IMPERIAL

Towards a **$0\nu\beta\beta$** decay search in the LUX-ZEPLIN (LZ) experiment: mitigating gamma-ray backgrounds

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on behalf of the LUX-ZEPLIN (LZ) Collaboration
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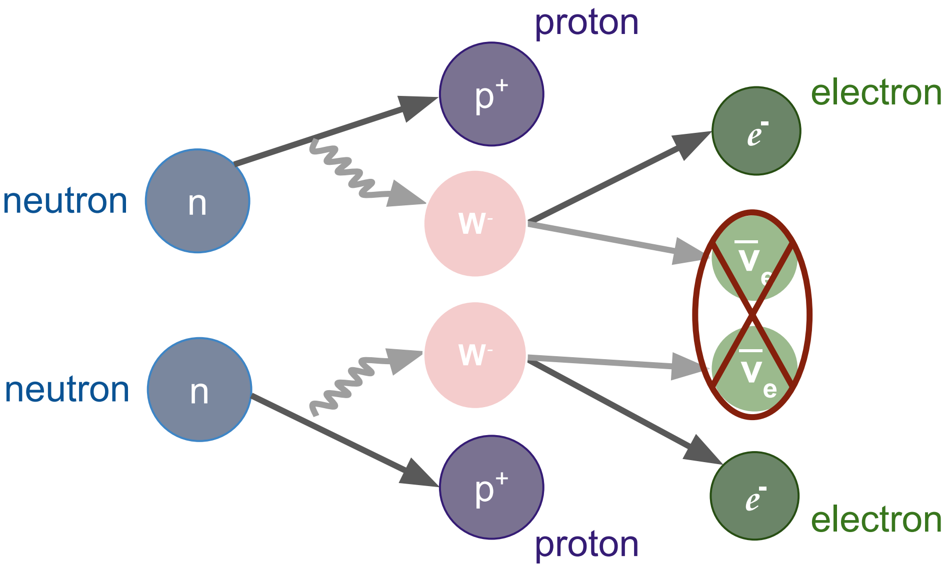
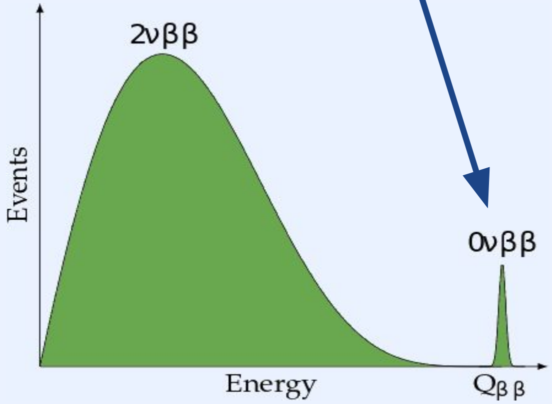
Neutrinoless Double Beta Decay (0νββ)



In LZ :

$$^{136}Xe \longrightarrow {}^{136}Ba + 2e^-$$

Observe the energy spectrum of outgoing electrons at $Q_{\beta\beta}$= 2458 keV



Neutrinoless Double Beta Decay (0νββ)

A measurement of the 0νββ decay rate would:

- Demonstrate that **neutrinos are their own antiparticle**
- Evidence of **lepton number violation**, a possible explanation for the **matter-antimatter asymmetry** in the universe
- Improve our understanding of the neutrino mass generation mechanism
- Inform about the neutrino mass hierarchy problem

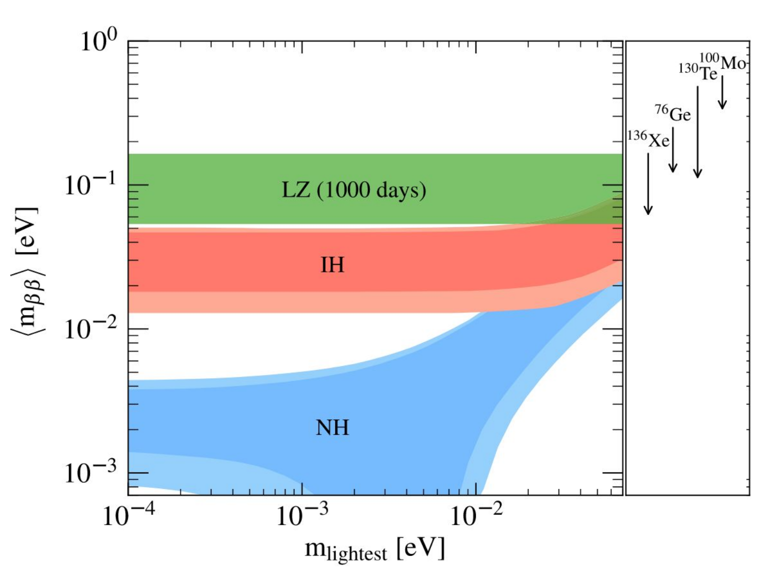


Figure taken from [1]

Dark Matter Detectors for 0νββ Decay

Current dark matter detectors are well suited to demonstrate the potential of next-generation experiments with natural xenon, such as XLZD.

The LUX-ZEPLIN (LZ) Experiment:

World-leading dark matter search with a projected sensitivity to 0νββ of

$T_{1/2}$ = 1.06 × 10^{26} yrs (90% CL), 1000 live days[1]

1. Main detector is a **7-tonne (active)** liquid xenon time projection chamber
   → **contains ^{136}Xe isotope at nat. ab. (8.86%, ~500kg)**
2. **Designed for rare-event searches** so excellent at minimizing and identifying backgrounds.
3. Has **excellent energy resolution** **(σ = 0.64% at $Q_{\beta\beta}$ = 2458 keV)**

See Alberto's talk for the latest LZ results!

Located 1 mile underground at the Sanford Underground Research Facility in Lead, South Dakota.

[1] D. S. Akerib and others, 'Projected sensitivity of the LUX-ZEPLIN experiment to the 0νββ decay of ^{136}Xe', Phys. Rev. C, vol. 102, no. 1, p. 014602, 2020, doi: 10.1103/PhysRevC.102.014602.

Detection Principle

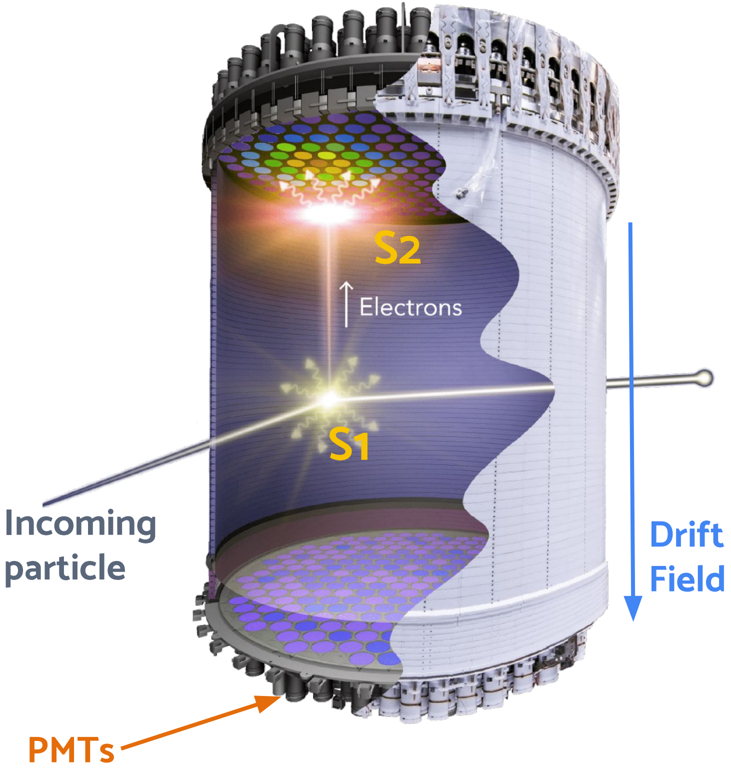
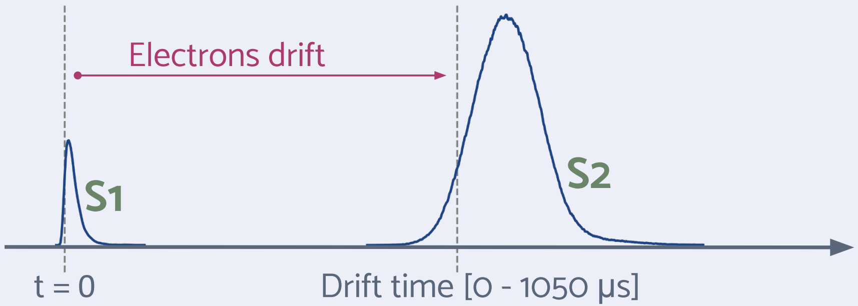
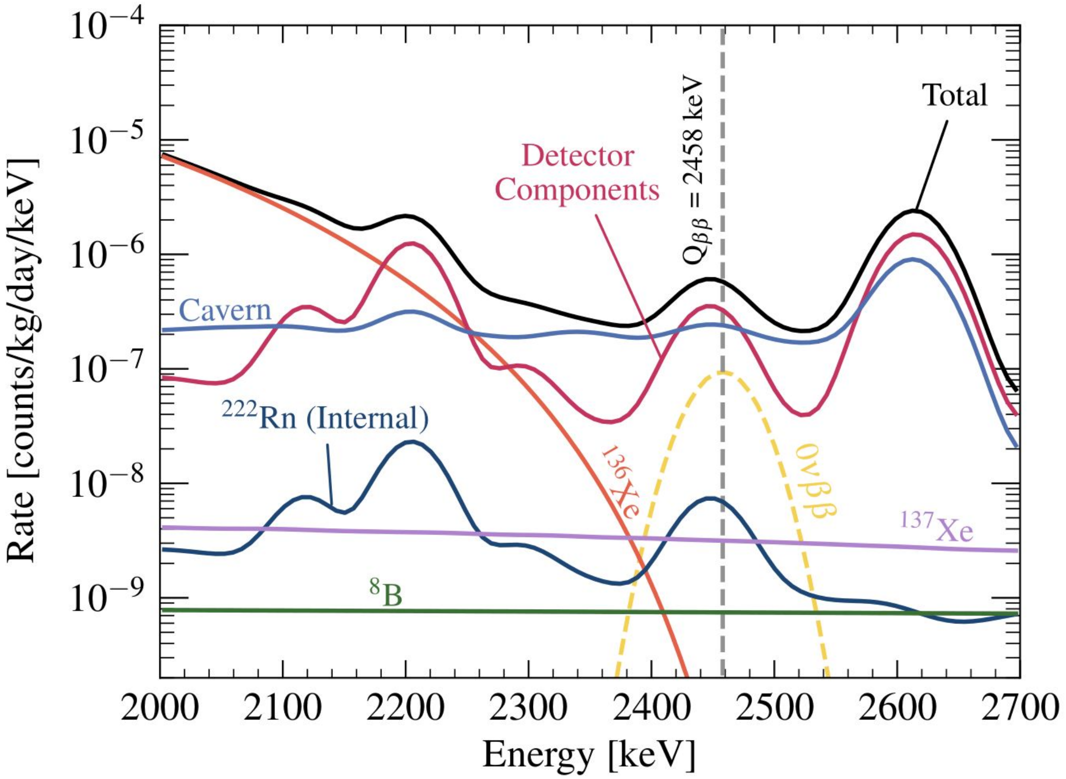


