Progress Toward An Effective Field Theory Analysis of the LUX WIMP Search

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On behalf of the LUX Collaboration
Xenon as a Direct Detection Target

- High density ($3 \text{ g/cm}^3$) and high atomic mass ($A = 131 \text{ g/mol}$)
- Scintillates brightly in the near-UV ($178 \text{ nm}$) with fast (ns) response time
- Excellent ionization threshold and long electron drift lengths ($\sim 1 \text{ m}$)
- High abundance of odd isotopes $\Rightarrow$ spin-dependent sensitivity.

No long-lived intrinsic backgrounds

- Scalable to multi-ton size
- Self-shielding possible with 3D reconstruction
Dual-Phase TPCs: Principle of Operation

- The target is cooled to condensation point => liquid topped by a thin layer of gas.
- An incident particle excites/ionizes a target atom, which emits primary scintillation (“S1”) light.
- Ionization electrons produced are drifted upwards by an applied electric field and extracted into the gas phase, where they are accelerated rapidly and caused to scintillate again (“proportional” or “S2” light).

3D imaging possible:
- Timing between the S1 and S2 pulses yields z-position.
- PMT hit patterns yield xy-position.

ER/NR discrimination possible:
- Nuclear recoils produce dense tracks
- Electron recoils produce less-dense tracks

=> \((S2/S1)_\gamma >> (S2/S1)_{\text{neutron}}\)
A Typical Event: 1.5 keV Gamma
The Large Underground Xenon Experiment

370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass
The Large Underground Xenon Experiment

122 2” PMTs (Hamamatsu R8778)
- QE (175 nm) ~33%
- U/Th ~9/3 mBq/PMT

2 x 61 PMT Array
• Detector cool-down January 2013; xenon condensed mid-February 2013; WIMP-search data collected from April to August 2013.

• Overall 95% data-taking efficiency during the WIMP search period

• Total: 85.3 live-days of WIMP-search data collected
LUX First Underground Run - Parameters

- Xenon purity: electron drift length 87-135 cm
  - Continuous circulation at 250 kg/day through an external purifier
  - Monitored weekly using $^{83}\text{mKr}$ injections
- Drift field: 181 V/cm (speed 1.5 mm/$\mu$s) with 99.6% ER discrimination
- Light collection efficiency: 14% (includes detector geometry and PMT QE; 3D corrections provided by $^{83}\text{mKr}$ calibrations)
- NR calibrations with external AmBe and $^{252}\text{Cf}$ sources
- Precision ER calibrations performed with CH$_3$T injections after the WIMP-search campaign
- Fiducial mass: 118.3 +/- 6.5 kg
- WIMP-search window: ~3-25 keVnr
Event Selection and Cuts

<table>
<thead>
<tr>
<th>Cut</th>
<th>Explanation</th>
<th>Events Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Triggers</td>
<td>S2 Trigger &gt;99% for S2_{raw}&gt;200 phe</td>
<td>83,673,413</td>
</tr>
<tr>
<td>Detector Stability</td>
<td>Cut periods of excursion for Xe Gas Pressure, Xe Liquid Level, Grid Voltages</td>
<td>82,918,901</td>
</tr>
<tr>
<td>Single Scatter Events</td>
<td>Identification of S1 and S2. Single Scatter cut.</td>
<td>6,585,686</td>
</tr>
<tr>
<td>S1 energy</td>
<td>Accept 2-30 phe (energy ~ 0.9-5.3 keVee, ~3-18 keVnr)</td>
<td>26,824</td>
</tr>
<tr>
<td>S2 energy</td>
<td>Accept 200-3300 phe (&gt;8 extracted electrons) Removes single electron / small S2 edge events</td>
<td>20,989</td>
</tr>
<tr>
<td>S2 Single Electron Quiet Cut</td>
<td>Cut if &gt;100 phe outside S1+S2 identified +/-0.5 ms around trigger (0.8% drop in livetime)</td>
<td>19,796</td>
</tr>
<tr>
<td>Drift Time Cut away from grids</td>
<td>Cutting away from cathode and gate regions, 60 &lt; drift time &lt; 324 us</td>
<td>8731</td>
</tr>
<tr>
<td>Fiducial Volume radius and drift cut</td>
<td>Radius &lt; 18 cm, 38 &lt; drift time &lt; 305 us, 118 kg fiducial</td>
<td>160</td>
</tr>
</tbody>
</table>

Only simple, obvious cuts – no tuning beyond selecting a threshold, higher energy cutoff, and fiducial volume.
After all selection cuts, 160 candidate events left in the fiducial volume.
Distribution is consistent with electron recoil background and no WIMP signal with a p-value of 0.35 from Profile-Likelihood Ratio Analysis with incorporated background models, detector effects, and efficiencies.
The LUX First WIMP-Search Result
And Beyond...

