Simulating Supernova CEvNS Interactions in the LUX-ZEPLIN Detector

Elise McCarthy
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Detector Response Working Group
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Overview

1. Introduction to LZ
2. Simulating CCSN neutrinos in LZ
3. Dependence of CEvNS scattering on the nuclear form factor, and why we must set a common standard
4. Future work

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The LUX-ZEPLIN (LZ) Collaboration

1. Center for Underground Physics (South Korea)
2. LIP Coimbra (Portugal)
3. MEPhI (Russia)
4. Imperial College London (UK)
5. Royal Holloway University of London (UK)
6. STFC Rutherford Appleton Lab (UK)
7. University College London (UK)
8. University of Bristol (UK)
9. University of Edinburgh (UK)
10. University of Liverpool (UK)
11. University of Oxford (UK)
12. University of Sheffield (UK)
13. Black Hill State University (US)
14. Brandeis University (US)
15. Brookhaven National Lab (US)
16. Brown University (US)
17. Fermi National Accelerator Lab (US)
18. Lawrence Berkeley National Lab (US)
19. Lawrence Livermore National Lab (US)
20. Northwestern University (US)
21. Pennsylvania State University (US)
22. SLAC National Accelerator Lab (US)
23. South Dakota School of Mines and Technology (US)
24. South Dakota Science and Technology Authority (US)
25. Texas A&M University (US)
26. University at Albany (US)
27. University of Alabama (US)
28. University of California, Berkeley (US)
29. University of California, Davis (US)
30. University of California, Santa Barbara (US)
31. University of Maryland (US)
32. University of Massachusetts (US)
33. University of Michigan (US)
34. University of Rochester (US)
35. University of South Dakota (US)
36. University of Wisconsin - Madison (US)
37. Washington University in St. Louis (US)
38. Yale University (US)

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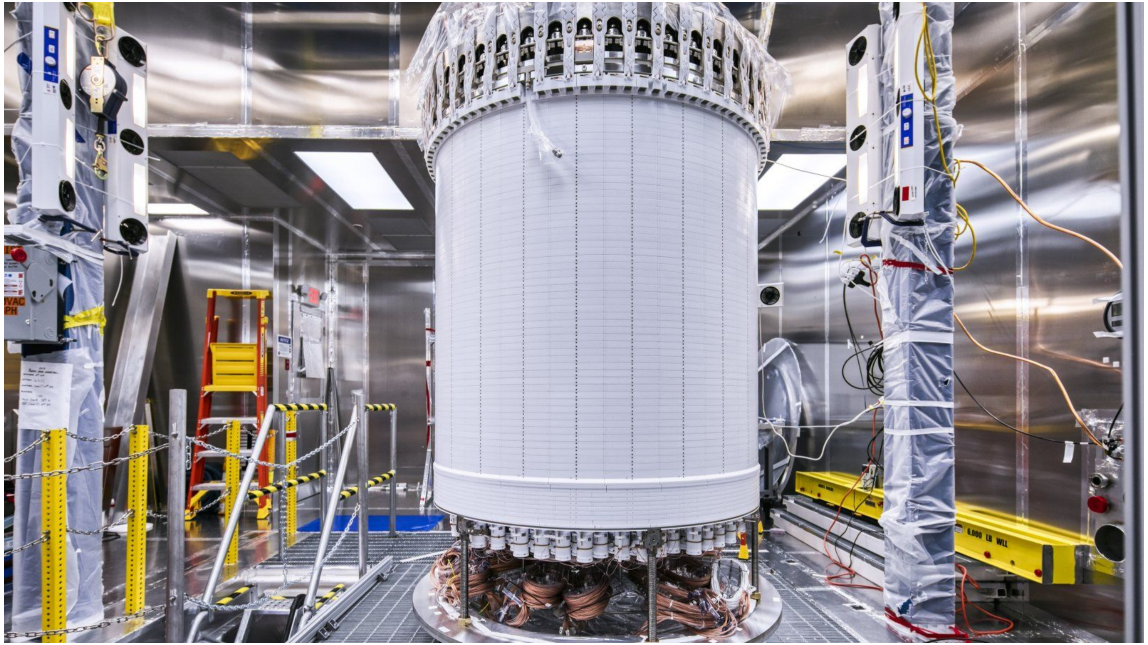
About LZ

Located in Lead, South Dakota at the Sanford Underground Research Facility.

First science run to occur in 2021.

Primary detector volume - TPC - contains 7 tons of liquid xenon.