Illustration of TPC Signal



- ➔ Energy of the interaction is proportional to the size of S1 and S2
- ➔ Location reconstruction:
  - Drift time ⟶ depth
  - PMT pattern ⟶ horizontal position

Projected Background Spectrum in LZ



Signal:

Xe-136 0νββ Decay
Assumed $T_{1/2}$= 1.06 x 10^{26} y

Backgrounds:

Detector Components:
^{60}Co, ^{238}U-late, ^{232}Th-late

Cavern: ^{238}U, ^{232}Th

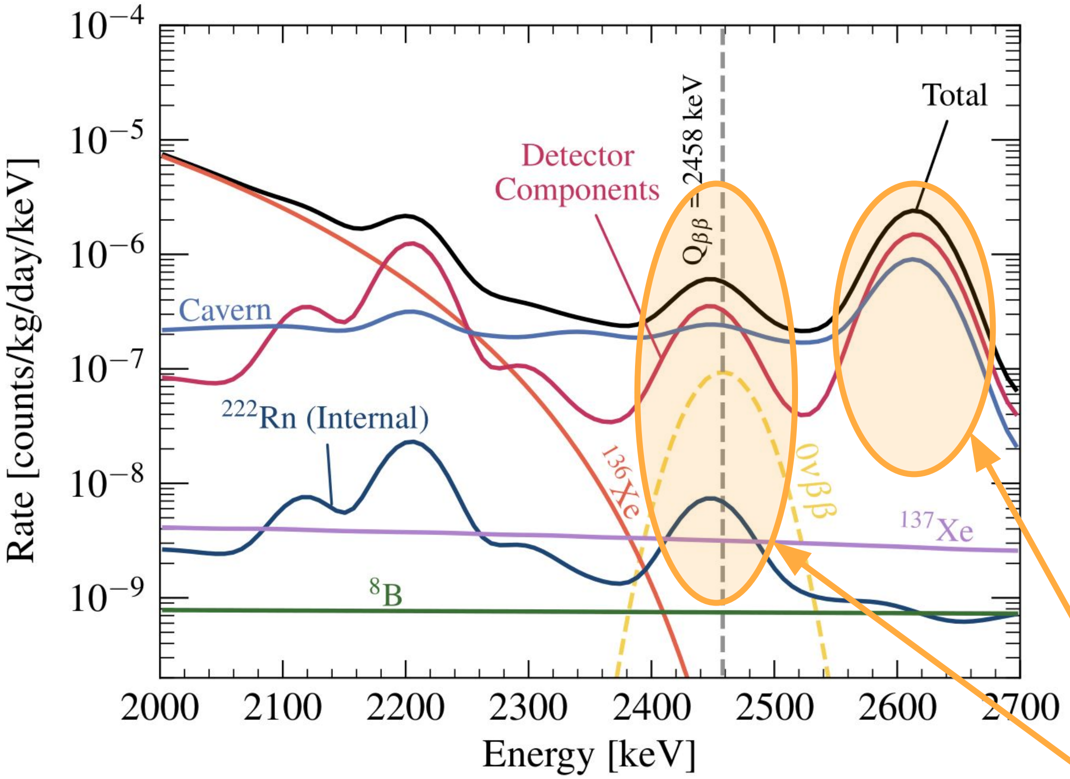
Internal ^{222}Rn (in LXe)

^{137}Xe (in LXe)

^{8}B (solar neutrinos)

Figure taken from [1]

Projected Background Spectrum in LZ



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Internal ^{222}Rn (in LXe)

^{137}Xe (in LXe)

^{8}B (solar neutrinos)

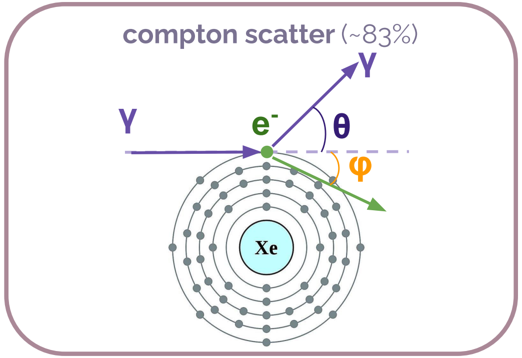
^{208}Tl gamma-rays (BR 99.79%)

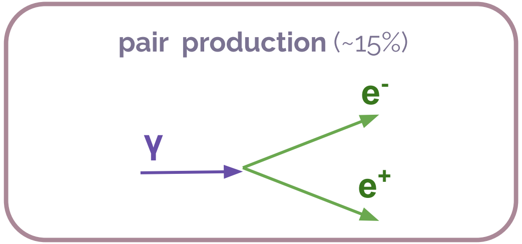
^{214}Bi gamma-rays (BR 1.55%)

How Does a ~2 MeV Photon Interact in LXe?

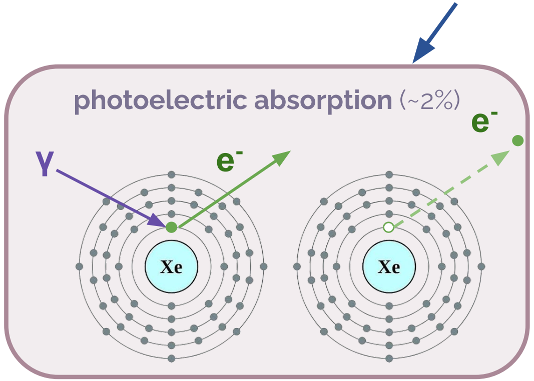
Photon interactions produce **a fast electron** which deposits its energy in LXe via :

1. Continuous energy loss ($dE/d\bar{x}$) due to collisions with atomic electrons
2. Bremsstrahlung radiation



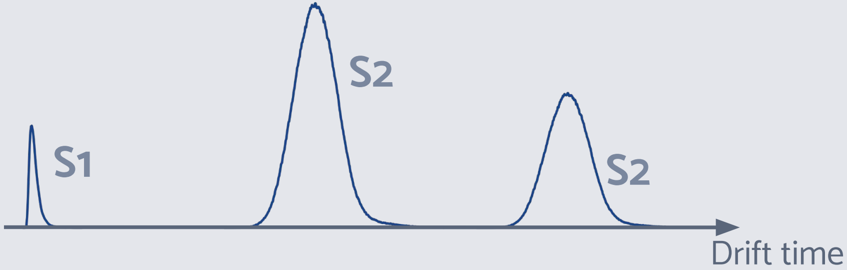


Single Site (SS) interaction



In general, **a photon interacts multiple times** in LXe before depositing all of its energy.

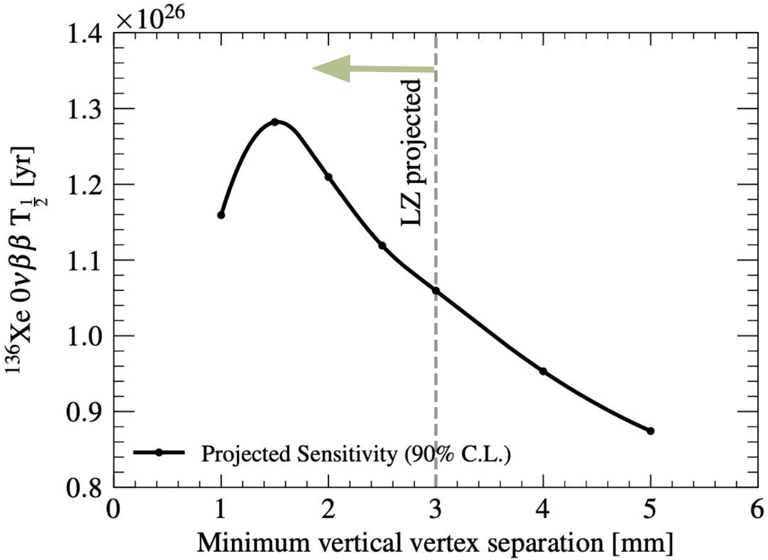
→ This leads to multiple scatter or **multiple site (MS)** signals in LZ that have one S1 and multiple S2s



Distinguishing Signal from Background

Background gamma-rays → mostly **multi-site interaction (MS)**
0νββ decay → mostly **single-site interaction (SS)**

If we **efficiently remove MS** in the data, we can improve our sensitivity!



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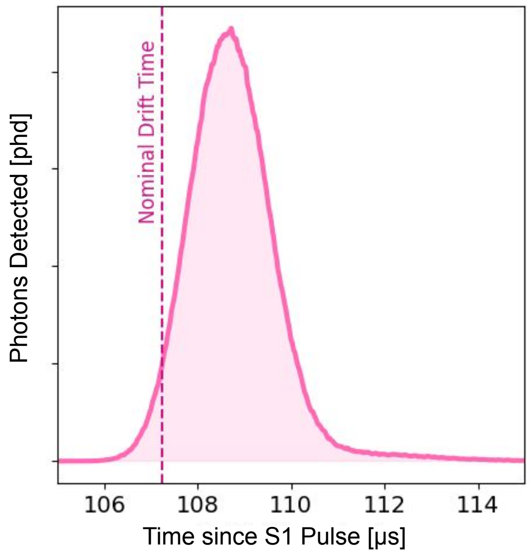
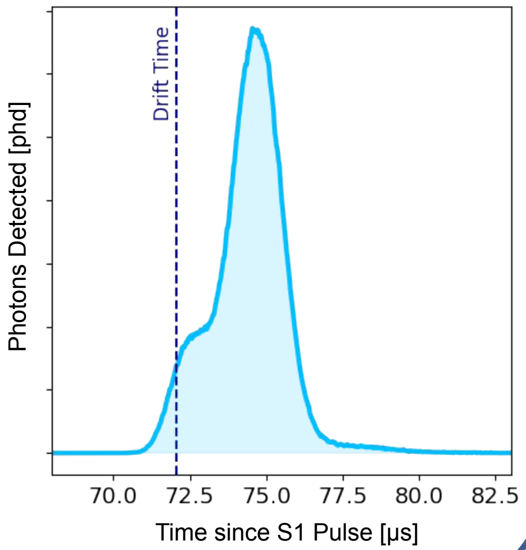
Distinguishing Signal from Background

