ER-NR Discrimination using S1 Pulse Shape
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Abstract

Dark matter constitutes the majority of the matter content of the universe, yet its fundamental nature remains unknown. Direct detection experiments using dual-phase liquid xenon time projection chambers, such as XENONnT, aim to observe rare dark matter interactions via nuclear recoils while suppressing electronic recoil backgrounds. In this work, we investigate the potential of scintillation pulse shape information from the primary light signal (S1) as an additional discriminant between electronic and nuclear recoils beyond the standard cS1–cS2 analysis. Using detailed simulations based on the NEST and FUSE frameworks, we study the expected differences in S1 timing structure arising from the distinct scintillation microphysics of electronic and nuclear recoils. While simulations predict measurable separation driven by differences in prompt light fraction and rise time, an analysis of XENONnT calibration data shows no significant discrimination under nominal operating conditions. These results suggest that detector effects and electric field configuration strongly influence observable pulse shape differences. We discuss the implications for current and future xenon-based detectors and motivate further studies at higher drift fields, where S1 pulse shape discrimination may provide enhanced background rejection and improved sensitivity to dark matter interactions.

Contents

1 Dark Matter

Despite forming the foundation of galaxies and influencing the large-scale structure of the universe, dark matter remains one of the most profound mysteries in modern physics. It does not interact with the electromagnetic force, making it invisible to us. Yet its gravitational effects are unmistakable. Astrophysical observations consistently show that there is far more mass present in the universe than we can account for with ordinary, visible matter.

The most direct evidence for dark matter comes from galaxy rotation curves. Stars in galaxies rotate at speeds that remain constant, or even increase, at large distances from the galactic center, defying expectations from Newtonian gravity if only visible matter were present. Additional evidence comes from gravitational lensing, the cosmic microwave background, and simulations of large-scale structure formation, all of which require a form of non-luminous matter to match observations.

Understanding dark matter is essential for completing our picture of the universe. According to current measurements, about 85% of the matter in the universe is dark matter, and it outweighs ordinary matter by roughly a factor of five. Yet the Standard Model of particle physics does not include a viable dark matter candidate. Discovering the nature of dark matter would therefore represent new physics, potentially a new particle or a new sector of interactions, and may help unify our understanding of cosmology, gravitation, and particle physics.

Since dark matter does not interact electromagnetically, we must look for it using other means. Broadly, detection strategies fall into three categories. [1]. First is producing dark matter. Experiments like those at the Large Hadron Collider (LHC) attempt to produce dark matter particles in high-energy collisions. While the particles themselves would go undetected, their presence could be inferred from missing energy and momentum in the event data. The second method is indirect detection. If dark matter particles can annihilate or decay into Standard Model particles (such as photons, positrons, or neutrinos), then telescopes and detectors can look for excesses in cosmic rays or gamma rays coming from regions of high dark matter density (like the galactic center or dwarf galaxies). Lastly is direct detection, using underground detectors that attempt to observe dark matter particles scattering off atomic nuclei. These experiments, such as XENONnT, LUX-ZEPLIN, and SuperCDMS, are designed to shield against cosmic radiation and background noise, in the hope of recording a rare dark matter interaction.

2 XENON Experiment

The XENON project is one of the leading efforts in the global search for dark matter, specifically aiming to detect Weakly Interacting Massive Particles (WIMPs) through direct detection. It uses ultra-pure liquid xenon as the detection medium, housed in deep underground laboratories to shield against background radiation. The experiment is located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, beneath 1.4 km of rock.

2.1 Why Xenon?

Xenon is an ideal material for direct detection due to its high atomic mass (which enhances the probability of WIMP-nucleus scattering), excellent self-shielding properties, and the ability to simultaneously measure both scintillation light and ionization from a single interaction. These dual signals allow for powerful discrimination between nuclear recoils (expected from dark matter interactions) and electronic recoils (typically from background radiation). Liquid xenon has emerged as a leading target material for dark matter direct detection due to a combination of favorable physical, chemical, and technological properties. It belongs to a class of noble liquids, defined as chemically inert elements that can be liquefied and used as detection media, alongside

Figure 1: XENONnT Experiment at Gran Sasso at LNGS.