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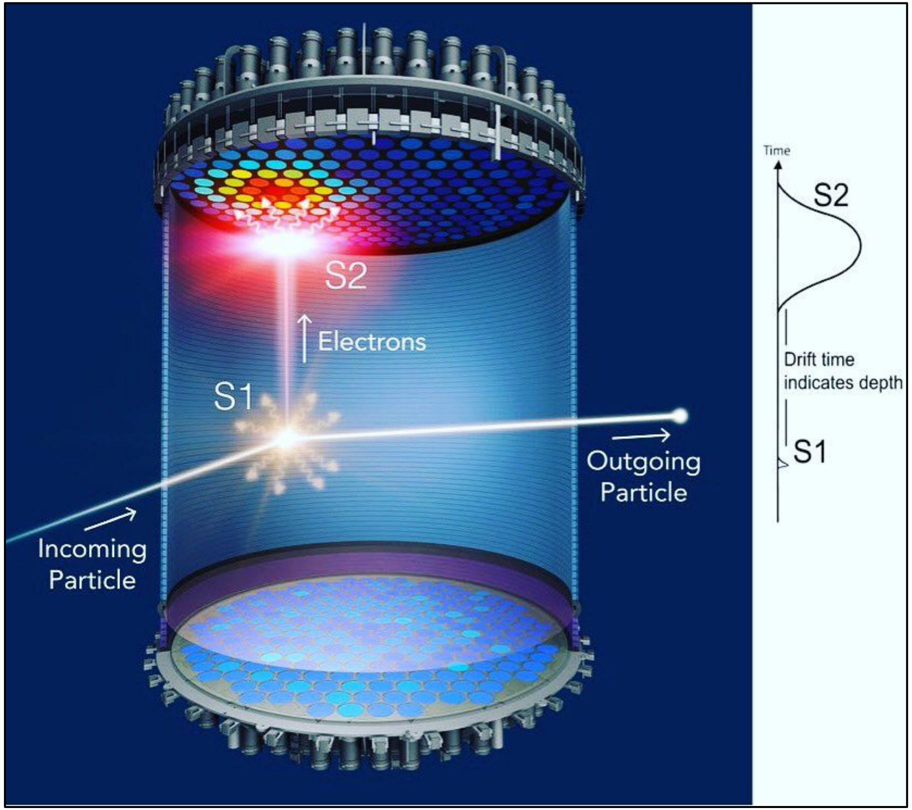
About LZ - continued



Incident neutrinos scatter off the xenon target nuclei.

Detect the energy of the recoiling nucleus E_R.

Events with energy $E_R > 0.5\,keV$ are detectable.

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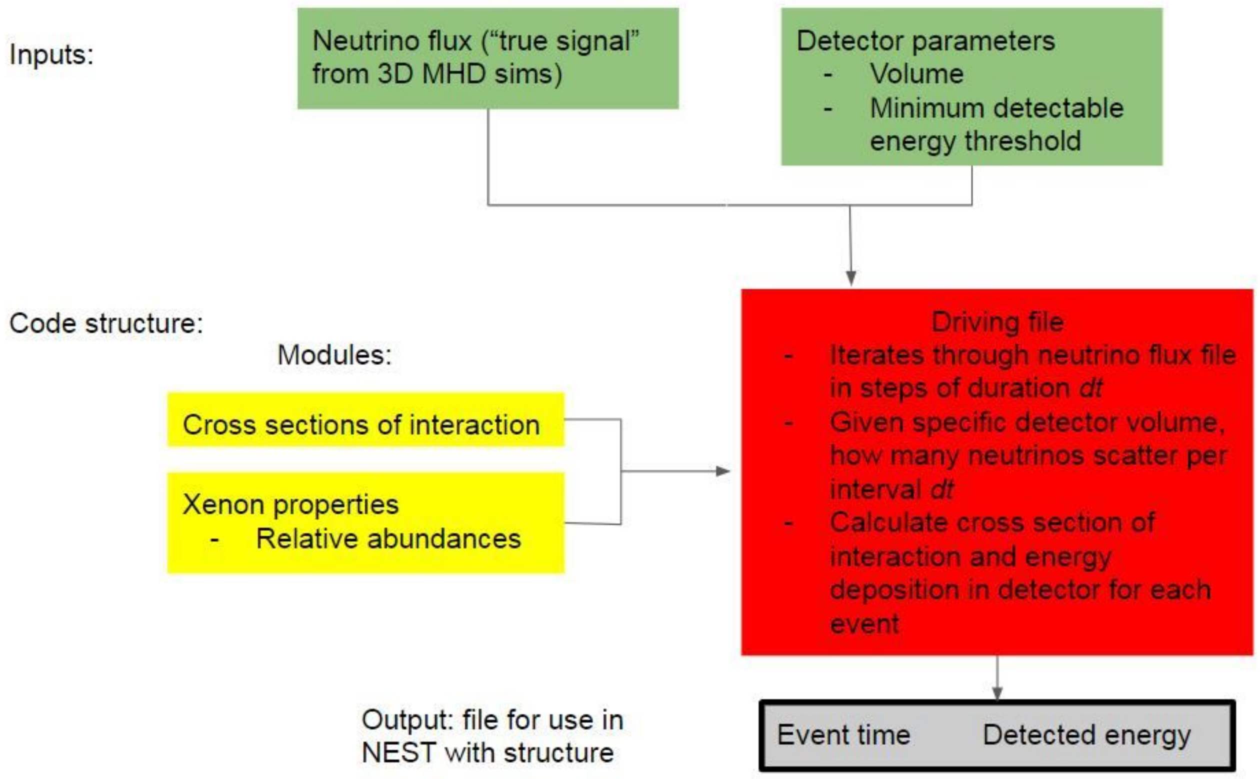
Simulating CCSN neutrinos in LZ