Unresolved MS S2s are an inefficiency in the categorisation of SS and MS

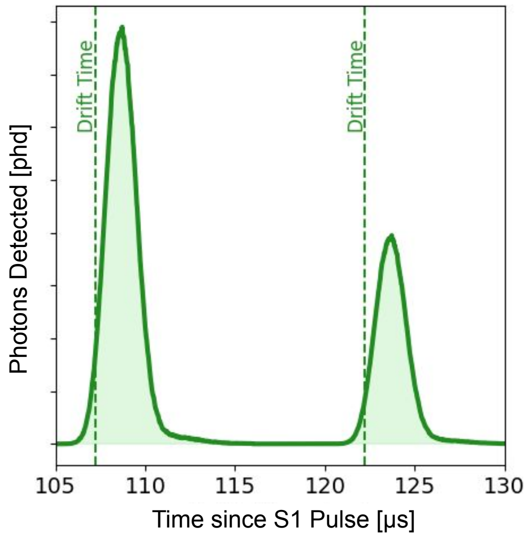
True SS Waveform



Unresolved MS Waveform



Resolved MS Waveform



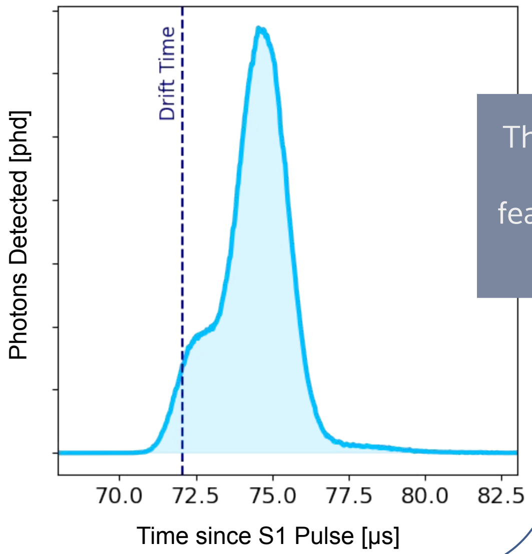
*These are toy-waveforms, for illustrative purposes.

Distinguishing Signal from Background

Unresolved MS S2s are an inefficiency in the categorisation of SS and MS

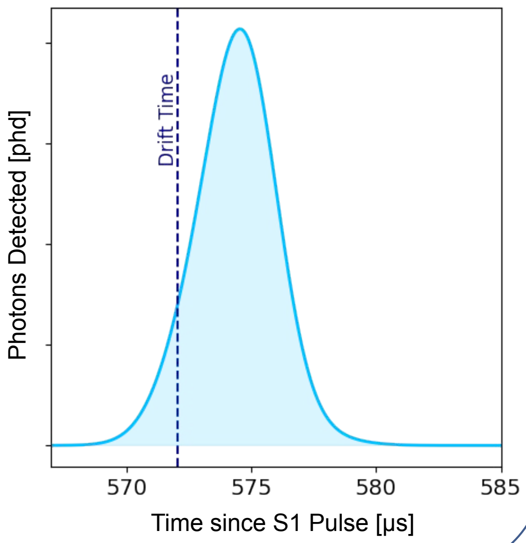
My goal: to develop a waveform-based analysis to identify the unresolved MS

Unresolved MS Waveform



The same waveform at a larger drift time, features are blurred out due to diffusion.

Unresolved MS Waveform



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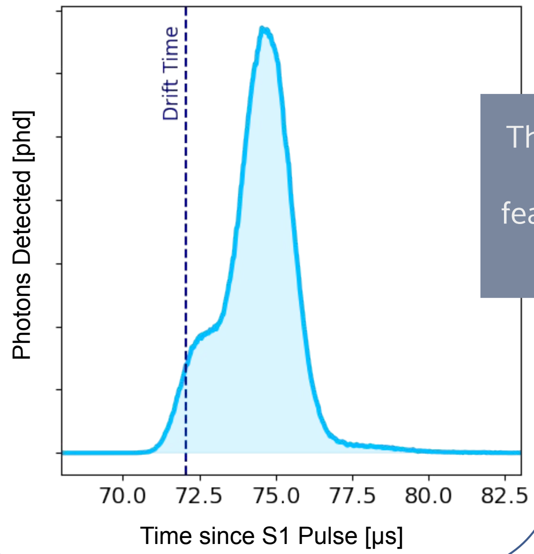

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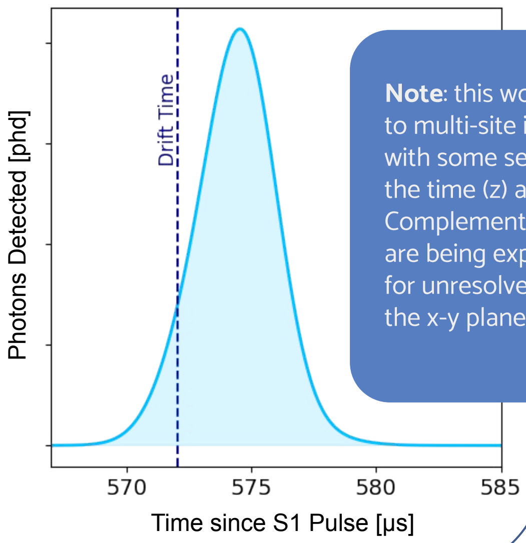
Unresolved MS Waveform



Note: this work is sensitive to multi-site interactions with some separation along the time (z) axis. Complementary approaches are being explored to search for unresolved MS events in the x-y plane[2] .

*These are toy-waveforms, for illustrative purposes.

[2] *Sazzad, A.B.M.R. et al. Predicting the single-site and multi-site event discrimination power of dual-phase time projection chambers. doi: https://doi.org/10.48550/arXiv.2510.02258 (2025)*

Overview of the analysis method

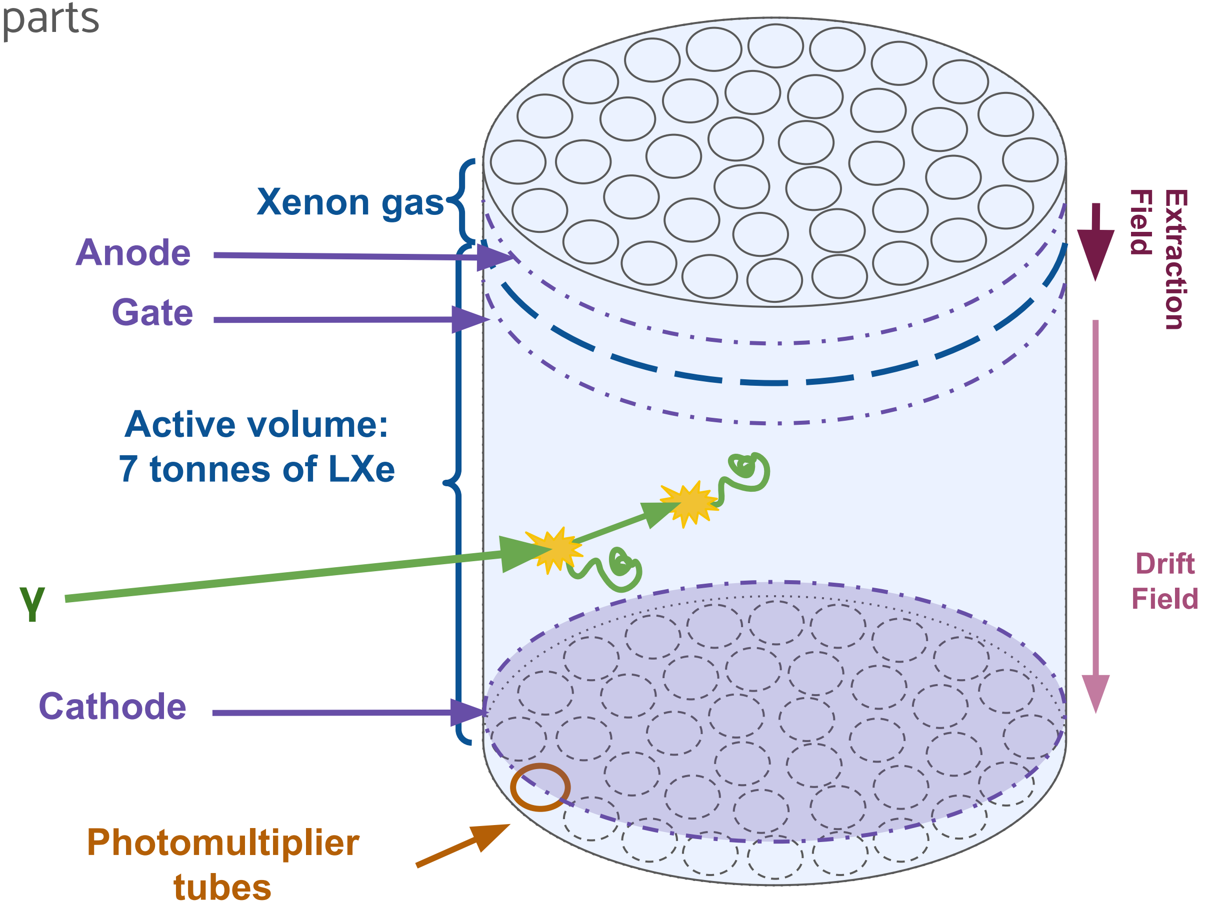
1. Build a forward model for S2 generation
2. Develop a deconvolution algorithm to remove detector effects from waveforms and recover underlying features
3. Preliminary results of the algorithm on simulated events

Developing the S2 Model

Decompose the waveform into 3 parts

1. An **extended track**:

- ➔ γ-ray interaction in liquid xenon (LXe) produces a fast electron.
- ➔ The electron deposits its energy continually along its **track**, producing a cloud of ionisation electrons