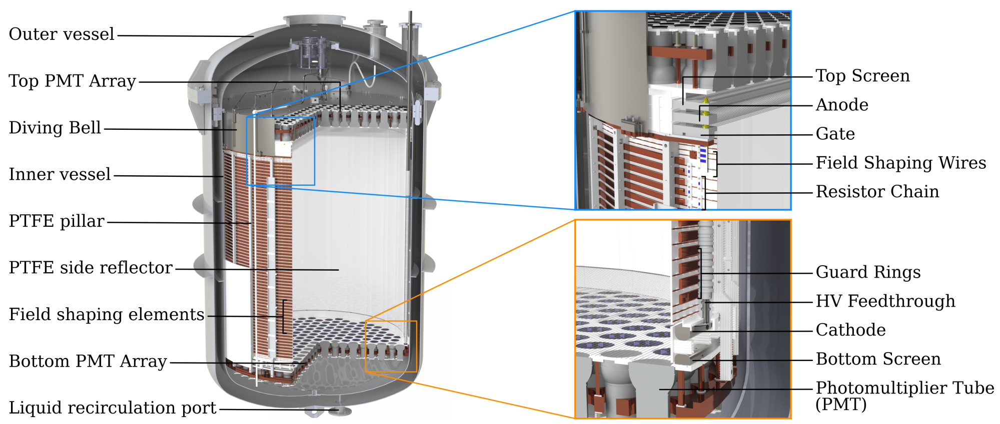
argon, neon, and helium. While all noble liquids share some useful properties, xenon stands out for several reasons. Dark matter detection via nuclear recoils benefits from targets with large nuclei due to the coherent enhancement of the WIMP-nucleus scattering cross section, which scales roughly with the square of the atomic mass number. Xenon, with an atomic mass around 131 u, provides a much stronger cross section than lighter targets like argon (40 u) or helium (4 u). This enhances its sensitivity to WIMPs, especially those with masses above $\sim$10 GeV/c^2. Xenon is very dense in its liquid state ($\sim$3.0 g/cm^3), which provides excellent self-shielding against external backgrounds such as gamma rays. Events in the outer layers of the detector can be rejected, allowing the experiment to define a low-background inner fiducial volume. This natural shielding is much more effective than in lower-density targets like liquid argon ($\sim$1.4 g/cm^3) or neon ($\sim$1.2 g/cm^3), allowing xenon detectors to be more compact for a given target mass. Unlike natural argon, which contains a long-lived radioactive isotope 39Ar, xenon is largely free of intrinsic radioactivity. This is a major advantage: the decay of 39Ar in argon (half-life $\sim$269 years) leads to a high background rate ($\sim$1 Bq/kg), which must be actively mitigated (e.g., by sourcing underground argon). Xenon does contain trace levels of radioactive 85Kr, but these can be removed to extremely low levels through cryogenic distillation. Xenon can be scaled to tonne-scale detectors while maintaining extreme purity. It is relatively easy to purify through gas-phase recirculation and getter systems, which remove electronegative impurities that would otherwise absorb ionization electrons. The high boiling point of xenon (165 K) also makes it easier to contain and manage compared to neon or helium, which require lower temperatures and more complex cryogenics.

2.2 Dual-Phase Time Projection Chamber

The XENON experiment employs a cylindrical dual-phase (liquid-gas) time projection chamber (TPC) as its central detector technology. This configuration allows for precise three-dimensional event localization and background rejection, while scaling effectively to multi-tonne target masses. The TPC is housed within a cryostat and supported by a suite of systems designed to maintain high purity, low backgrounds, and stable electric fields. The TPC is a vertically oriented cylinder filled with ultra-pure liquid xenon (LXe), with a thin layer of gaseous xenon (GXe) above the liquid surface. The active volume is defined by:

- A field cage constructed from polytetrafluoroethylene (PTFE) panels, chosen for their high reflectivity at 178 nm (the wavelength of xenon scintillation) and radiopurity.
- Field-shaping rings, typically made from oxygen-free high-conductivity (OFHC) copper, embedded in the PTFE walls and connected via a resistor chain to ensure a uniform electric drift field along the vertical axis.
- A cathode grid at the bottom of the TPC, maintained at a negative high voltage to establish the drift field.
- A gate grid near the top of the liquid surface, just below the gas layer, which defines the upper boundary of the drift region.
- An anode or extraction grid above the liquid surface, used to generate the high electric field required for electron extraction into the gas phase.

The TPC is enclosed in a double-walled cryostat, which maintains the xenon at its operating temperature (∼165 K) and protects the detector from external environmental fluctuations. Photodetection is achieved via two arrays of photomultiplier tubes (PMTs). The bottom array, located beneath the cathode, is in the liquid and optimized for efficient light collection and energy resolution. The top array, mounted above the gas region, is used for spatial reconstruction of event positions in the x–y plane, based on the light pattern produced near the liquid-gas interface. All optical components are selected for radiopurity and performance at cryogenic temperatures.



Schematic of the XENONnT TPC within the cryostat, with zoomed views showing the field cage, top and bottom electrode stacks, and PMT array layout. [3]

2.3 Observables

The XENON detectors utilize two distinct observables to detect and characterize interactions in the liquid xenon target. These signals are the primary scintillation signal (S1) and the secondary electroluminescence signal (S2), which arise from the excitation and ionization of xenon atoms and are central to the detector's ability to reconstruct event energy, position, and topology. When a particle interacts with the liquid xenon, it loses energy via collisions with xenon atoms, leading to excitation and ionization. Excited xenon atoms form short-lived excimers, which decay radiatively to the ground state and emit vacuum ultraviolet (VUV) photons at 178 nm. This forms the S1 signal. Ionized atoms release free electrons. Some of these electrons recombine with positive ions, producing additional VUV photons that contribute to S1. The remaining electrons are drifted upward by the applied electric field and used to generate the ionization signal. The detected S1 signal amplitude depends on several factors, including the The S1 and S2 scintillation signals in a dual-phase TPC provide both the time and spatial information necessary to reconstruct and characterize particle interactions. The S1 signal arises within a few nanoseconds when an incoming particle deposits energy in the liquid xenon, exciting xenon atoms and forming excimers that decay with the emission of VUV photons. This prompt scintillation light is detected nearly simultaneously by both the top and bottom photomultiplier tube position of the interaction within the TPC. In contrast, the S2 signal is delayed and arises from the ionization component of the interaction. Free electrons liberated during the energy deposition are drifted upwards under the influence of an electric field, typically at velocities around 1–2 mm/μs. Upon reaching the liquid-gas interface, these electrons are extracted into the gas phase and accelerated by a much stronger electric field on the order of 10 kV/cm. This process induces proportional scintillation, which produces a secondary light signal in the gas phase. The S2 signal is thus delayed relative to S1 by a time that encodes the depth of the original interaction, and its time profile is broader due to the longitudinal diffusion of electrons during their drift and the spatial extent of the electroluminescence region.