Will utilize models collected and standardized by the Modelling WG

Currently optimized for use in the Noble Element Simulation Technique (NEST) environment [1].

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Detection Mechanism - Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

Independent of neutrino flavor.

Neutrinos with low energy ($E_I \lessapprox 100 MeV$) coherently scatter off the xenon nucleus rather than individual nucleons.

For low-energy nuclear recoil events in xenon, CEvNS has largest cross section of all neutrino-nucleus couplings.

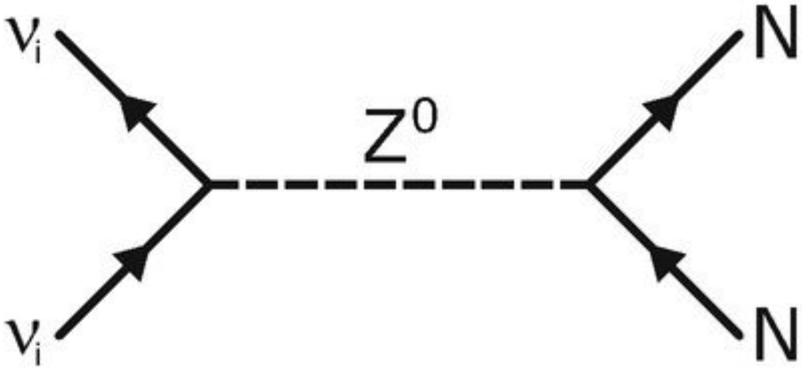

Figure from B. Scholz, *First Observation of Coherent Elastic Neutrino-Nucleus Scattering* (2018)

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Differential cross section of interaction

The differential cross section of interaction is given by

$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{2\pi} M \left[2 - \frac{2E_R}{E_I} + \left(\frac{E_R}{E_I}\right)^2 - \frac{ME_R}{E_I^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

where

$$Q_W = N - [1 - 1sin^2(\theta_W)]Z, \;\; sin^2(\theta_W) = 0.213$$

is the weak mixing term, and $F(Q^2)$ is the nuclear form factor as a function of the momentum transfer Q. [2]

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Form Factor: A source of systematic uncertainty

$F(Q^2)$ is a representation of the nucleon distribution in the xenon nucleus. It is separable into neutron and proton components -

$$F(Q^2) \approx \frac{1}{Q_W}\left(F_N(Q^2) - [1 - 4sin^2(\theta_W)]F_P(Q^2)\right)$$

The neutron distribution is dominant.

A variety of expressions for $F(Q^2)$ are used in the neutrino astrophysics community.

- Measurements of the neutron distribution have only recently become available.

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Form Factors

Patton [2]

$$F(Q^2) \approx \frac{N}{Q_W}\left(1 - \frac{Q^2}{3!}\langle R_N^2\rangle + \frac{Q^4}{5!}\langle R_N^4\rangle\right)$$

where the $\langle R_N^i\rangle$ are expectation values of the neutron distribution.

- Specifically for CEvNS.
- Based on experimental data.

Helm [3]

$$F(Q^2) = 3J_1(Qr_n)\frac{e^{-\frac{1}{2}(Qs)^2}}{Qr_n}$$

where $J_1(Qr_n)$ is the first-order spherical Bessel Function.

- Commonly used in direct detection dark matter experiments.
- Notation from [4].

Klein-Nystrand [4]

$$F(Q^2) = 3\frac{J_1(QR_A)}{QR_A}\frac{1}{1+Q^2a_k^2}$$

which assumes a hard sphere of radius R_A and a Yukawa potential of range a_k.

- Notation from [4].