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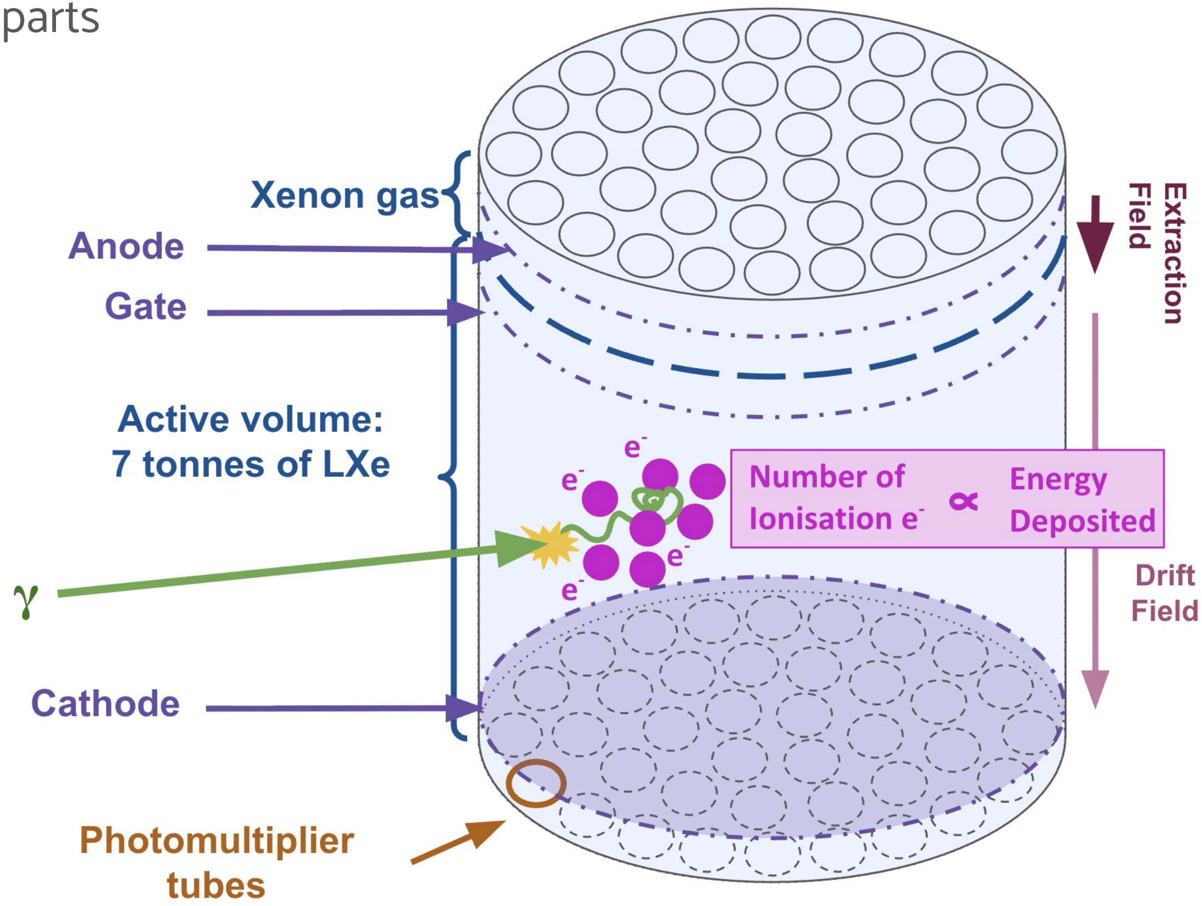
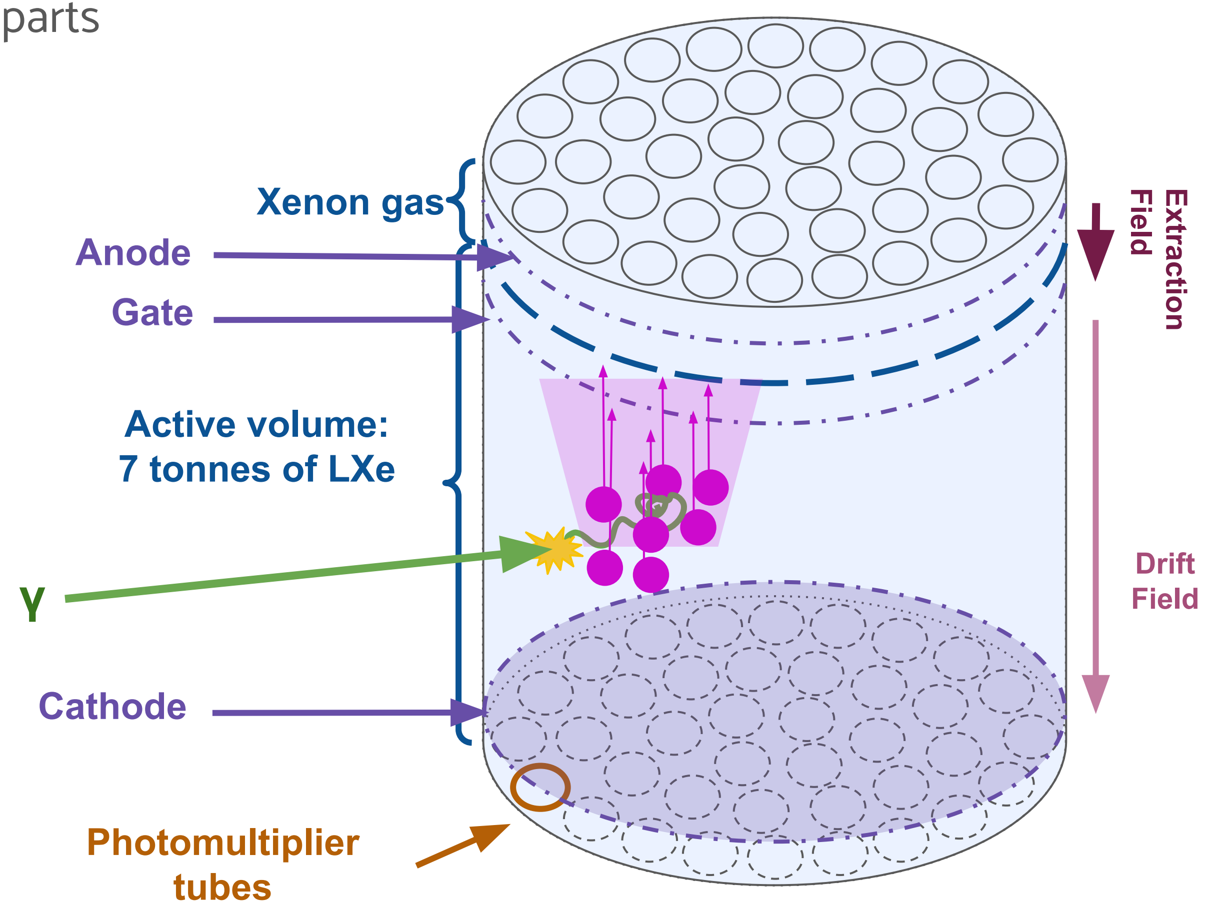


Developing the S2 Model

Decompose the waveform into 3 parts

2. The **longitudinal diffusion**, which describes the gaussian smear of the electrons as they drift up the TPC for a time t_d . The smearing is determined by the diffusion coefficient D_L and the electron's drift velocity v_d .

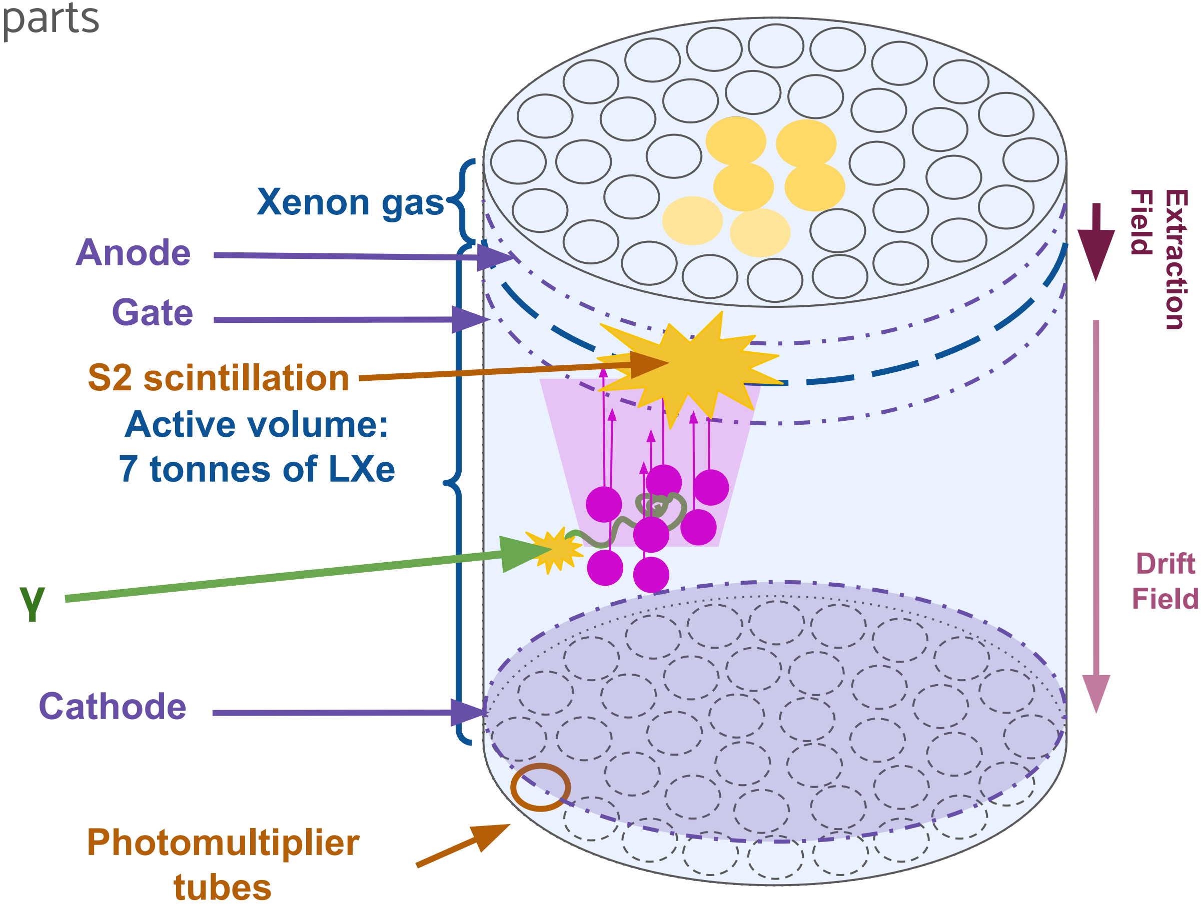
$$G\left(0, \sqrt{\frac{2D_L t_d}{v_d^2}}\right)$$



Developing the S2 Model

Decompose the waveform into 3 parts

3. The **Impulse Response Function (IRF)** of the extraction region, which describes how the ionisation signal (electrons) is transduced to detected VUV light.



Developing the S2 Model

Measuring each element of the S2 model : v_d , D_L, IRF

Extended track (dE/dz) * Longitudinal diffusion gaussian * Impulse Response Function = S2

To make the measurements, select alpha decays from Rn-222 and Po-218:

1. Nearly "point-like" interactions: to ensure that the drift time is precise and that the widening of S2 pulses is only due to diffusion and not track length.
2. Reasonable-size S2 to have smooth pulses but no saturation.
3. Population on the gate and cathode grids: to obtain drift velocity
4. Evenly spread population within the bulk of the TPC

Developing the S2 Model

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1. Nearly “point-like” interactions: to ensure that the drift time is precise and that the widening of S2 pulses is only due to diffusion and not track length.

Approximated by a δ-function so it does not need to be modelled in this case.

