Multiple Neutron Scatter Events in the LUX-ZEPLIN Dark Matter Search Experiment

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Abstract

The LUX-ZEPLIN (LZ) direct dark matter search experiment uses a dual phase time projection chamber (TPC) with a liquid xenon target to detect nuclear recoils caused by WIMP dark matter. To identify a WIMP-induced nuclear recoil signal, a comprehensive understanding of the expected backgrounds is required. One potential source of irreducible background events is the scattering of Xe nuclei by neutrons generated by radioactivity in the detector components or surroundings. Unlike in the case of WIMPs, an incoming neutron will sometimes generate multiple nuclear scatters in the active volume of the detector, and these multiple scatter events can be used to gain a better understanding of the neutron background.

LUX-ZEPLIN (LZ)

The LUX-ZEPLIN (LZ) experiment is a collaboration of 35 institutes and around 250 scientists, engineers, and technical staff. The detector used in this dark matter search is housed at the Sanford Underground Research Facility (SURF) in South Dakota, and builds on the preceding work in the field carried out by the LUX and ZEPLIN collaborations.

LZ [1] is a direct detection dark matter search experiment, meaning that it aims to detect the interactions of weakly interacting massive particle (WIMP) dark matter with a target material in the detector. In the case of LZ, as with several other current direct dark matter detectors, this target is xenon. The excitation and ionisation of the xenon can be detected in the form of two signals, referred to as S1 and S2, as shown in figure 1. LZ uses a dual-phase time projection chamber (TPC), meaning that both liquid and gaseous xenon are present in the detector.

An incoming particle causes excitation and ionisation of the liquid xenon, causing the emission of both photons and electrons. The photons are detected by photomultiplier tubes (PMTs) at the top and bottom of the detector, and this signal is denoted S1. The emitted electrons are drifted upwards by an electric field to the gas region. At this stage, the electrons cause electroluminescence in the gas. The pulse produced from the detection of these photons is the S2 signal. An illustration of a PMT output waveform containing the S1 and S2 pulses is shown at the bottom of figure 1. Thich allows for three-dimensional spatial reconstruction of events.