The top PMT array is primarily responsible for reconstructing the x–y position of the event based on the S2 light pattern, while the bottom array provides good light collection efficiency for S1 and contributes to energy resolution.

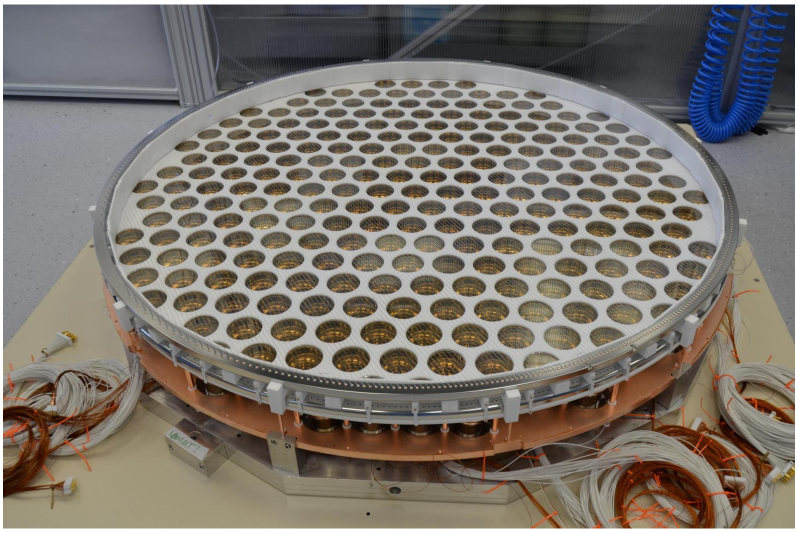


Figure 2: Top PMT array in the XENONnT experiment.

2.4 Background Mitigation

Because the expected dark matter interaction rate is extremely low (fewer than a few events per tonne per year) background suppression is critical in any direct detection experiment. Even rare interactions from ambient radioactivity, cosmic rays, or secondary particles can mimic or obscure a potential WIMP signal. To mitigate these backgrounds, the XENON detectors employ a multi-layer shielding strategy combining passive shielding and active vetoes.

2.4.1 Cherenkov Muon Veto

The innermost cryostat containing the TPC is located at the center of a large cylindrical water tank, typically 10 meters in diameter and height. The several meter thick layer of high-purity water attenuates environmental gamma rays and neutrons originating from natural radioactivity in the surrounding rock and laboratory infrastructure. Water is an effective neutron moderator and absorber, as well as a gamma attenuator, making it ideal for reducing ambient radiation without introducing additional radioactive backgrounds. Despite being located underground at LNGS, which provides 3600 meters water equivalent of overburden, a residual flux of high-energy cosmic muons remains. These muons can produce neutrons via spallation or photonuclear interactions in surrounding materials, which can in turn mimic nuclear recoils in the detector. To tag and reject these events, the water tank is instrumented with photomultiplier tubes that detect Cherenkov light emitted by muons traversing the water. Any coincident signal in the TPC and water tank can be vetoed in software.

2.4.2 Neutron Veto

A major upgrade in XENONnT compared to its predecessor XENON1T is the addition of an inner neutron veto system surrounding the TPC cryostat. This veto consists of a layer of liquid scintillator doped with gadolinium, enclosed in an acrylic tank between the cryostat and water shield. The scintillator detects neutrons that scatter in the xenon and subsequently escape, or neutrons produced by radiogenic or cosmogenic processes in surrounding materials. When a neutron captures on a nucleus, it emits gamma rays that deposit energy in the scintillator, producing detectable scintillation light. The neutron veto is optically isolated from the xenon detector and instrumented with its own array of PMTs. Events in the TPC that are accompanied by energy deposition in the veto volume are rejected. The inclusion of the neutron veto in XENONnT improves background rejection and helps define a cleaner region of interest for WIMP searches. It also allows for better characterization of the ambient neutron background and validation of Monte Carlo simulations used in background modeling.