DEVELOPING AN S2 MODEL

Measuring each element of the S2 model : v_d , D_L, IRF

Extended track (dE/dz) * Longitudinal diffusion gaussian * Impulse Response Function = S2

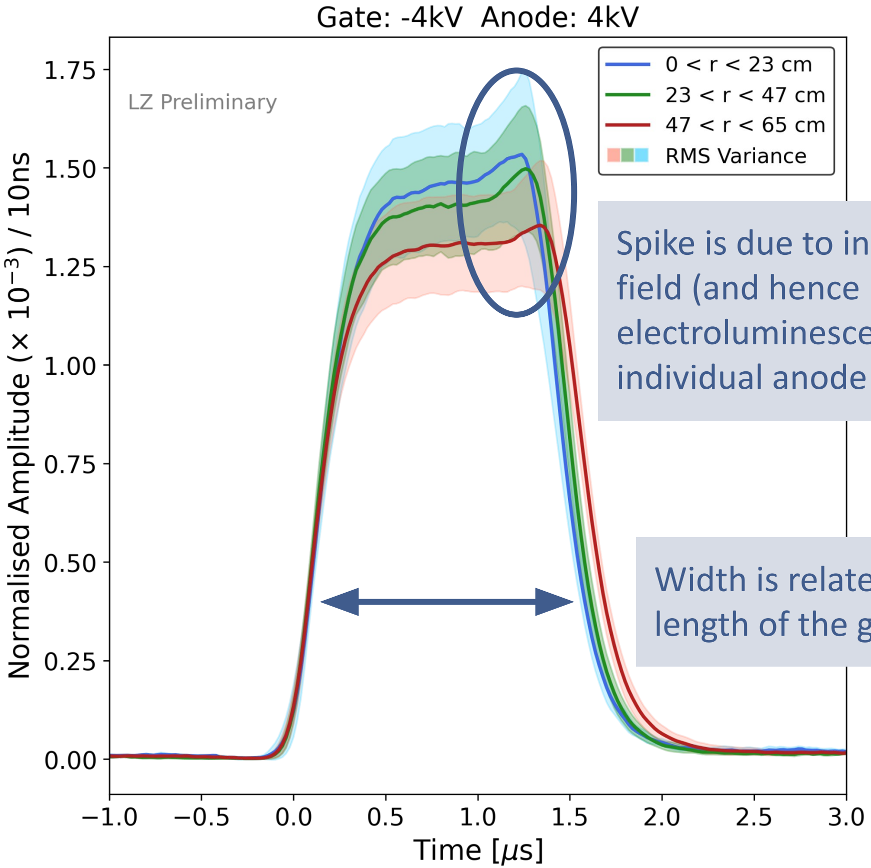
Data-driven template of S2s from **alpha decays** very **close to the gate grid**.

Point-source, S2 width is not due of the size of the continuous track

Minimal effect of diffusion on the S2 to obtain the true IRF of an non-diffused localised electron cloud.

Developing the S2 Model

Measuring each element of the S2 model : v_d , D_L, IRF



Spike is due to increased field (and hence electroluminescence) near individual anode wires.

Width is related to the length of the gas-gap.

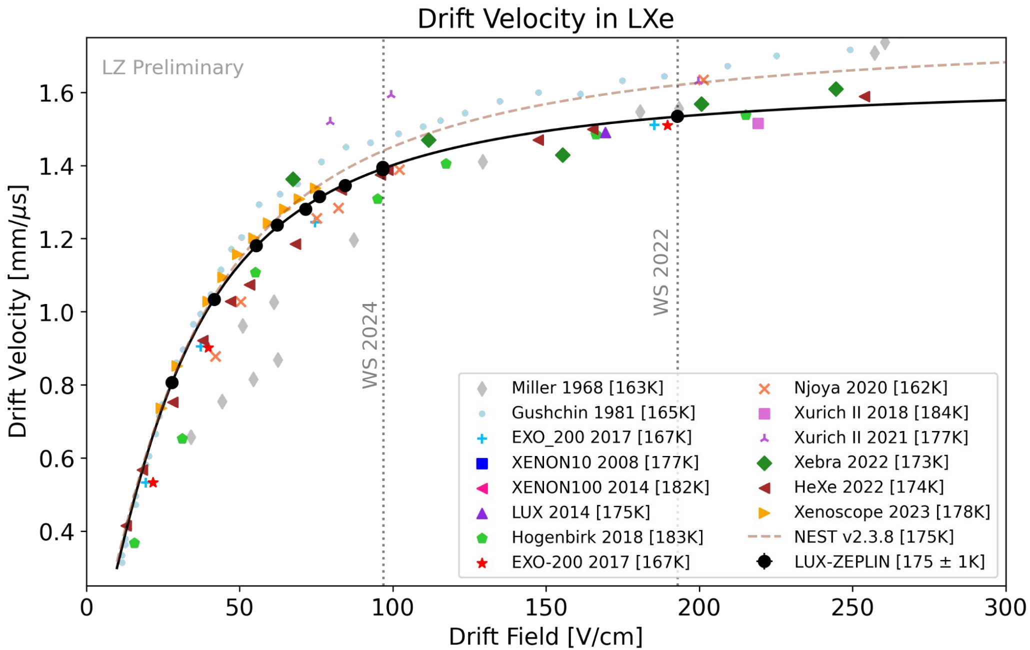
Impulse Response Function = S2

The example shown is for WS-2022 field conditions.

Developing the S2 Model

Measuring each element of the S2 model : v_d , D_L, IRF

Extended track (dE/dz) * Longitudinal diffusion gaussian $G\left(0, \sqrt{\frac{2D_L t_d}{v_d^2}}\right)$ * Impulse Response Function = S2



Measured using **alpha decays** on the **gate** and **cathode** grids to determine the amount of time it takes to drift electrons a known drift distance (d = 145.6 cm).

Developing the S2 Model

Measuring each element of the S2 model : v_d , D_L, IRF

Extended track (dE/dz)

*

Longitudinal diffusion gaussian $G\left(0, \sqrt{\frac{2D_L t_d}{v_d^2}}\right)$

*

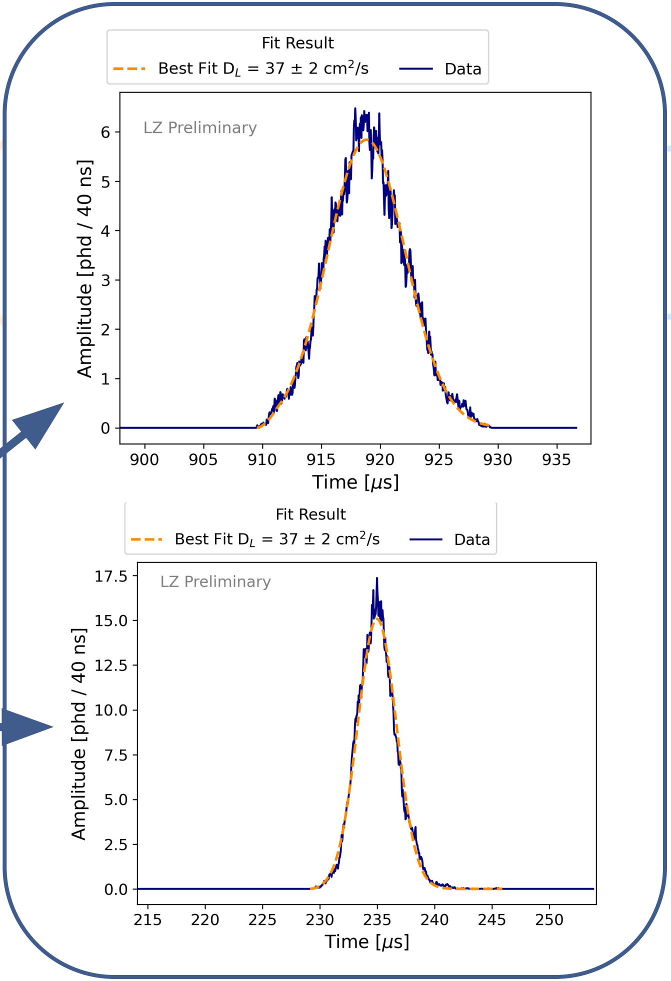
Fit an S2 model for a point source:

$$S2 = G\left(0, \sqrt{\frac{2D_L t_d}{v_d^2}}\right) \star \mathrm{IRF}$$

to S2 waveforms from **alpha** decays **in the bulk of the TPC** to find best-fit value of D_L for each waveform.

Deep event

Shallow event



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Extended track (dE/dz)

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Longitudinal diffusion gaussian

$$G\left(0, \sqrt{\frac{2D_L t_d}{v_d^2}}\right)$$

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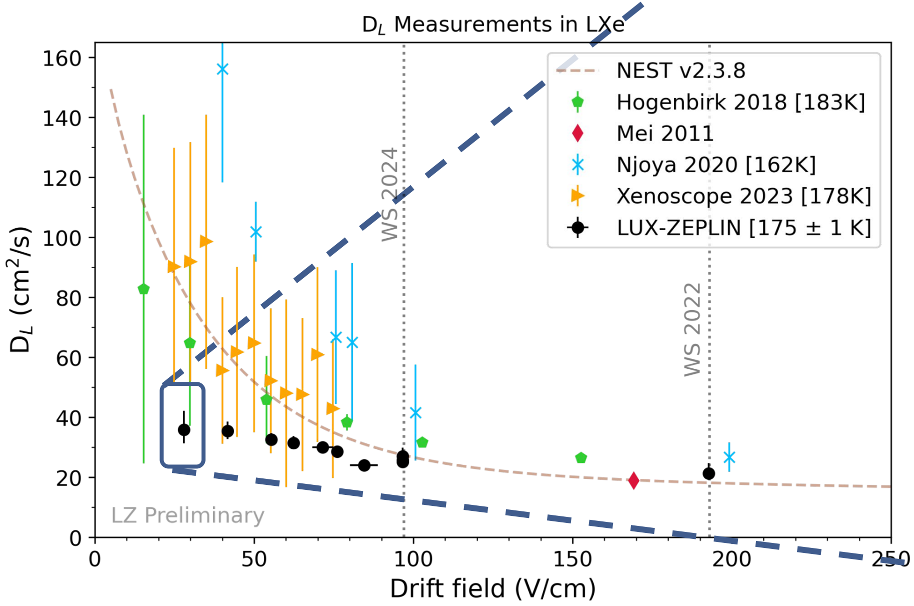
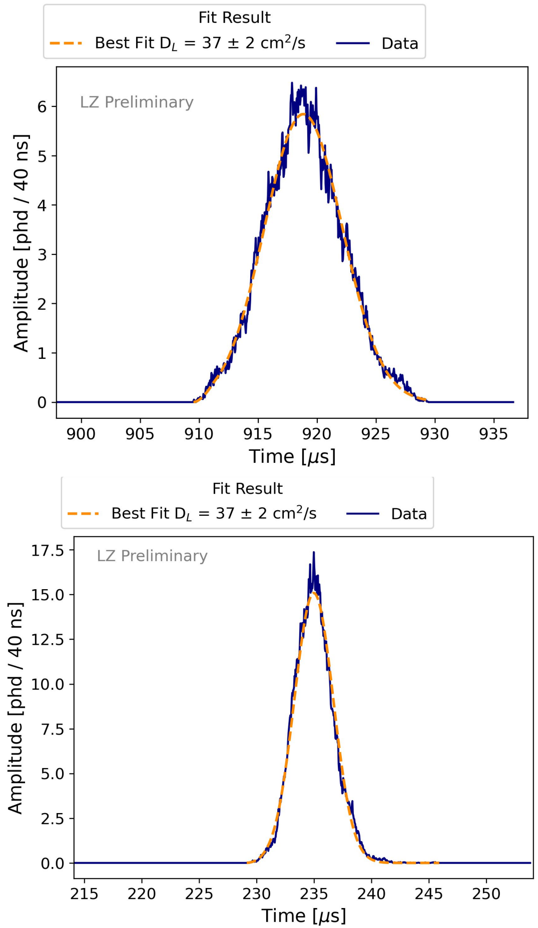




