Electro-nuclear scattering measurements for neutrinos with LDMX

Wes Ketchum (Fermilab) for LDMX collaboration

23rd International Workshop for Neutrinos from Accelerators (NuFact)

2 August 2022
Neutrino systematic uncertainties

Neutrino oscillation (and other!) measurements require careful control of systematic uncertainties.

Typically use a near detector to constrain flux and interaction uncertainties in far detectors.

Can be complex: e.g. DUNE-PRISM allows scanning across beam axis to match FD with combination of ND fluxes.
Interaction uncertainties

Neutrino interaction modeling on nuclei in GeV range difficult

Must consider wide range of interactions (from QE to DIS)

Translation of observed final state to initial neutrino energy very difficult

Reconstruction of full final state (e.g. neutrons) very difficult

Modeling uncertainties in observable final state observable (e.g. FSI)

https://arxiv.org/abs/1706.03621

W. Ketchum – “Electro-nuclear scattering measurements for neutrinos with LDMX” – NuFact 2022
Constraining interaction uncertainties for DUNE

Limited (but growing!) neutrino data on Argon

Future experiments like SBN will continue adding

DUNE near detectors will provide strong constraints

Requires ‘More Capable Near Detector’ to reach full $\delta_{CP}$ sensitivity

Complex fit including flux and detector systematics

(Not to mention: possible that NDs may see new physics of their own!)

W. Ketchum – “Electro-nuclear scattering measurements for neutrinos with LDMX” – NuFact 2022
Electron scattering analog

Charged lepton interactions are an important external constraint on neutrino interactions

Much of the same physics

Many identical nuclear effects

High-statistics datasets

Initial lepton kinematics are known → allows tests of initial lepton reconstruction
### Electron scattering experiments

<table>
<thead>
<tr>
<th>Collaborations</th>
<th>Kinematics</th>
<th>Targets</th>
<th>Scattering</th>
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<tbody>
<tr>
<td>E12-14-012 (JLab)</td>
<td>$E_e = 2.222$ GeV</td>
<td>Ar, Ti</td>
<td>$(e, e')$</td>
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<td>(Data collected: 2017)</td>
<td>$15.5^\circ \leq \theta_e \leq 21.5^\circ$</td>
<td>Al, C</td>
<td>$e, p$ in the final state</td>
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<td>$E_e = [1, 2, 4, 6$ GeV</td>
<td>H, D, He, C, Ar, $^{40}$Ca, $^{48}$Ca, Fe, Sn</td>
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<tr>
<td>(Data collected: 1999, 2022)</td>
<td>$\theta_e &gt; 5^\circ$</td>
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<td>$e, p, n, \pi, \gamma$ in the final state</td>
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<tr>
<td>LDMX (SLAC)</td>
<td>$E_e = 4.0, 8.0$ GeV</td>
<td>W, Ti, Al</td>
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<tr>
<td>(Planned)</td>
<td>$\theta_e &lt; 40^\circ$</td>
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<td>$e, p, n, \pi, \gamma$ in the final state</td>
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<tr>
<td>A1 (MAMI)</td>
<td>$50$ MeV $\leq E_e \leq 1.5$ GeV</td>
<td>H, D, He, C, O, Al, Ca, Ar, Xe</td>
<td>$(e, e')$</td>
</tr>
<tr>
<td>(Data collected: 2020)</td>
<td>$7^\circ \leq \theta_e \leq 160^\circ$</td>
<td></td>
<td>2 additional charged particles</td>
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<td>(More data planned)</td>
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<tr>
<td>A1 (eALBA)</td>
<td>$E_e = 500$ MeV</td>
<td>C, CH, Be, Ca</td>
<td>$(e, e')$</td>
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<tr>
<td>(Planned)</td>
<td>- few GeV</td>
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Range of existing and planned electron-scattering datasets

- Variety of targets and energies
- Detectors with varying capabilities

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Al, C | $(e,e')$  
e, p in the final state |
| **e4nu/CLAS (JLab)** (Data collected: 1999, 2022) | $E_e = 1, 2, 4, 6$ GeV  
$\theta_e > 5^\circ$ | H, D, He,  
C, Ar, $^{40}$Ca, $^{48}$Ca, Fe, Sn | $(e,e')$  
e, p, n, $\pi$, $\gamma$ in the final state |
| **LDMX (SLAC)** (Planned) | $E_e = 4.0, 8.0$ GeV  
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| **A1 (MAMI)** (Data collected: 2020) (More data planned) | 50 MeV $\leq E_e \leq 1.5$ GeV  
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**Range of existing and planned electron-scattering datasets**

**Variety of targets and energies**

**Detectors with varying capabilities**

Light Dark Matter eXperiment

Search for light dark matter in electron fixed-target experiment at SLAC LCLS-II

Phase 1: \( \sim 4 \times 10^{14} \) EoT @ 4 GeV,
Phase 2: \( \sim 1 \times 10^{16} \) EoT @ 8 GeV

Missing momentum/energy signature

Requires excellent tracking and particle detection in forward regions

\(< 1\) background event achievable → strong sensitivity to light dark matter Candidates

Expecting data 2026

See M. Solt’s LDMX Talk in WG4 on Thursday!
LDMX Detector

Thin W target (with additional targets e.g. Ti being considered)

Si-strip tagger and recoil electron trackers
→ $p > 50$ MeV sensitivity

High-granularity Si-W ECAL

Fast response → TS+ECAL form trigger

$\sim 17 \lambda_I$ sampling HCAL

https://arxiv.org/abs/2203.08192
**eN Scattering in LDMX**

Electro-nuclear scattering in LDMX matches well with phase-space for DUNE

Consider 4 GeV electrons on Ti target

- blue lines: constant recoil electron angle in LDMX
- green lines: constant recoil electron $p_T$