2.5 WIMP-Nucleon Cross Section

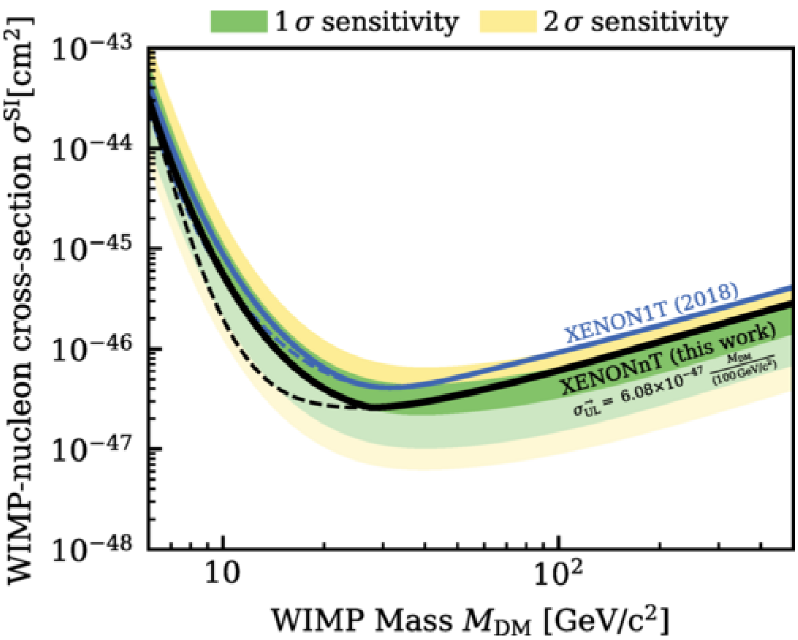


Figure 3: Upper bound on the spin-independent WIMP–nucleon cross section at the 90% confidence level (solid black curve) as a function of WIMP mass. [2]

The full black line shown in the exclusion plot represents the 90% confidence level upper limit on the spin-independent WIMP-nucleon cross section as a function of the WIMP mass. This limit defines the maximum interaction strength allowed by the data: for any given WIMP mass, models predicting a cross section above this curve are excluded at the 90% confidence level. In other words, the experiment did not observe any excess events consistent with WIMPs in that parameter region, and therefore it can rule out those models with high statistical confidence.

This type of exclusion limit is a key result in direct dark matter detection experiments. It provides an empirical constraint on theoretical models and helps narrow down the viable parameter space for WIMP dark matter candidates. The shape of the exclusion curve is influenced by the detector's sensitivity across a range of recoil energies, which in turn depends on factors such as detector mass, exposure time, energy resolution, and background suppression techniques.

To improve these exclusion limits, particularly to probe weaker WIMP-nucleon interactions (i.e., smaller cross sections), it is essential to develop and operate more sensitive detectors. Sensitivity improvements can come from scaling up the target mass, reducing background through material purification and shielding, and extending the total exposure by running the experiment over longer time periods. Advanced analysis techniques, such as improved signal discrimination (e.g., using pulse shape information or machine learning classifiers), also contribute significantly by increasing the effective signal-to-background ratio.

2.6 cS1-cS2 Space

The S1 produced by an event is affected by the event's depth in the detector. Due to geometrical and optical effects, such as photon absorption, reflections, and solid angle coverage, events that occur deeper in the liquid xenon tend to result in a larger observed S1 signal, even if the true deposited energy is the same. This introduces a position-dependent variation in light collection, complicating any analysis that relies on comparing S1 amplitudes across events. To account for this variation, experiments apply a position-dependent correction to the raw S1 signal, resulting in a quantity called corrected S1 (cS1). This correction effectively transforms the observed S1 light yield as if the interaction had occurred at a reference location (typically the center of the detector) where light collection is assumed to be uniform and well-characterized. The cS1 value thus reflects the intrinsic light yield of the interaction, decoupled from positional artifacts. Using cS1 provides several advantages. It allows for uniform comparison of events throughout the active volume of the detector, improving the fidelity of background modeling and signal identification. More importantly, cS1 plays a central role in energy reconstruction, particularly when combined with the S2 to estimate the total deposited energy. Position-corrected observables like cS1 are therefore essential for precision measurements and event classification in dark matter searches, calibration studies, and background characterization.

3 Why S1?

Traditional dark matter analyses in dual-phase xenon detectors primarily rely on the combined use of cS1 and cS2 signals to infer both the type of interaction and the deposited energy. The ratio of cS2 to cS1 has proven effective in distinguishing electronic recoils from nuclear recoils. While this method has enabled powerful background discrimination, there remains room for improvement, especially in enhancing sensitivity at low energies, where the WIMP signal is expected to lie. One promising direction is to leverage information encoded in the S1 pulse shape, rather than just its total area. The S1 signal in liquid xenon consists of photons emitted by excited xenon dimers that decay with both singlet and triplet lifetimes. The relative populations of these states, and thus the timing profile of the S1 signal, are known to differ between ER and NR events due to differences in ionization density and recombination processes. As a result, the shape of