Developing the S2 Model

There is now a fully characterised forward model for any S2 in the LZ TPC

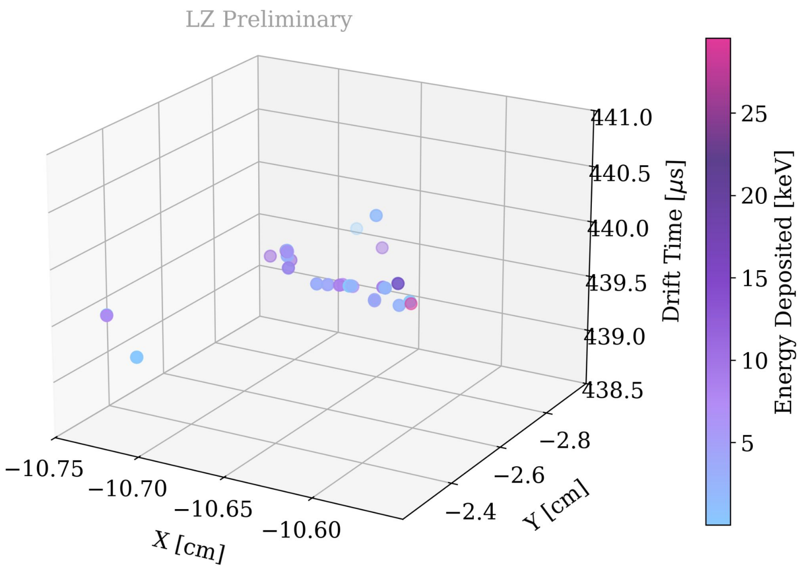
Extended track (dE/dz) * Longitudinal diffusion gaussian * Impulse Response Function = S2

The S2 Forward Model

Use the forward model to simulate ^{208}Tl S2 pulses and compare to data in LZ.

Simulation steps:

1. Electron tracks are obtained using GEANT4-based (*G4EmLivermore* physics list) simulations of ^{208}Tl gammas in the LZ TPC , and projected along the drift-time axis.



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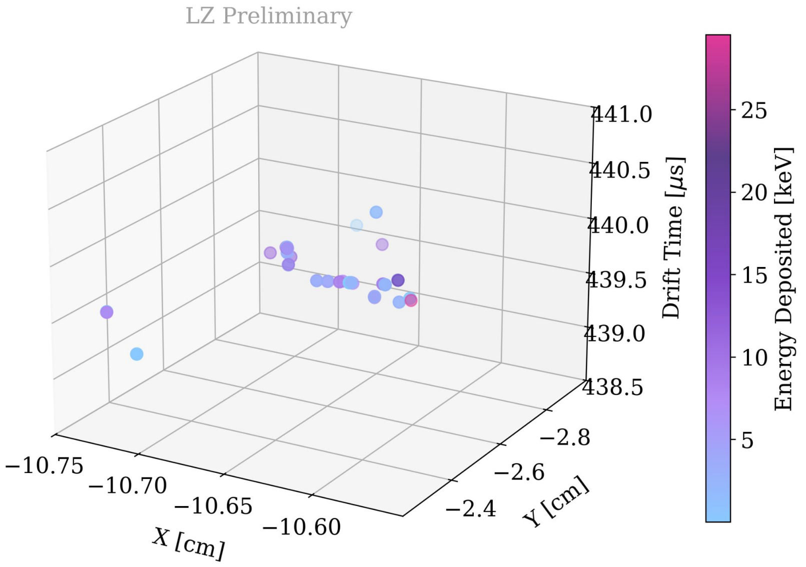

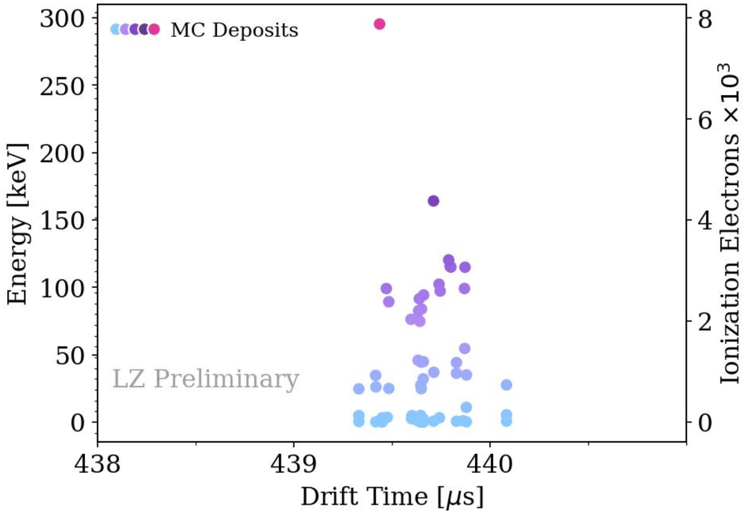

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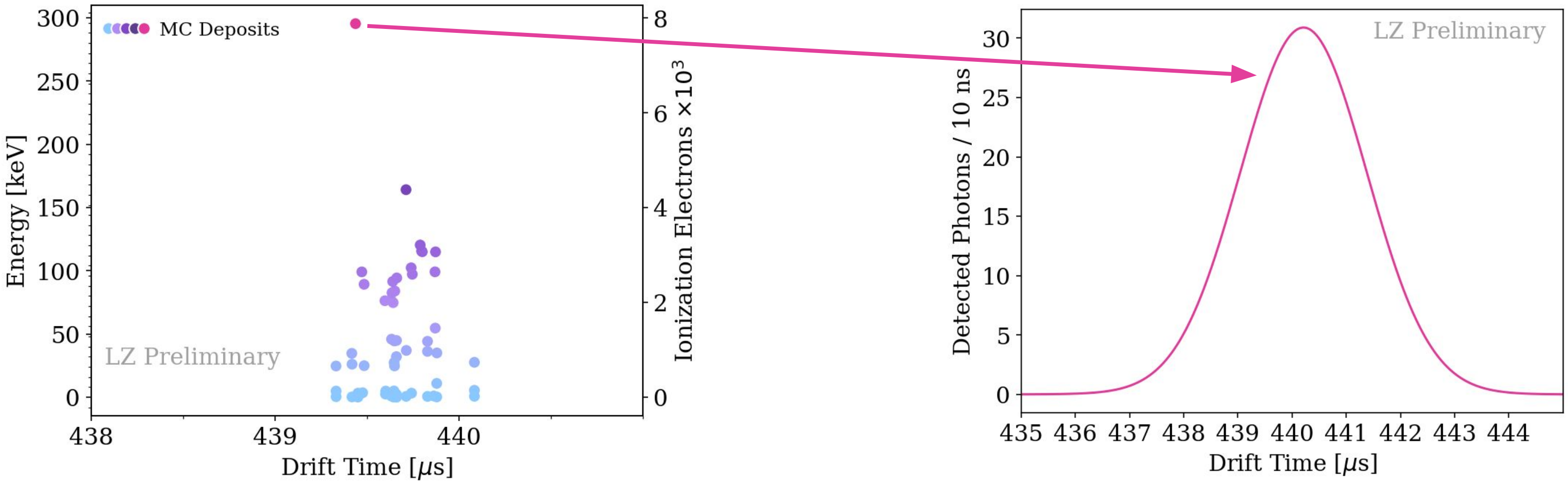

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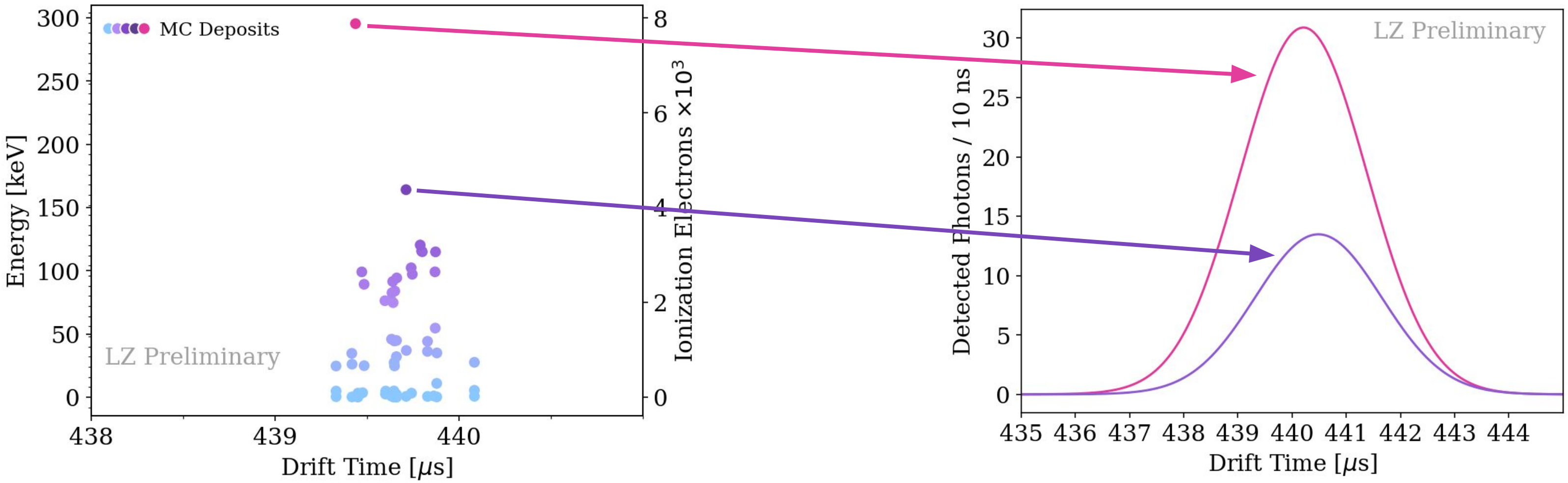

