV, depth (D) in units of number of layers and final z position (z) in units of mm. The truth particle's positions at the target and calorimeter are also shown.

III. RESULTS

We start by setting a threshold on the momentum in the y-direction (p_y), this ignores magnetic field effects present in the x-direction (p_x). Behavior in the y-direction is the simplest to understand. We can transform this momentum threshold to a threshold event rate by creating a rate plot. Rate plots are created by taking the number of events that would be saved for a threshold cut, finding what fraction of the total number of events they are, and multiplying by the rate at which events occur.

$$\text{cut rate} = \frac{\text{num. events after cut}}{\text{total num. events}} * 37.2 \text{ MHz} \quad (1)$$

The p_y threshold for 1 kHz was determined by an initial rate plot (Figure 5). This threshold of 435 MeV was too high, saving just a small portion of desirable events. To lower this threshold, we examined the reconstruction of events with large p_y (Figure 6a, 6b) and observed poor reconstruction of y-direction properties such as position, displacement, and mo-

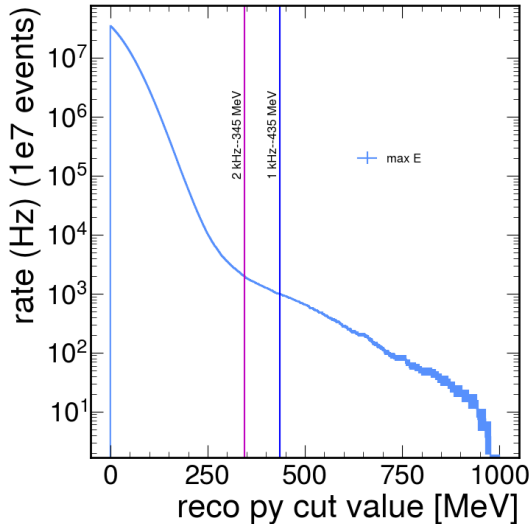


FIG. 5. Event rate as a function of electron py for the full set of electrons on target.

mentum (Figure 6c, 6d).

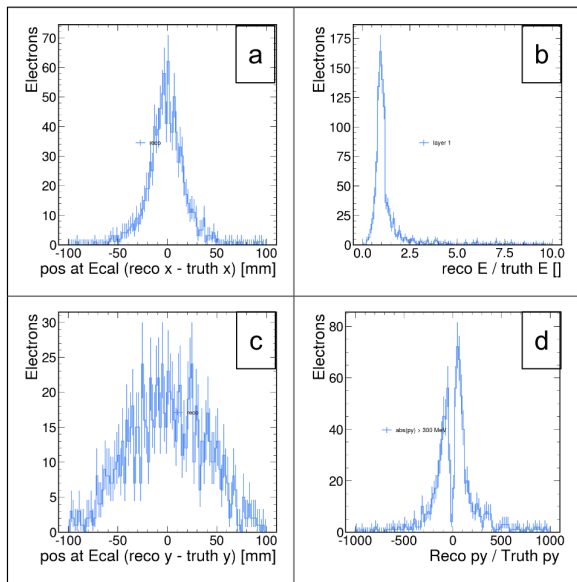


FIG. 6. a. Residual comparison in x position for events with $|py| > 300$ MeV. b. Ratio comparison in energy for events with $|py| > 300$ MeV. c. Residual comparison in y position for events with $|py| > 300$ MeV. This comparison has poor resolution, with some events being mis-reconstructed by up to 100mm in y position. d. Ratio comparison in py for events with $|py| > 300$ MeV.

When then examined event displays for events with the most egregious mis-reconstructions, aiming to determine a pattern correlating mis-reconstruction to some other event property that predicted mis-reconstruction.

Comparisons of events with large py and the set of all elec-

trons on target revealed a bias in large py events towards large z -positions, beyond typical for the data set as a whole (Figure 7). Z -position proved to be a useful tool to discard events with mis-reconstructed and large py .