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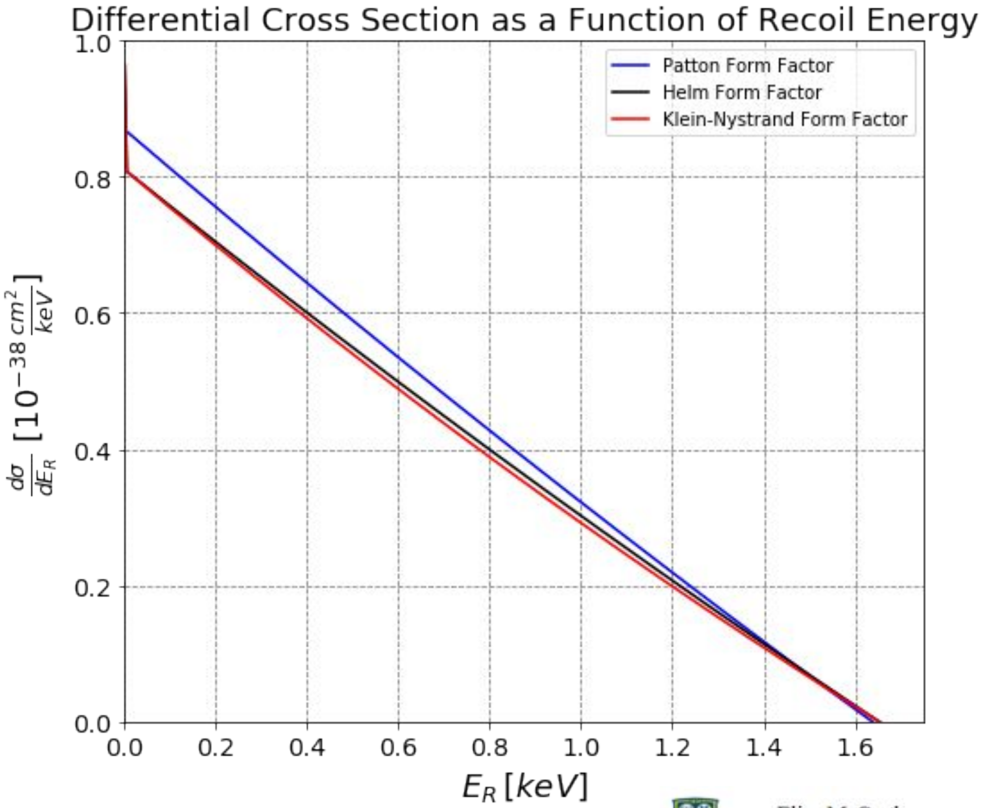
Impact of different form factors

These form factors have non-trivial impact on the differential cross section, shown here as function of recoil energy for a 10 MeV incident neutrino.

Patton FF exhibits ~10% divergence at low recoil energies.

Event rate per year-ton-keV differs by ~1% between Helm and Klein Nystrand [5], ~10% between Helm and Patton.



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What does the CCSN neutrino community use?

Experiment	Form Factor	Source
COHERENT	Klein-Nystrand	Private communication
XENON	Helm	[6]
DarkSide-20k	Helm	[7]
DUNE	Klein-Nystrand	Follows COHERENT standard
DARWIN	Helm	[8]
SUPER-CDMS	Exponential	[9]
LUX-ZEPLIN	Patton	[10]

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A standard form factor is necessary

CEvNS-sensitive experiments must utilize a common form factor to compare results across experiments and simulations.

- Critical for effective data sharing

The SNEWS collaboration is in a position to set a standard for the neutrino astrophysics community.

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Summary and Future Work

- As a flavor-independent interaction, CEvNS is a powerful tool for the detection of CCSN neutrinos.
- CEvNS-sensitive SNEWS experiments currently utilize different form factors, hampering our ability to compare results across experiments and simulations.
- SNEWS must set a common standard for CEvNS-sensitive member experiments.

Future work:

1. Simulated CCSN events in LZ available in the next 9 months
2. SNOwGLoBES
   - Implement support for CEvNS interactions
3. Develop real-time trigger for LZ detection of CCSN neutrinos

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Questions?

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References

[1] NEST - http://nest.physics.ucdavis.edu/

[2] Patton et al. (2012) - http://arxiv.org/abs/1207.0693

[3] Lewin & Smith (1996) - http://www.sciencedirect.com/science/article/pii/S0927650596000473

[4] Klein & Nystrand (1999) - http://arxiv.org/abs/hep-ph/9902259

[5] Sierra et al. (2019) - http://arxiv.org/abs/1902.07398

[6] Aprile et al. (2016) - https://doi.org/10.1088%2F1475-7516%2F2016%2F04%2F027

[7] Aalseth et al. (2018) - http://arxiv.org/abs/1707.08145

[8] Aalbers et al. (2016) - http://arxiv.org/abs/1606.07001

[9] Agnese et al. (2017) - http://arxiv.org/abs/1610.00006

[10] Khaitan (2018) - https://arxiv.org/abs/1801.05651

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