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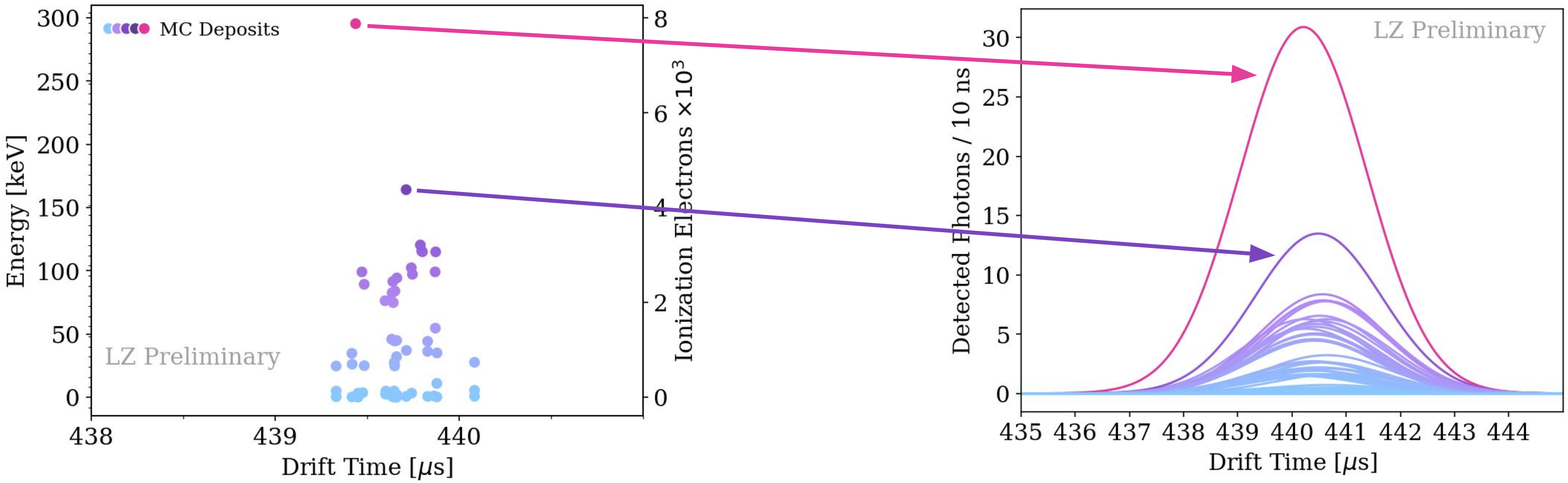

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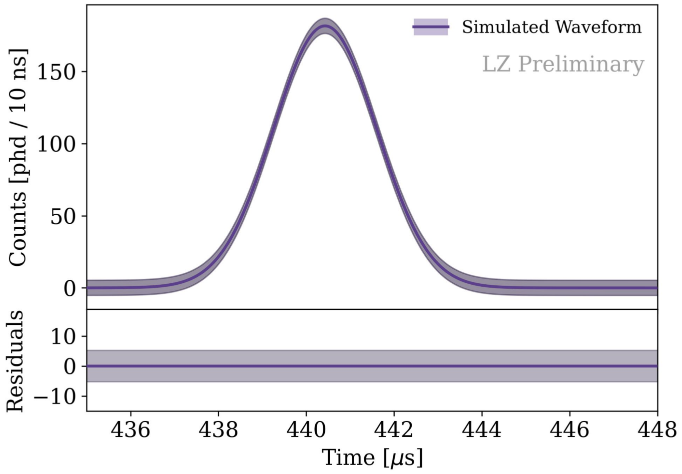
3. For each individual deposit , a point-waveform (IRF * $G_{diffusion}$) is generated. All these waveforms are then added to produce realistic S2 simulations of extended tracks.



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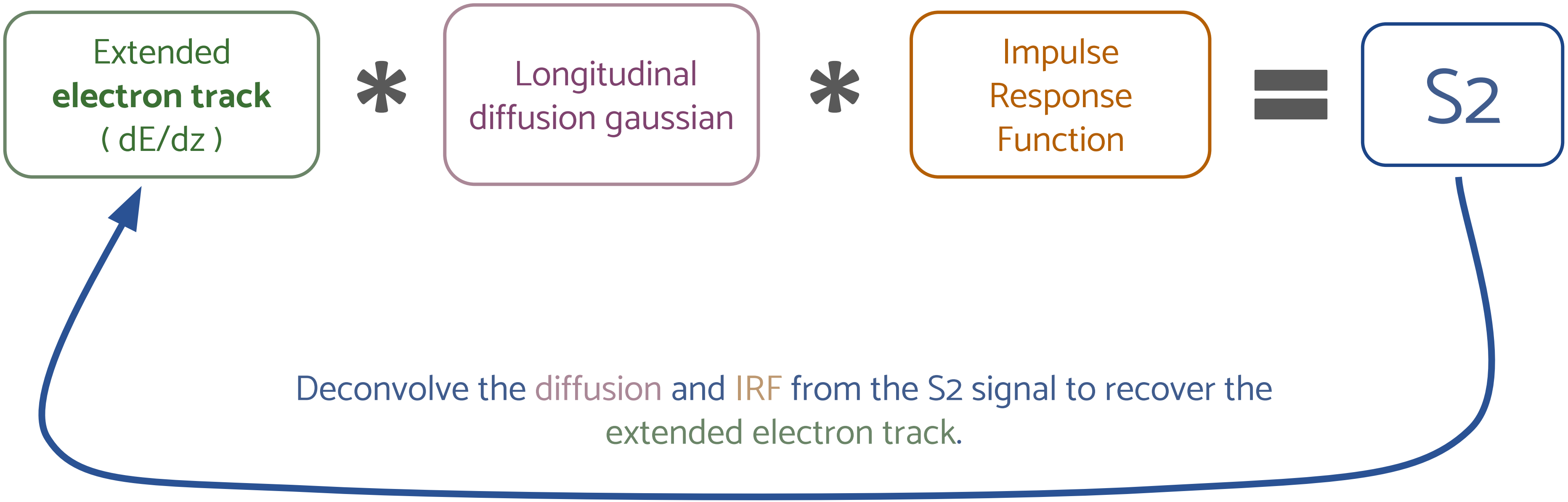
There is now a general S2 model for any event in the TPC.

It can be used to recover more detailed information about S2 waveforms to classify events as **MS-like** or **SS-like**, to remove unresolved MS waveforms from the dataset.

Deconvolving S2

To recover a proxy for the continuous extended **electron track** from a ~2 MeV gamma interaction



Deconvolve the diffusion and IRF from the S2 signal to recover the extended electron track.

Use **Stochastic Variational Inference** to perform this deconvolution.

Deconvolving S2

1. Reconstruct a binned proxy of the continuous extended track from the S2 waveform.
2. **Model the number of electrons** in each bin as a normal distribution.
   - The algorithm optimises the μ and σ of these distributions.
3. At each step, compare the S2 waveform generated from the estimated binned track to the measured data using a χ^2 metric.

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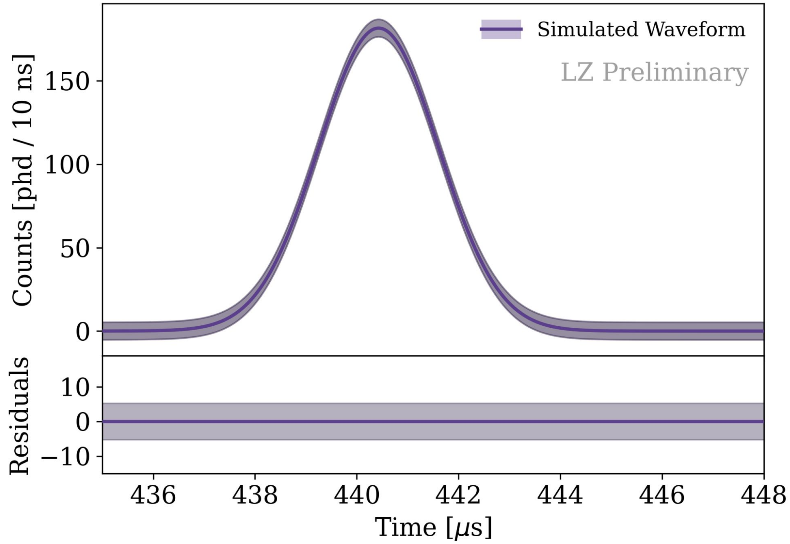
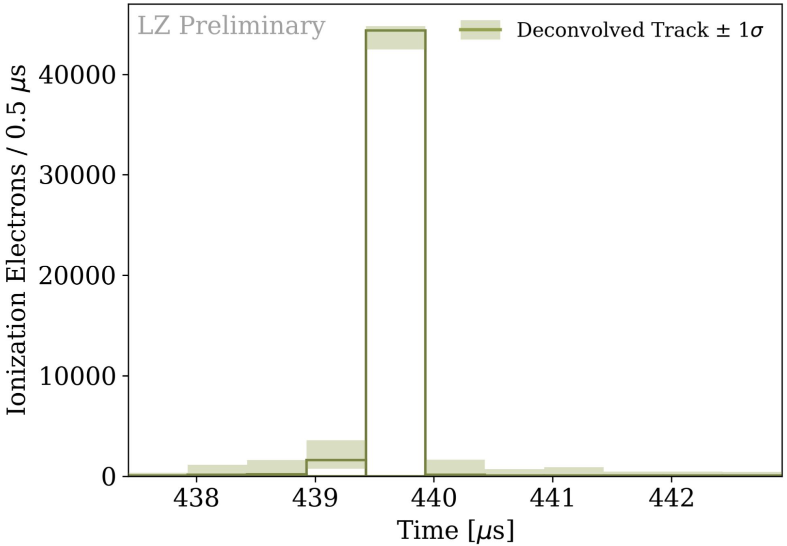
Input into algorithm