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Ankowski et al., PRD 101, 053004 (2020)

W. Ketchum – “Electro-nuclear scattering measurements for neutrinos with LDMX” – NuFact 2022
LDMX as part of an eN dataset for neutrinos

Kinematic reach well-matched to future DUNE oscillation program

Particularly in RES and DIS region

Excellent coverage and reconstruction for $\theta < 40^\circ$, including for neutral hadrons

→ allows a program of inclusive and exclusive measurements that complement existing/planned experiments
**eN Trigger for LDMX**

Nominal dark matter trigger insufficient for eN interactions

- Requires large (>2.5 GeV) energy transfer
- Newly developed high-$p_T$ trigger algorithm
- Fast reconstruction of energy and cluster position in ECAL
- Correlate to electron position in trigger scintillator to determine $p_T$
- Further studies to improve rejection of Bremsstrahlung photons

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W. Ketchum – “Electro-nuclear scattering measurements for neutrinos with LDMX” – NuFact 2022
Inclusive Scattering Measurements

Can leverage excellent electron reconstruction and high statistics to make sensitive measurements in 2D/3D/… See studies in Ankowski et al., PRD 101, 053004 (2020)

Note: >200 MeV/c $p_T$ cut applied here

Detector coverage at lower angles, but will require lower-$p_T$ or alternate trigger

W. Ketchum – “Electro-nuclear scattering measurements for neutrinos with LDMX” – NuFact 2022
dE/dx measurements in tracker

Separation of protons and charged pions critical for probing interaction models

E.g. QE vs. RES/DIS discrimination, particle multiplicities, FSI studies

Promising early studies of PID using dE/dx in tracker

With (very) simplified model of tracker response, good separation for KE < 500 MeV

W. Ketchum – “Electro-nuclear scattering measurements for neutrinos with LDMX” – NuFact 2022
Neutron reconstruction

Primary goal of LDMX HCAL is to veto long-lived neutral hadrons

Effort underway on reconstruction of kinematics of neutrons

Consider both HCAL and ECAL+HCAL cases, sum energy across calorimeters

Further work ongoing for shower shape, angular reconstruction
Simulation studies on observables

Through developments, check impact on simulation samples (two GENIE v3.2 tunes)

Apply lepton trigger cuts, and require final-state particles well-reconstructable ($\theta < 40^\circ$)

Still to-do: energy resolution smearing, PID efficiencies, etc.

Particle Multiplicities

LDMX will have very high stats samples! Will be sensitive to these differences.
Simulation studies on observables

Through developments, check impact on simulation samples (two GENIE v3.2 tunes)

Apply lepton trigger cuts, and require final-state particles well-reconstructable ($\theta < 40^\circ$)

Still to-do: energy resolution smearing, PID efficiencies, etc.

LDMX will have very high stats samples! Will be sensitive to these differences.
Simulation studies on observables

Beginning to look at higher-level observables, e.g. momentum imbalance

Modeling effects of limited detector acceptance will be critical

Todo: explore ability to veto additional activity (rather than require good reconstruction)
→ DM detector well-designed for this!

W. Ketchum – “Electro-nuclear scattering measurements for neutrinos with LDMX” – NuFact 2022
Testbeam at CERN

Testbeam run with trigger scintillator and HCAL prototypes earlier this year

Electrons, muons, pions, 500 MeV - 8 GeV

See H. Herde’s talk at ICHEP for more details!
https://agenda.infn.it/event/28874/contributions/169115/

W. Ketchum – “Electro-nuclear scattering measurements for neutrinos with LDMX” – NuFact 2022
HCAL response / PID

MIP candidate
Sequential, crisp signature in HCal

Pion candidate
MIP-like deposits followed by cloud in HCal

https://agenda.infn.it/event/28874/contributions/169115/
Future/ongoing studies

Continuing work on improving simulation and reconstruction

$\pi^0$ acceptance, charged particle tracking, ECAL and HCAL clustering

Understand effects of limited “well-reconstructed” acceptance, ability to veto additional activity

Investigate model comparisons and impact for sensitivity to model parameters
Summary

Electron scattering measurements are an important external constraint on neutrino interaction uncertainties

Proposed LDMX offers unique dataset for eN measurements particularly relevant to DUNE

Leverage dark-matter design for sensitivity to forward particles, particularly neutrons

Design for feasible eN trigger ($p_T > 400$ MeV/c) in place

Further work on reconstruction, PID, and event selection/observables ongoing
Thanks!

[Logos of various institutions]
Backups
Beamline
Detector rendering

Diagram showing a detector rendering with labels for ECAL, HCAL, tagging tracker, recoil tracker, and target. The diagram also includes a 36” measurement and a 4 GeV electron indication.
Recoil tracker resolution
Kinematic overlap with DUNE

4 GeV electrons

8 GeV electrons
## GENIE Model Descriptions

<table>
<thead>
<tr>
<th>Modelling CMC</th>
<th>Ground State</th>
<th>Quasi-elastic</th>
<th>Meson Exchange Current</th>
<th>Resonance</th>
<th>Shallow and Deep Inelastic</th>
<th>Final State Interactions</th>
</tr>
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<tbody>
<tr>
<td>G18_02a</td>
<td>Relativistic Fermi Gas Model</td>
<td>Llewellyn-Smith QE model</td>
<td>Dyman</td>
<td>Berger-Sehgal</td>
<td>Bodek and Yang Model</td>
<td>hA18 (Effective intranuclear transport model)</td>
</tr>
<tr>
<td>G21_11b</td>
<td>Local Fermi Gas Model</td>
<td>SuSAv2</td>
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<td>Berger-Sehgal</td>
<td>Bodek and Yang Model</td>
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