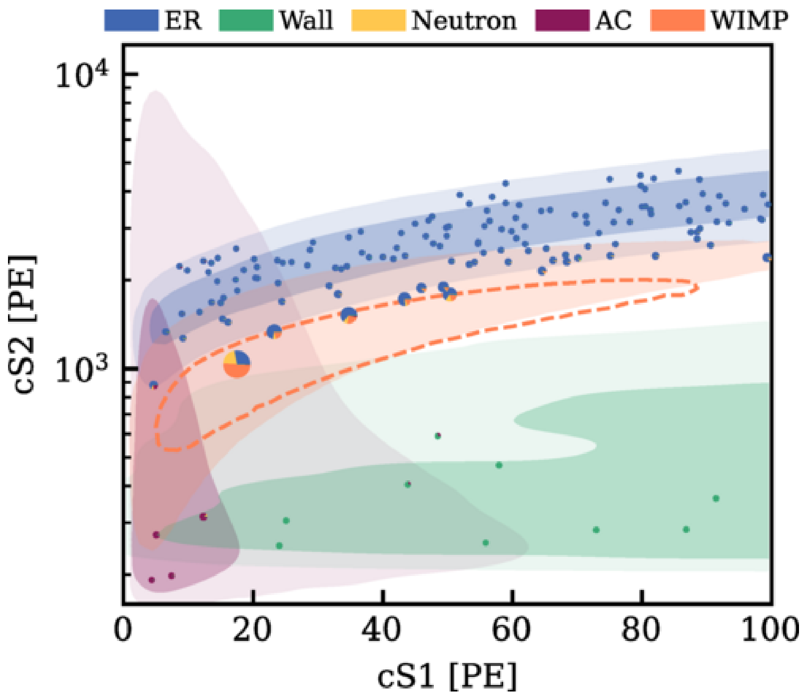


Figure 4: DM search data in the cS1-cS2 space. [2]

the S1 pulse carries additional information that is largely independent of the traditional cS1/cS2 discrimination method. By analyzing the S1 pulse shape, we can potentially improve the separation between ER and NR events, improving the detector's ability to suppress background noise and isolate true WIMP-like interactions. This is especially valuable in low-background regions or in searches pushing toward the neutrino floor, where traditional discrimination methods begin to lose effectiveness. If successful, incorporating S1 shape analysis could lead to better background rejection and an overall increase in discovery potential. This motivates a dedicated study of S1 pulse shapes in both simulation and calibration data, to systematically investigate whether there are consistent differences between ER and NR interactions. Establishing the reliability of these differences is a key step toward integrating pulse shape information into future analyses for dark-matter detection.

4 Simulation Data

Simulated data plays a critical role in the development and validation of analysis techniques for dark matter searches. In particular, it enables controlled studies of detector response and interaction properties under idealized or parameterized conditions, which may be difficult or impossible to isolate in real data alone. This is especially important when investigating subtle observables, such as the S1 pulse shape, where differences between electronic recoil and nuclear recoil interactions must be disentangled from detector effects, noise, and other confounding factors. To generate simulated events, this work utilizes the Noble Element Simulation Technique (NEST). NEST models the fundamental microphysics of particle interactions in liquid noble gases, including the processes of excitation, ionization, and the subsequent production of scintillation light and electroluminescence. It incorporates empirical data and theoretical models to simulate how different particles deposit energy and produce light in liquid xenon. NEST outputs include quantities such as the number of photons and electrons generated for each event, along with detailed timing distributions of photon production. These outputs serve as the physical "input" for further event-level simulation. Building on this foundation, the Framework for Unified Simulated Events (FUSE) is used to convert NEST outputs into realistic detector-like events. FUSE introduces additional elements such as geometric effects, detector response, and time digitization, simulating how these physical interactions would appear in the actual data acquisition system. This includes constructing full S1 and S2 waveforms, applying spatial and timing resolution effects, and modeling noise and electronic shaping. By combining NEST and FUSE, we obtain a detailed and physically motivated simulation of ER and NR interactions in a dual-phase xenon detector. These simulated events allow us to study how S1 pulse shapes differ between interaction types, under controlled conditions. They also provide a benchmark for comparing with calibration data, enabling us to assess whether observed pulse shape differences are consistent with physical expectations and can be used to enhance ER/NR discrimination.

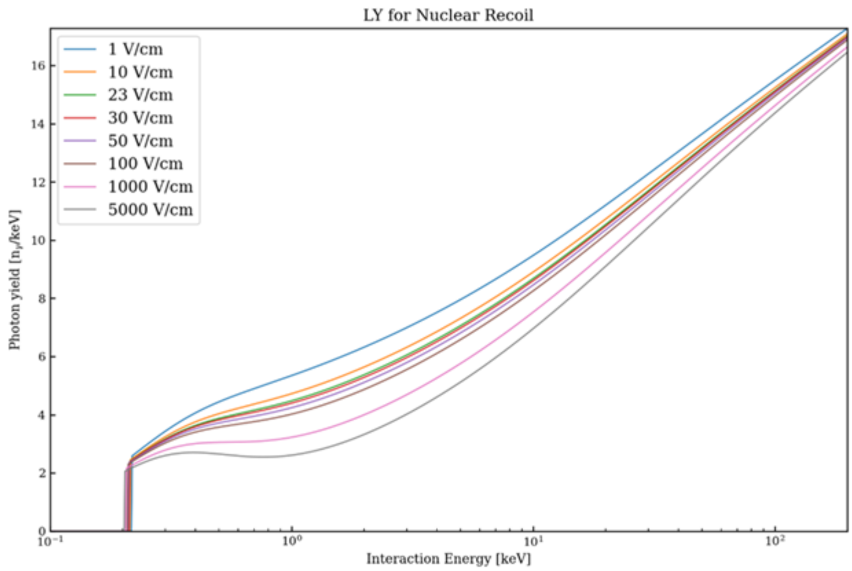


Figure 5: Example of NEST's output, plotting the photon yield (n/keV) at various drift field strengths for nuclear recoil.