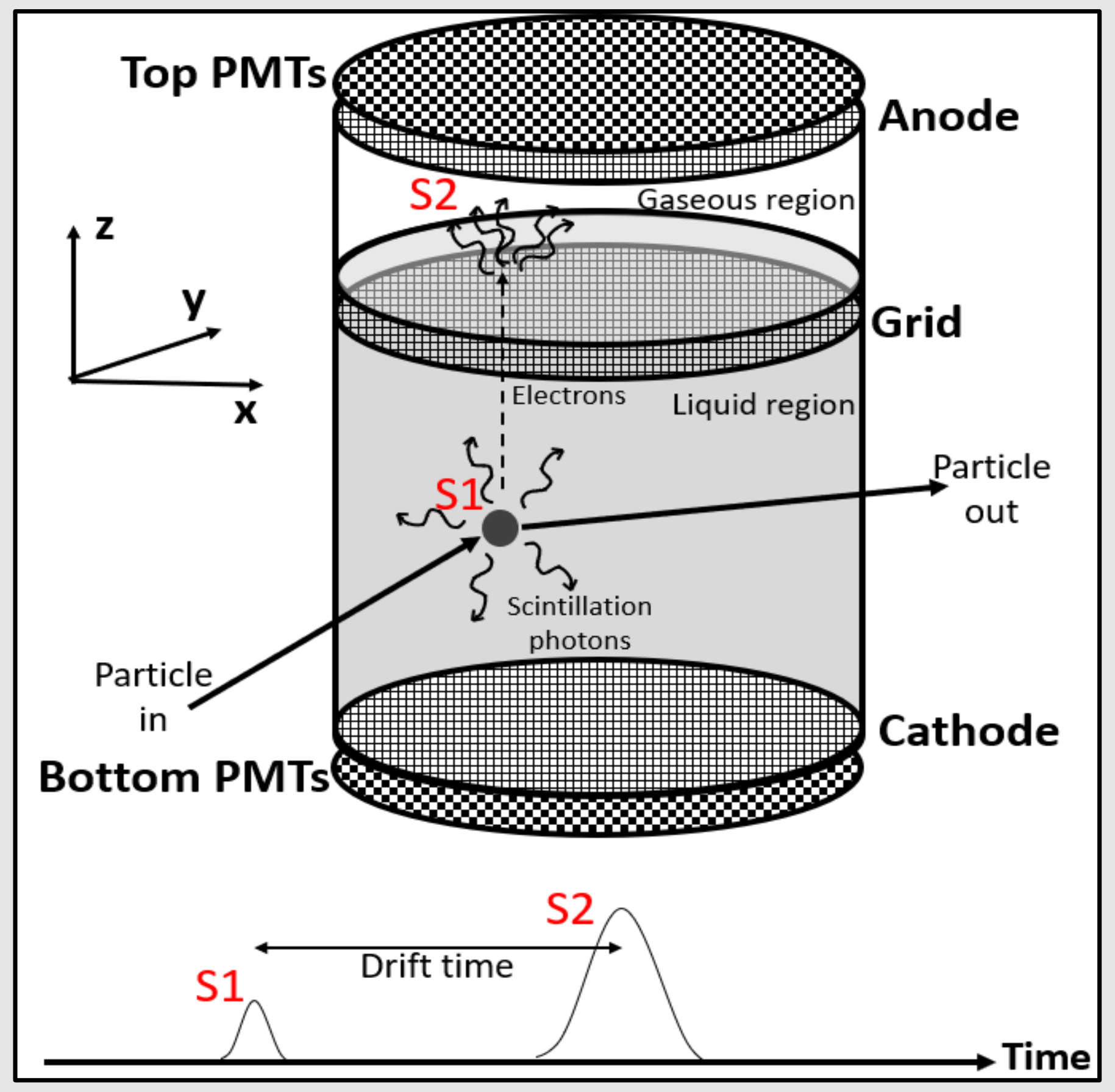

Fig 1. A diagram of a dual-phase time projection chamber, as used in LZ. An example waveform including the S1 and S2 pulses is also shown

The relative sizes of the S1 and S2 pulses can be used to identify the type of event that occurred in the detector. Two types of events are electron recoils (ERs), caused by Compton scattering or beta decay, and nuclear recoils (NRs), caused by background neutron or WIMP interactions. Both of these types of event will cause the emission of photons and electrons and hence will produce these S1 and S2 signals. ER and NR events can be distinguished when they are plotted in S1 vs. log(S2) space, as the two types of event form two distinct bands.