• To date, LUX has set the setting the world’s best limit on spin-independent WIMP-nucleon elastic scattering cross section:
  \[ 7.6 \times 10^{-46} \text{ cm}^2 \text{ for 33 GeV-WIMPs} \]

• Since the end of the first run:
  • New NR calibration using a beam of mono-energetic neutrons from DD source => improved sensitivity at low masses
  • Currently: re-analysis taking place with improved low energy threshold

• 300-live-day run to take place in 2015
  • Extending sensitivity by a factor of ~5
  • Discovery still possible!

LUX 2013 result: PRL.112.091303 (arXiv:1310.8214)
Direct Detection Revisited

- Direct detection experiments either:
  - Detect no excess of events, then use the energy spectrum predicted by a specific model of a specific interaction to set a limit on that particular interaction.
  - Detect an excess of events, in which case it is necessary to find a model that fits the observation.

- Direct detection experiments like LUX typically only work with two interaction models: spin-independent (SI) and spin-dependent (SD) elastic scattering interactions.
  - Comes from the assumption that momentum transfers involved in WIMP-nucleus scatters are nonrelativistic.
  - SI, SD interactions are the only interactions that do not vanish in the zero-momentum-transfer limit.
Direct Detection Revisited

But there are several momentum- and velocity-dependent interactions also allowed by basic symmetry considerations.

- The usual SI and SD interactions could be suppressed.
- Momentum transfer is not necessarily small on a parton scale.
- Novel nuclear responses such as angular-momentum-dependent (LD) and angular-momentum/spin-dependent (LSD) responses are allowed.
- These LD and LSD responses can interfere with the SI and SD responses.

Cirelli et al. arXiv:1307.5955
Three Goals:

**GOAL 1:** Investigate the extent to which momentum/velocity-dependent interactions affect our signal in xenon.

**GOAL 2:** For a given target material (xenon), optimize analysis techniques to best probe these momentum/velocity-dependent interactions.

**GOAL 3:** (General) Check that the array of direct detection target materials currently in use do not leave any “blind spots” in WIMP parameter space.
The Effective Field Theory Setup

- WIMP-nucleon elastic scattering is analogous to a four-fermion contact interaction in standard weak interaction theory.

- The general interaction Lagrangian:

\[ \mathcal{L}_{\text{int}} = c \sum_{i=1}^{N} \left( O_i^{(n)} + O_i^{(p)} \right) \]

- Restrict to operators \( O_i \) that are Galilean-invariant and Hermitian.
- Remaining \( O_i \)'s are combinations of WIMP spin \( S_{\chi} \), nucleon spin \( S_N \), incident velocity \( v^2 \), and momentum transfer \( q^2 \).
- Allow the \( O_i \)'s to be at most quadratic in \( v \) (i.e. restrict to exchange of a spin-0 or spin-1 boson) and \( q \) (absorb higher powers of \( q \) into form factors).
The Set of Allowed EFT Operators

- Each nuclear form factor $F_{ij}$ associated with the EFT operators can be written as a linear combination of five macroscopic nuclear responses that depend only on the nuclear physics: (arXiv:1203.3542)

$$
\begin{align*}
\mathcal{O}_1 &= \frac{1}{2} \chi N \\
\mathcal{O}_2 &= (v^\perp)^2 \\
\mathcal{O}_3 &= i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \\
\mathcal{O}_4 &= \vec{S}_N \cdot \vec{S}_N \\
\mathcal{O}_5 &= i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \\
\mathcal{O}_6 &= \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) \\
\mathcal{O}_7 &= \vec{S}_N \cdot \vec{v}^\perp \\
\mathcal{O}_8 &= \vec{S}_N \cdot \vec{v}^\perp \\
\mathcal{O}_9 &= i \vec{S}_N \cdot \left( \vec{S}_N \times \frac{\vec{q}}{m_N} \right) \\
\mathcal{O}_{10} &= i \vec{S}_N \cdot \frac{\vec{q}}{m_N} \\
\mathcal{O}_{11} &= i \vec{S}_N \cdot \frac{\vec{q}}{m_N}
\end{align*}
$$