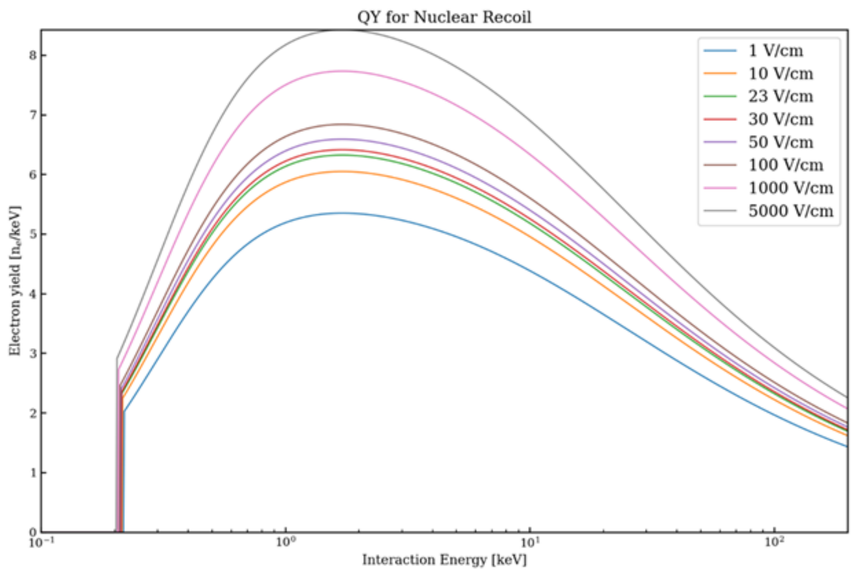


Figure 6: Example of NEST's output, plotting the electron yield (n/keV) at various drift field strengths for nuclear recoil

5 Calibration Data

Calibration data refers to data collected during controlled exposures of the detector to known particle sources or well-defined energy depositions. These datasets are essential for accurately characterizing the detector's response and for validating both simulation models and analysis techniques. In the context of dark matter searches, where the ability to distinguish between electronic recoils and nuclear recoils is paramount, calibration data provides the ground truth needed to study and quantify such differences under realistic conditions.

ER calibration is typically performed using radioactive sources that emit low-energy electrons or gammas, which mimic background-like interactions. The most common sources for simulating ERs are:

- ^{220}Rn, which provides a distributed beta-emitting source throughout the detector volume, ideal for studying spatial dependence and low-energy ER responses.
- ^{83m}Kr, a short-lived isomeric state that emits two mono-energetic conversion electrons (32.1 keV and 9.4 keV), commonly used due to its well-understood energy deposition and uniform dispersion in the detector.

To study NR responses, calibration data is taken using a deuterium-deuterium (D-D) neutron generator, which produces mono-energetic neutrons via the fusion reaction:

$$^{2}\mathrm{H} + {}^{2}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \mathrm{n} + 3.27\,\mathrm{MeV}$$

These neutrons elastically scatter off xenon nuclei, creating nuclear recoil events that closely resemble those expected from WIMP interactions. By selecting events in well-defined kinematic regions (e.g., based on angle or time-of-flight), we can construct clean NR samples for analysis.

Together, ER and NR calibration data allow us to study the detector's behavior across different interaction types and energy scales. For this work, these datasets are particularly important in evaluating whether S1 pulse shape differences between ER and NR events, as predicted in simulation, are also observed in real data. They provide the necessary benchmark for validating the use of S1 pulse shape as a potential discriminating observable in future dark matter analyses.

5.1 Event Selection and Data Quality Cuts

To ensure accurate interpretation of calibration data, it is essential to apply selection cuts that remove events inconsistent with the desired physics or affected by detector artifacts. Calibration datasets are used to characterize detector response under controlled conditions, but even these datasets can include background events, pile-up, noise, or misidentified interactions. Cuts allow us to isolate a clean and well-defined event population, enabling reliable comparisons between data and simulation and enhancing the fidelity of downstream analyses, such as energy reconstruction and pulse shape discrimination.

5.1.1 Multiple Scatter Cuts

One of the most important selection criteria is the multiple scatter cut, which removes events where more than one interaction occurs within the detector volume during a single event window. In dual-phase xenon detectors, a genuine single scatter event will produce a single S1 pulse followed by a single S2 pulse. However, if a particle scatters multiple times within the active volume, the resulting waveform may contain multiple S2 pulses or a distorted S1 signal. These events are not representative of the single-site interactions expected from WIMP or neutron scatters, and their inclusion can bias energy spectra, timing distributions, and discrimination studies. The multiple scatter cut ensures that only single scatter events, which are physically meaningful for most analyses, are retained.