Neutron Calibration

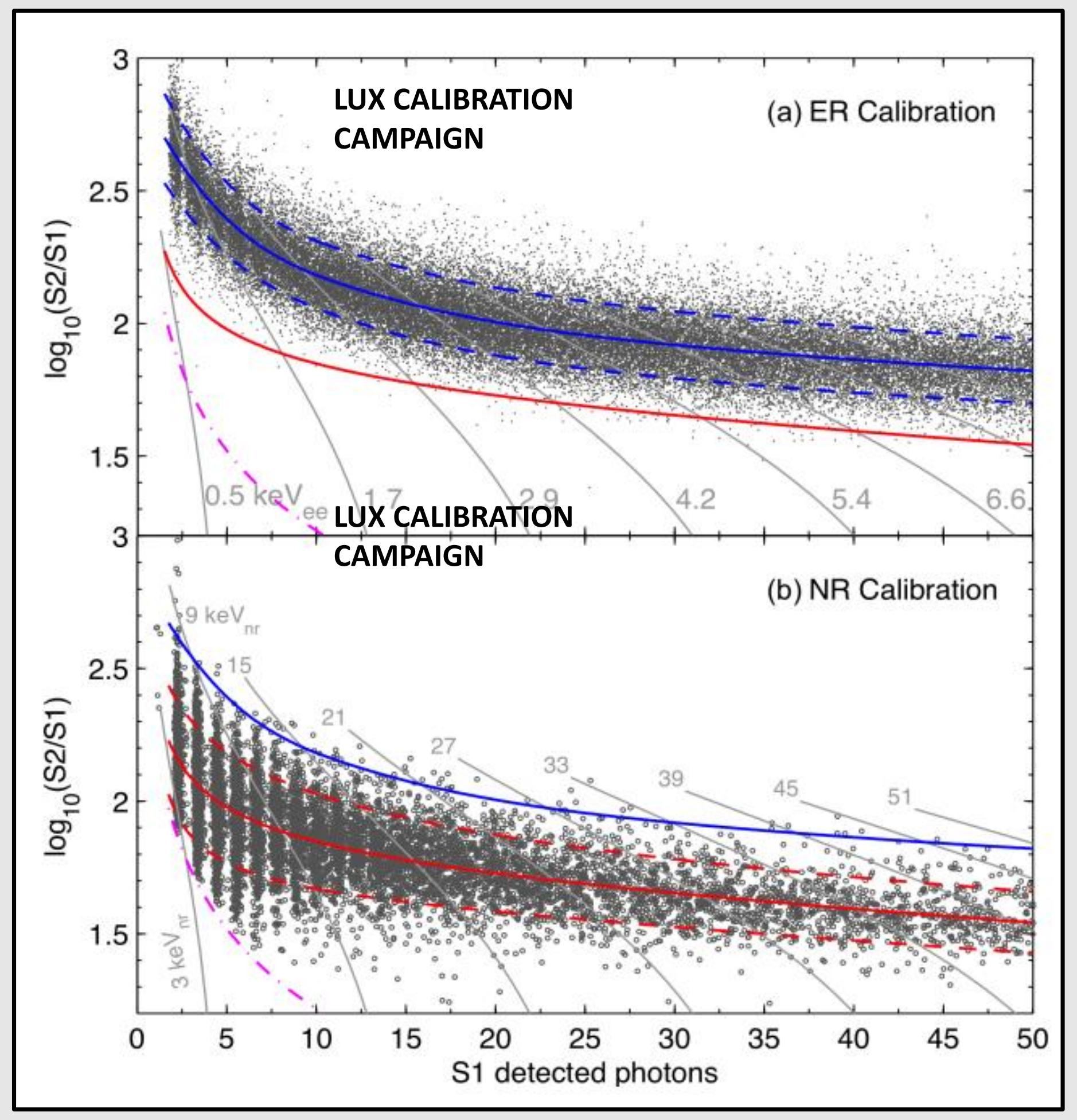

Fig 2. log(S2/S1) plotted against S1 for the LUX calibration campaign [2]. The ER band (a) was found from beta decays from a ^{3}H source, and the NR band (b) used a calibration source of DD neutrons.

Before data can be gathered on a run with a given detector, calibration is necessary. In the calibration process, the bands in S1 vs. log(S2) space for NR and ER events are produced. An example of this is shown in figure 2 [2] which shows the calibration bands produced by the LUX collaboration.

To do this requires the introduction of a source of particles into the detector that are known to interact in the desired way with the liquid xenon. This is done either by use of source delivery tubes or by dispersing a source in the liquid target. For the NR calibration, neutron sources are the favoured method of calibration. A source used in recent experiments, including LZ, has been a deuterium-deuterium (DD) neutron generator, as this uses fusion to produce monoenergetic neutrons, which leads to less complicated analysis than neutron spectra.

Figure 3 shows a region of this S1 vs. log(S2) space for a DD neutron NR calibration run of LZ, with plots for single scatter (SS) events (left) and multiple scatter (MS) events (right). For an MS event, the separate S2s can normally be resolved due to the different electron drift times, so these are just summed to give the total S2 signal. However, the S1 signals are only separated in time by the time between collisions, so only one S1 pulse appears for an MS event. As can be seen from the figure, there is a clear NR band visible in the calibration data. However, this band appears to be higher and thicker when multiple nuclear recoils occur in a given event.