- SI Interaction
- Cannot obtain at lowest order
- SD Interaction

<table>
<thead>
<tr>
<th>$M$</th>
<th>$\Sigma'$</th>
<th>$\Sigma''$</th>
<th>$\Delta$</th>
<th>$\Phi''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI response</td>
<td>SD response (longitudinal component)</td>
<td>SD response (transverse component)</td>
<td>LD (angular-momentum-dependent) response</td>
<td>LSD (spin-orbit) response</td>
</tr>
</tbody>
</table>

16
Converting Between the EFT Operators and the Macroscopic Nuclear Responses

<table>
<thead>
<tr>
<th></th>
<th>M (SI)</th>
<th>Σ” (SD long.)</th>
<th>Σ’ (SD trans.)</th>
<th>Δ (LD)</th>
<th>Φ” (LSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₁</td>
<td>q-indep.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₃</td>
<td></td>
<td>~ q⁴, q²v²</td>
<td></td>
<td>~ q⁴</td>
<td></td>
</tr>
<tr>
<td>O₄</td>
<td></td>
<td>q-indep.</td>
<td>q-indep.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₅</td>
<td>~ q⁴, q²v²</td>
<td>~ q⁴</td>
<td></td>
<td>~ q⁴</td>
<td></td>
</tr>
<tr>
<td>O₆</td>
<td>~ q⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₇</td>
<td></td>
<td>~ q², v²</td>
<td></td>
<td>~ q²</td>
<td></td>
</tr>
<tr>
<td>O₈</td>
<td>~ q², v²</td>
<td>~ q²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₉</td>
<td></td>
<td></td>
<td>~ q²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₁₀</td>
<td></td>
<td>~ q²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₁₁</td>
<td></td>
<td>~ q²</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparing Target Materials

• Estimate the number of predicted events as:

\[
\frac{dN}{dE_R} \sim 5000\text{keV}^{-1} \left(\frac{\text{exposure}}{\text{kg} \cdot \text{day}}\right) \left(\frac{100\text{GeV}}{m_\chi}\right)^3 L_{\text{int}}^2
\]

• Comparing the interaction terms for different targets:

<table>
<thead>
<tr>
<th></th>
<th>$S_n^2$</th>
<th>$S_p^2$</th>
<th>$L_n^2$</th>
<th>$L_p^2$</th>
<th>$(S_n \cdot L_n)^2$</th>
<th>$(S_p \cdot L_p)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>$8 \cdot 10^{-5}$</td>
<td>0.2</td>
<td>0.04</td>
<td>0.05</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Na</td>
<td>0.0004</td>
<td>0.06</td>
<td>0.1</td>
<td>0.8</td>
<td>5.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Ge</td>
<td>0.02</td>
<td>$5 \cdot 10^{-6}$</td>
<td>1.1</td>
<td>0.003</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td>I</td>
<td>0.004</td>
<td>0.07</td>
<td>0.4</td>
<td>2.</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Xe</td>
<td>0.02</td>
<td>$2 \cdot 10^{-5}$</td>
<td>0.4</td>
<td>0.04</td>
<td>500</td>
<td>300</td>
</tr>
</tbody>
</table>

(arXiv:1211.2818)

• Xenon is sensitive to not only SD WIMP-neutron interactions, but also to the new LD (Δ) and LSD (Φ”) interactions for both nucleons.
SI and LD WIMP-n Recoil Spectra

A note on normalization of spectra: Note that the usual WIMP-nucleon cross section $\sigma_0$ refers to “cross section at zero-momentum-transfer”. This only makes sense for the usual SI and SD interactions.

- All coupling constants $C_i$ normalized to each other.
- $C_1$ chosen to correspond to $\sigma_0 = 1$ pb
$O_1$ (the usual SI interaction) and $O_{11}$ both produce an SI response, but the spectra have different slopes due to different $q$-dependence.

$O_5$ and $O_8$ each produce both an LD and an SI response, again with different $q$-dependence.

For $m_{\text{WIMP}}$ large, the EFT spectra stay relatively flat out to ~few hundred keV.
Integrating under each of the spectra, we find that in order to capture 90% of the signal, we require an upper energy threshold of up to ~40 keV for 50-GeV WIMPs and up to ~300 keV for 500-GeV WIMPs.
The two types of SD response (transverse and longitudinal to the momentum transfer $q$) exhibit distinctly different behaviors.