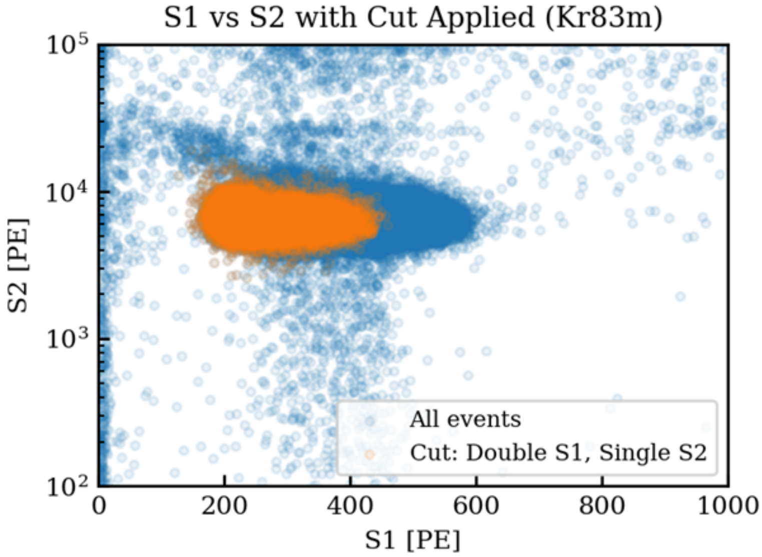


Figure 7: Neutron generator data events before (Blue) and after (Orange) applying double S1, single S2 cut.

5.1.2 Double S1 Selection in ^{83m}Kr Calibration

An additional and unique selection is applied to events from ^{83m}Kr calibration data: the double S1 selection. The decay of ^{83m}Kr proceeds in two steps: a 32.1 keV transition followed by a 9.4 keV transition, with a typical half-life between them of approximately 154 ns. This results in two distinct energy depositions in quick succession, each producing a separate S1 pulse but only a single S2 pulse, as the electrons from both decays drift together and are extracted simultaneously. Identifying events with two closely spaced S1 pulses and a single S2 pulse allows us to isolate clean ^{83m}Kr decays.

This double S1 topology is useful for several reasons. It provides a clear time structure that helps validate the S1 detection efficiency and timing response of the detector. Furthermore, by selecting the first or second S1 pulse separately, it becomes possible to study the detector's response to two well-known energy depositions under nearly identical conditions. These events also serve as an excellent benchmark for evaluating S1 pulse shape reconstruction, since the timing separation between pulses is well understood and can be used to test pulse-finding algorithms and signal decomposition methods.

6 Final Results and Discussion

6.1 Results from Simulation

Using the combined simulation framework, samples of ER and NR events were generated under controlled conditions. The simulated S1 waveforms show a clear difference in their timing structure: NR events exhibit a systematically faster rise time and a larger fraction of prompt light compared to ER events. This behavior is consistent with expectations based on the differing singlet-to-triplet population ratios and recombination dynamics for ER and NR interactions in liquid xenon. When quantified using the S1 pulse width, the simulated distributions show visible separation between ER and NR, indicating that S1 timing information has the potential to provide additional discrimination power beyond traditional cS1/cS2 methods.

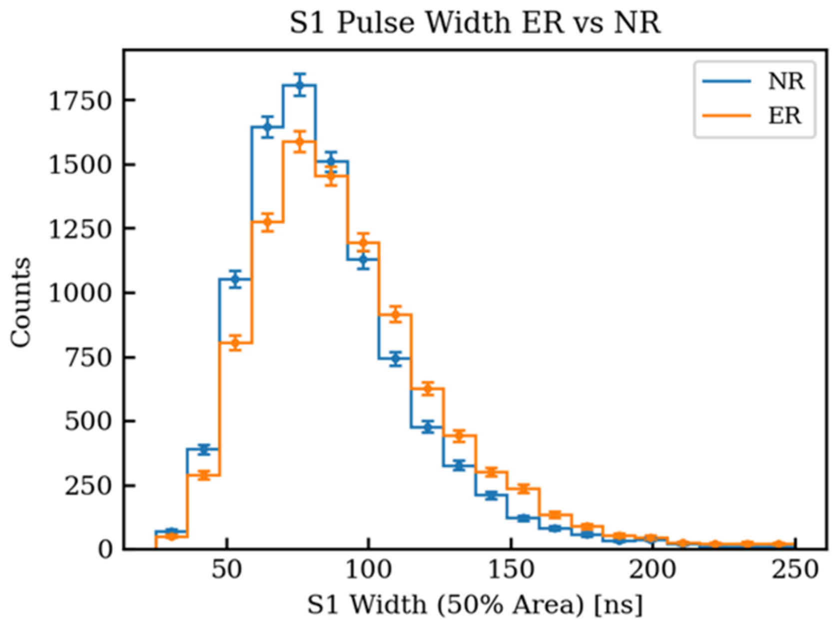


Figure 8: Simulated S1 pulse shape distributions for electronic recoil (ER) and nuclear recoil (NR) events generated using the NEST + FUSE framework. The two signals show visible separation, indicating potential discrimination power from S1 pulse shape information.