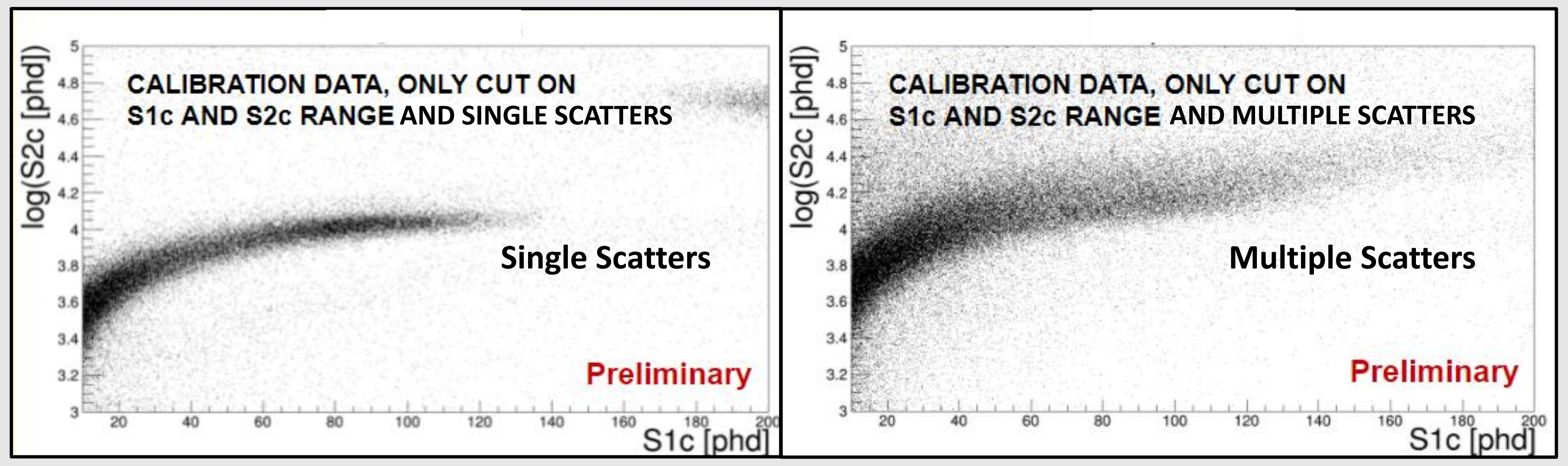

Fig 3. Plots of corrected (c) S1 and S2 signals for DD calibration data, showing the nuclear recoil (NR) band for both single scatter and multiple scatter events of neutrons in the TPC.