Again the slope of the spectrum depends on the $q$-dependence of the operator.

$O_3$ (green) is the only LSD operator. Its spectrum increases sharply to around 50 keV and does not begin to decrease until ~300 keV for heavy WIMPs.
Integrating under the spectra, we again find that in order to capture 90% of the prospective signal we require a WIMP-search window that goes up to ~60 keV for a 50-GeV WIMP and several hundred keV for a 500-GeV WIMP.

Holds true for essentially all the operators.
Optimizing the WIMP-Search Window

Table: The minimum upper bound on the WIMP-search window in keVnr for the WIMP-search region to contain 50% or 90% of the integrated spectrum

<table>
<thead>
<tr>
<th>Operator</th>
<th>50-GeV WIMP</th>
<th>500-GeV WIMP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50%</td>
<td>90%</td>
</tr>
<tr>
<td>Standard SI</td>
<td>10.8</td>
<td>27.3</td>
</tr>
<tr>
<td>O₁</td>
<td>9.9</td>
<td>24.6</td>
</tr>
<tr>
<td>O₁₁</td>
<td>16.4</td>
<td>34.4</td>
</tr>
<tr>
<td>O₅</td>
<td>15.3</td>
<td>32.8</td>
</tr>
<tr>
<td>O₈</td>
<td>9.3</td>
<td>23.0</td>
</tr>
<tr>
<td>Standard SD</td>
<td>8.6</td>
<td>21.6</td>
</tr>
<tr>
<td>O₄</td>
<td>10.0</td>
<td>27.6</td>
</tr>
<tr>
<td>O₆</td>
<td>33.6</td>
<td>64.1</td>
</tr>
<tr>
<td>O₉</td>
<td>14.4</td>
<td>38.6</td>
</tr>
<tr>
<td>O₁₀</td>
<td>22.2</td>
<td>49.0</td>
</tr>
<tr>
<td>O₇</td>
<td>14.4</td>
<td>38.6</td>
</tr>
<tr>
<td>O₃</td>
<td>26.3</td>
<td>49.2</td>
</tr>
</tbody>
</table>

For many of the new momentum-dependent operators, we require a search window of up to several hundred keVnr to capture most of the signal.
Constraints on Representative Operators

\[ \begin{align*}
O_1 & \text{ WIMP-N scattering (M)} \\
O_3 & \text{ WIMP-N scattering (} \Sigma^1 \text{ and } \Phi^{1'}) \\
O_5 & \text{ WIMP-N scattering (M and } \Delta) \\
O_6 & \text{ WIMP-N scattering (} \Sigma^2') \\
O_9 & \text{ WIMP-p scattering (} \Sigma^2) \\
\end{align*} \]
Constraints on Representative Operators

![Diagram of exclusion curves for different WIMP-nucleon scatterings](image)

All exclusion curves shown are for a xenon target with 10000 kg-day exposure.
Summary

• Direct detection experiments traditionally only present limits on interactions that vanish in the zero-momentum-transfer limit (SI and SD).
  • There is at least one additional momentum-dependent interaction ($O_{11}$) that can produce a spin-independent nuclear response.
  • There are at least four additional momentum-and-velocity-dependent interactions ($O_6, O_9, O_{10}, O_7$) that can produce a spin-dependent nuclear response, with transverse and longitudinal components of the spin-dependent response showing distinctly different behaviors.
  • There are two additional operators that produce an entirely new angular-momentum-dependent nuclear response ($O_5, O_8$) in addition to producing an SI response.
  • There is one additional operator that produces an entirely new angular-momentum-and-spin-dependent nuclear response ($O_3$) in addition to producing an SD response.

Xenon is sensitive to these new interactions but the bulk of the signal lies well above the 3-25 keVnr WIMP-search window used by LUX and other experiments.
Current Status and Next Steps

- Current status: Spectra have been generated and simple cut-and-count limits produced for each of the new operators for a xenon target.

- Short-term: Generate signal models using these EFT spectra and run them through the LUX PLR to produce limits on each of the new operators using the WIMP-search data from the LUX first underground run.

- Next, increase the upper threshold of the WIMP-search window from ~25 keVnr to ~few hundred keVnr.
  - This will allow us to better optimize signal-to-background based on where the spectrum peaks for each of the momentum/velocity-dependent EFT operators.

- At higher recoil energies pulse-shape cuts and other discrimination techniques can be used to help with signal-to-noise ratio.
Thank you!

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