6.2 Results from Calibration Data

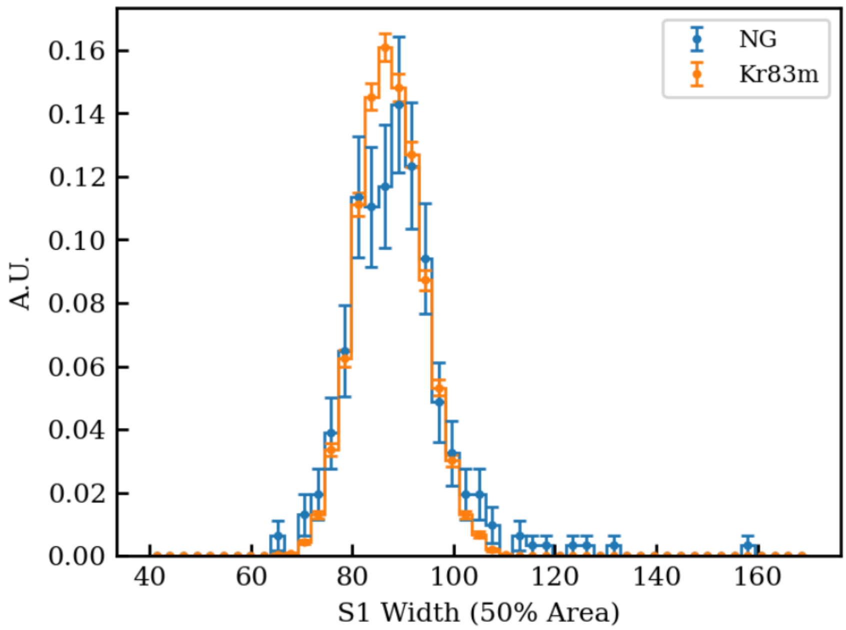


Figure 9: S1 pulse shape distributions for ER and NR events from XENONnT calibration data. The ER and NR populations show significant overlap, indicating no clear discrimination using S1 timing information at the nominal XENONnT drift field.

In contrast, when the same pulse shape analysis techniques are applied to calibration data from XENONnT, no clear separation between ER and NR populations is observed. The ER calibration data (from sources such as ^{83m}Kr and ^{220}Rn) and the NR calibration data (from D-D neutron runs) show largely overlapping distributions in S1 timing space. Within the current statistical and systematic uncertainties, the S1 pulse shapes appear consistent between ER and NR in the XENONnT operating conditions. This suggests that, at the nominal XENONnT drift field, the intrinsic physical differences in scintillation timing are either too small or are washed out by detector effects such as photon transport, PMT response, electronic shaping, and electronic noise.

6.3 Interpretation

The discrepancy between simulation and data highlights the importance of detector operating conditions, particularly the applied electric drift field. The drift field influences recombination rates and, therefore, the relative contributions of prompt and delayed scintillation components. In XENONnT, the drift field is optimized for charge extraction and energy resolution, but may not be optimal for enhancing S1 pulse shape differences. The absence of clear discrimination in data therefore motivates the exploration of alternative operating conditions.

6.3.1 Implications for Future Detectors

Future detectors such as XLZD will operate at significantly higher drift fields, which may amplify differences in recombination dynamics between ER and NR interactions. Higher fields suppress recombination more strongly for ER than for NR, potentially increasing the contrast in singlet and triplet populations and making pulse shape differences more pronounced. Repeating this analysis with XLZD data, or with dedicated high-field calibration runs, may reveal clearer S1 timing separation and enable S1 pulse shape to become a useful additional discriminant.

If successful, incorporating S1 pulse shape information into analysis frameworks could improve ER/NR discrimination, reduce background leakage, and enhance sensitivity to low-mass WIMPs, especially in regimes where traditional cS1/cS2 discrimination begins to lose effectiveness. Although no clear discrimination is observed in current XENONnT calibration data, the results of this study provide valuable guidance for future detector design and analysis strategies and motivate continued investigation into pulse shape-based methods for dark matter detection.

7 Conclusion

In this work, we investigated the potential of S1 pulse shape information as an additional discriminant between electronic recoil and nuclear recoil events in dual-phase liquid xenon detectors. Motivated by the known differences in scintillation microphysics between ER and NR interactions, we studied S1 timing characteristics using both detailed simulation and calibration data from the XENONnT experiment.

Using the combined NEST + FUSE simulation framework, we observed clear differences in the structure of S1 signals between ER and NR events. In simulation, NR interactions exhibit a larger fraction of prompt light and faster rise times, leading to visible separation in timing-based observables. These results indicate that, in principle, S1 pulse shape carries information that could enhance ER/NR discrimination beyond traditional cS1/cS2 methods.

However, when the same analysis techniques were applied to XENONnT calibration data, no clear discrimination between ER and NR populations was observed. The S1 pulse shape distributions for ER and NR events show significant overlap under the nominal XENONnT operating conditions. This suggests that, at the current drift field, intrinsic differences in scintillation timing are either too small or are obscured by detector effects such as photon transport, electronic response, and noise.

The discrepancy between simulation and data highlights the importance of detector operating parameters, particularly the electric drift field, which influences recombination and scintillation dynamics. This motivates further investigation at higher drift fields, where differences between ER and NR interactions may become more pronounced. Future detectors such as XLZD, as well as dedicated high-field calibration campaigns, provide promising opportunities to revisit S1 pulse shape discrimination under more favorable conditions.

Although S1 pulse shape discrimination does not appear to provide additional separation power in XENONnT at present, this study establishes a framework for such analyses and provides valuable guidance for future detector design and analysis strategies. Continued exploration of pulse shape-based methods may contribute to improved background rejection and enhanced sensitivity in next-generation dark matter searches.

8 Acknowledgements

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