Multiple Scatter Nuclear Recoil Band for DD Neutrons

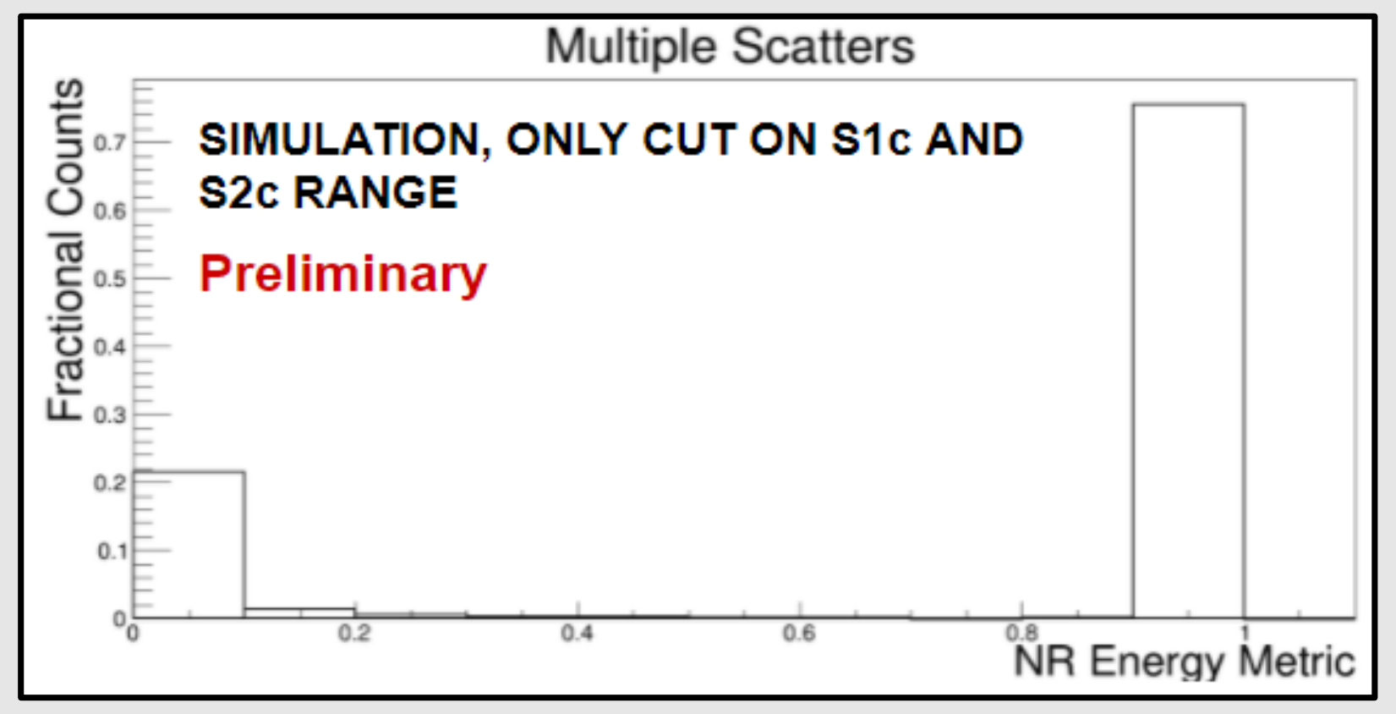

Fig 4. Plot of the NR energy metric for simulated multiple scatter DD neutron events with S1c < 200 phd, 2 phd < log(S2c) < 6.5 phd. Plotted as a fraction of the total counts recorded.

There are a few hypotheses that could explain this effect of the rising and thickening of the MS NR band. One is that, in a given MS event, some of the scatters counted may not be nuclear recoils, and hence move the log(S2) position of the event upwards. To investigate this further, simulated datasets for DD neutrons were studied, so as to have access to the truth information for the interactions.

$$\boxed{\textit{NR Energy Metric} = \frac{\textit{Total Energy of Nuclear Recoils}}{\textit{Total Energy Deposited}}}$$

To do this, an NR energy metric was defined as the fraction of energy deposited in nuclear recoils. Figure 4 displays this metric for the MS events in the region of the NR band, and it shows that only a very small fraction of the events are mixed NR and non-NR, suggesting that mixed events is not the explanation for the effect.

Maintaining this requirement of pure NR events (NR energy metric equal to 1), the MS band was separated out according to the number of scatters in the event. The results of this are shown in figure 5, and it can be seen as the number of scatters increases, the band rises to higher values of log(S2).