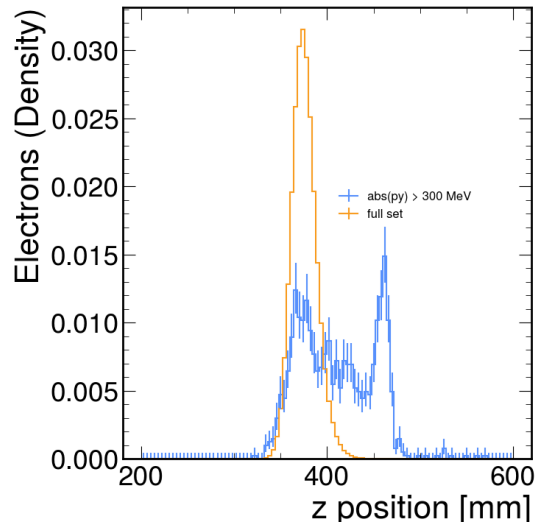


FIG. 7. Distribution comparison of z -position in the EM calorimeter for the full set of electrons on target vs. electrons with large py . Electrons with large py are biased towards larger z -positions compared to the full set of EOT. Both distributions are normalized such that the areas under their curves are both equal to one. This was done due to the large discrepancy between number of events in the two distributions.

In EN interaction events, the electron is not expected to penetrate deeply into the EM calorimeter, and thus, these events that do go deep in the calorimeter could be eliminated. This significantly improved the event rates for particle momentum in the y direction. Where the trigger threshold for a 1 kHz event rate was initially 435 MeV y -momentum, it was lowered to 325 MeV y -momentum.

The efficacy of this EN trigger threshold was then put to the test on a set of simulated EN events. This data set represented a wide variety of EN interactions that could occur in the LDMX experiment. Testing the EN trigger involved creating an efficiency plot (Figure 8), which displays what percentage of EN interactions with certain py would be collected and saved by the EN trigger.

The improvement in trigger efficiency is apparent between the trigger with the z -position quality cut on data and that without.

IV. CONCLUSION

The LDMX experiment has an EN trigger which will be able to save EN interaction events with high efficiency in the large- py range, moderate efficiency in the mid- py range, and very low efficiency in the low- py range. The interactions collected in the large- py and medium- py range will be of use to

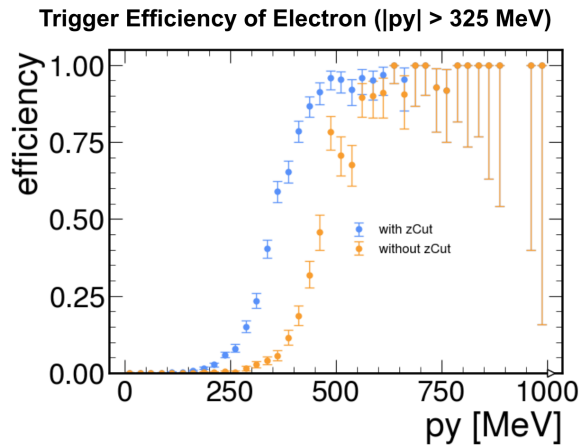


FIG. 8. Efficiency of collecting EN interactions as a function of electron p_y . Efficiency distributions for trigger thresholds both using the z-position cut and not using the z-position cut are plotted.

neutrino scientists, who will be able to use them to inform neutrino-nucleus interaction modelling. The EN trigger will be implemented alongside a z-position cut on data which allows for a lower trigger rate and improved EN interaction collection efficiency.

Further work could include investigations into the poor reconstruction performance of y-direction properties in events with large p_y . In addition, it would be possible to determine the efficiency of collection for each EN interaction type by

comparing interaction electron momentum to the efficiency plot created for the EN momentum trigger.

ACKNOWLEDGMENTS

I would like to thank my supervisors, Cristina Mantilla Suarez and Christian Herwig, as well as all the other collaborators on LDMX for their guidance this summer. In addition, thank you to the Internship administration team at Fermilab.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI).

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