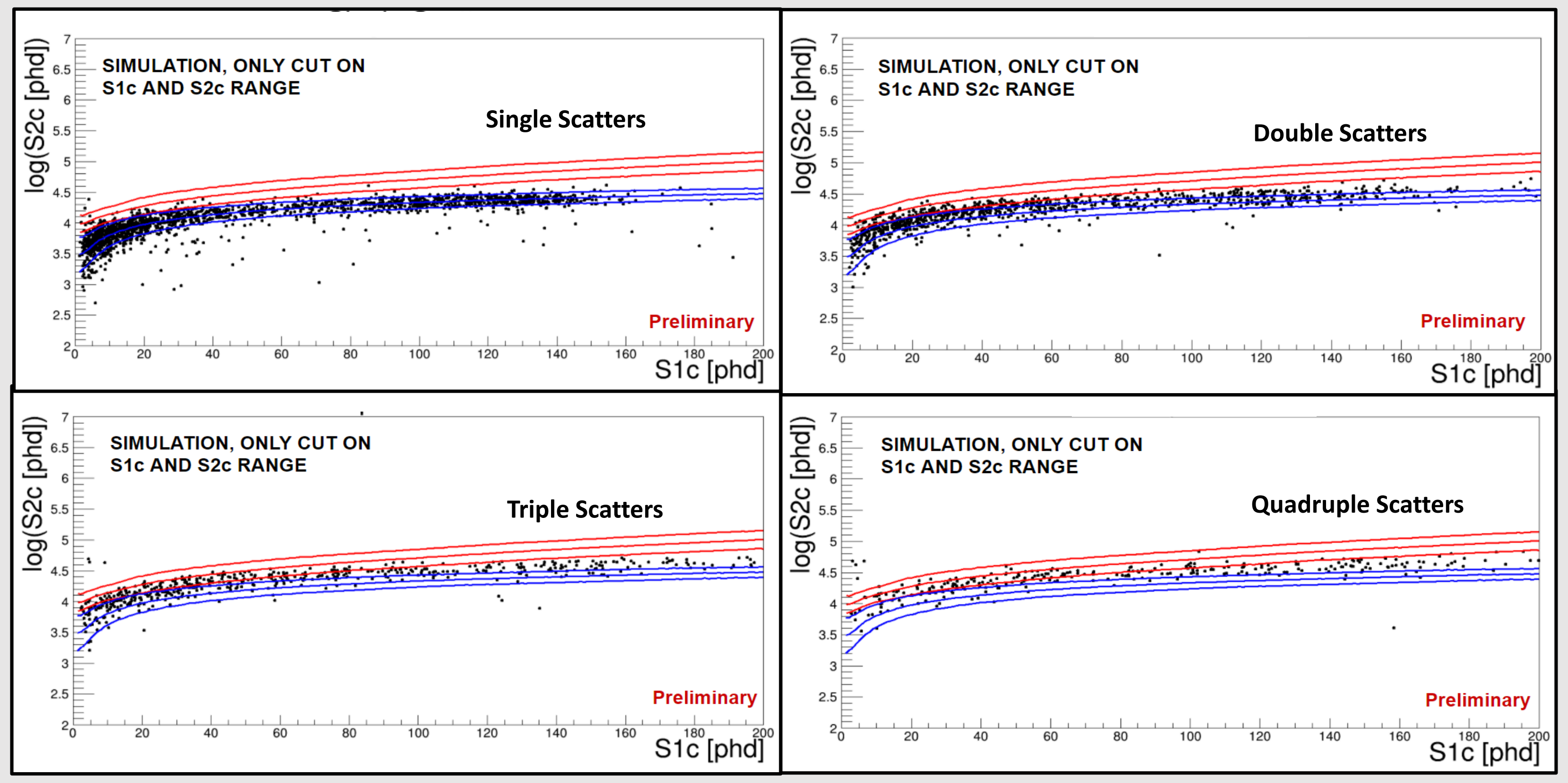

Fig 5. The nuclear recoil band for simulated, pure (NR energy metric = 1) nuclear recoil multiple scatter events, separated by number of scatters. The NR SS band is in blue and the ER SS band is in red.

Two further potential explanations are a non-linearity in either the xenon microphysics or the reconstruction of the event. Therefore, the next step with this work is to produce NR bands for each number of scatters using a detailed simulation of the xenon microphysics, and compare this to the rising bands seen. Further work is ongoing.

Bibliography

[1] B.J.Mount *et al.* LZ Technical Design Report. *arXiv:1703.09144* (2017)

[2] D. S. Akerib *et al. Calibration, event reconstruction, data analysis, and limit calculation for the LUX dark matter experiment*, Phys. Rev. **D93** 102008 (2018)

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