Output: reconstructed track



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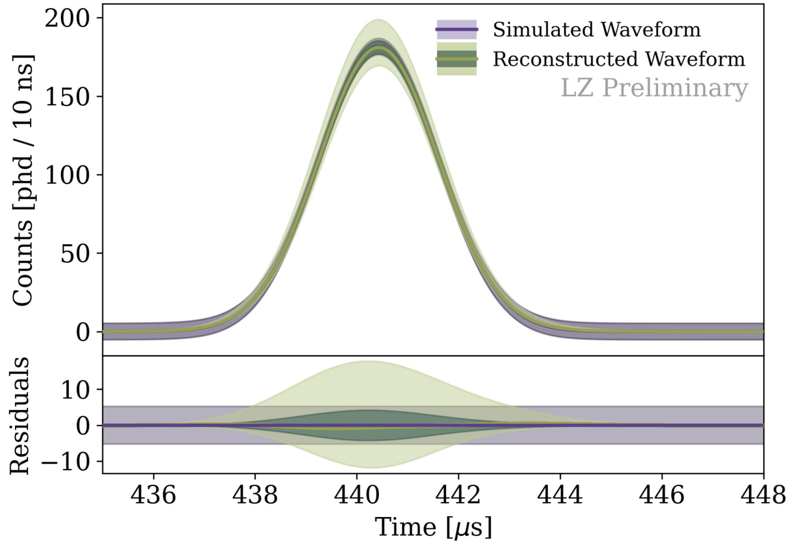
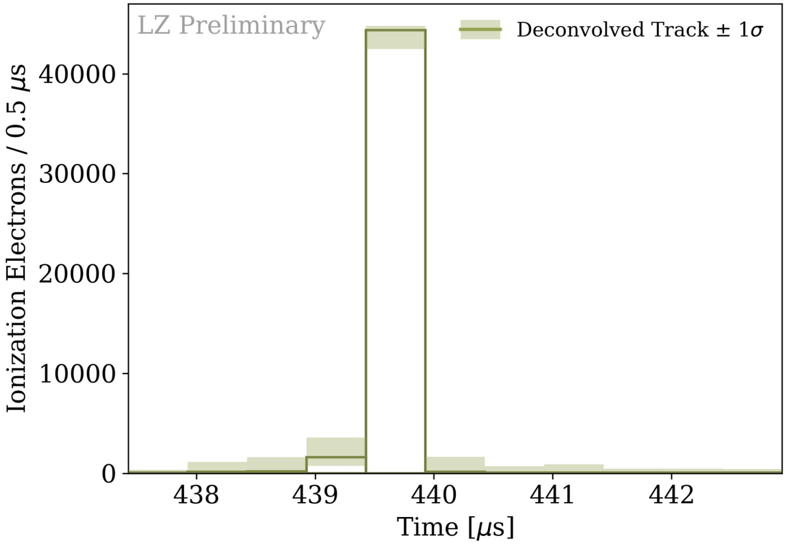
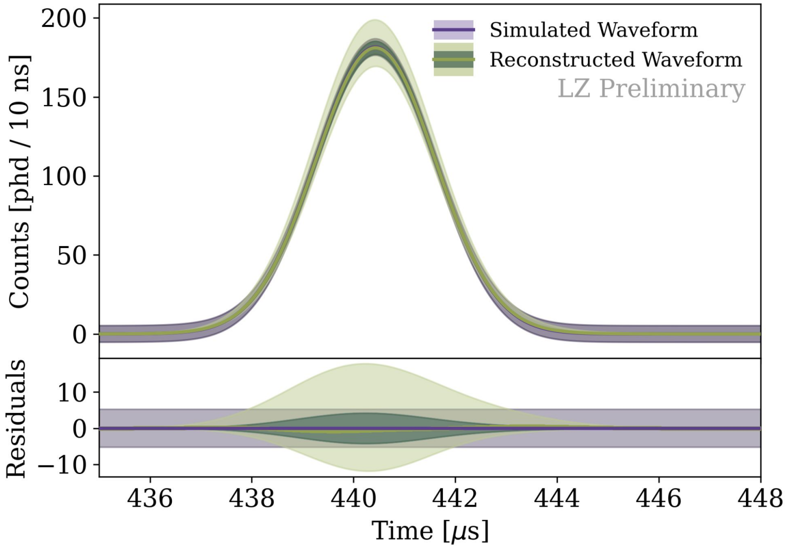


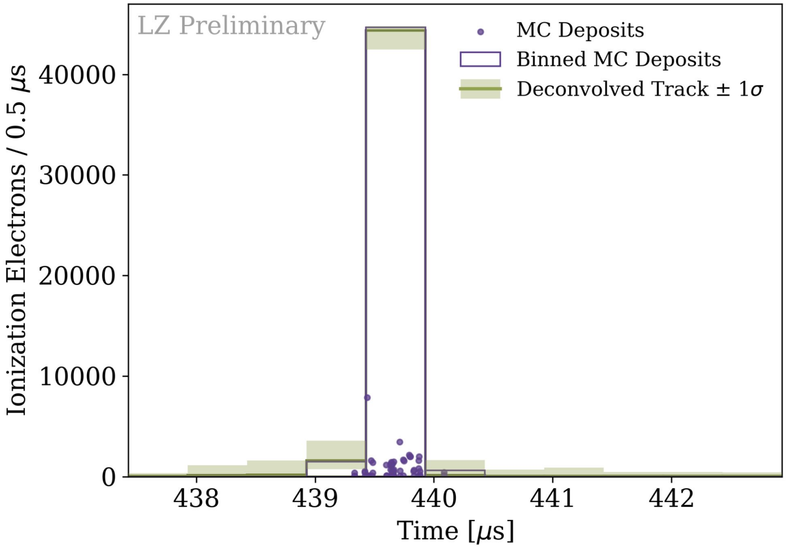
Output: reconstructed track



Deconvolving S2

1. Reconstruct a binned proxy of the continuous extended track from the S2 waveform.
2. **Model the number of electrons** in each bin as a Normal distribution.
   - The algorithm optimises the μ and σ of these distributions.
3. At each step, compare the S2 waveform generated from the estimated binned track to the measured data using a χ^2 metric. **This would be a Single Site-like interaction.**





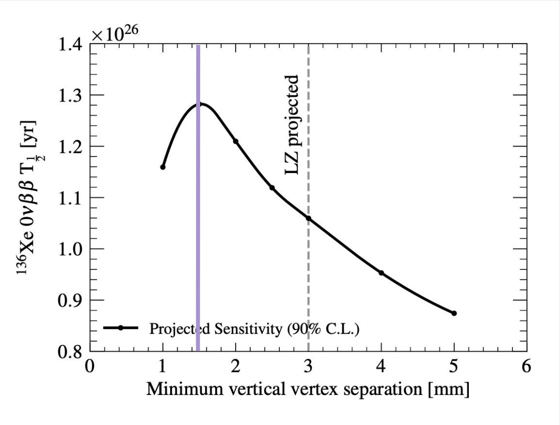
Preliminary Results: simulated ^{208}Tl gammas

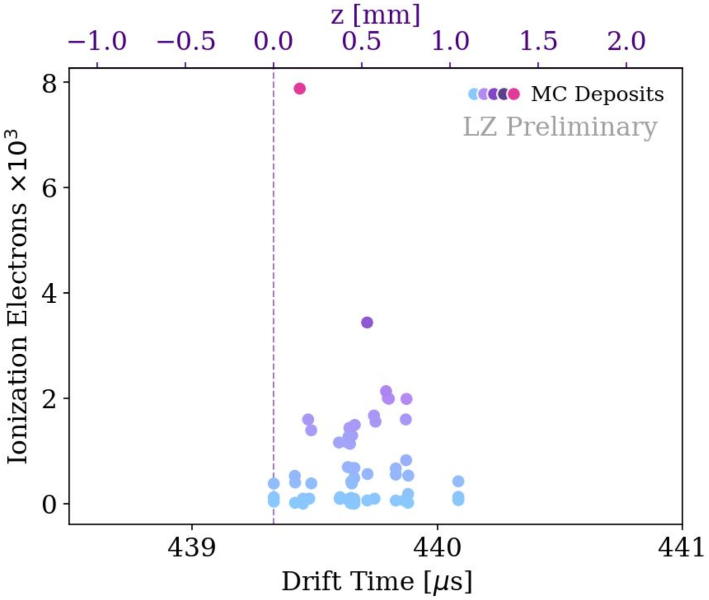
I classify simulated decays based on the MC deposits as:

→ **Single Site-like Interaction :** no consecutive energy deposits along the drift direction are separated by more than 1.5 mm.

Single-Site Events:

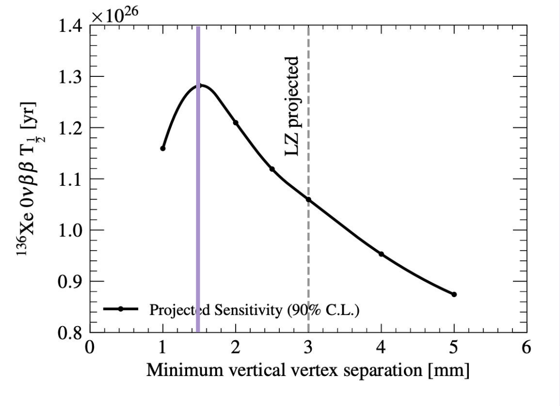
Chosen according to maximum sensitivity projections.





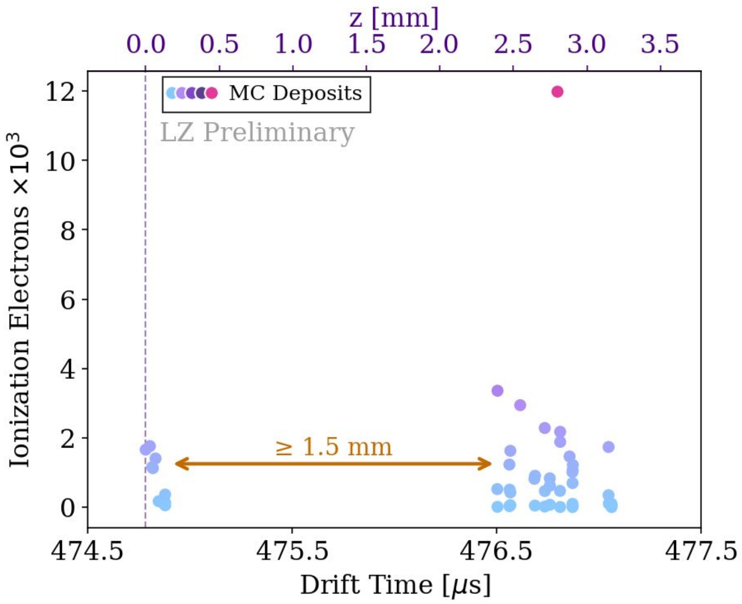
Preliminary Results: simulated ^{208}Tl gammas

Single-Site Events:
Chosen according to maximum sensitivity projections.



I classify simulated decays based on the MC deposits as:

→**Multi Site-like Interactions :** has consecutive energy deposits along the drift direction separated by more than 1.5 mm.
These are the unresolved MS events



Preliminary Results: simulated ^{208}Tl gammas

Generate ^{208}Tl gammas simulations.

- Simulated events are selected to match the LZ nominal 3 mm vertex separation threshold (no events with gaps in the drift time distribution of deposits > 3 mm).

Get the truth:

Classify events as SS-like or MS-like based on the MC deposits directly.

Get the deconvolution output:

1. Generate S2 waveforms with the forward model.
2. Apply the deconvolution algorithm on the simulated waveforms.
3. Classify events as SS-like or MS-like *based on the reconstructed tracks.*

Preliminary Results: simulated ^{208}Tl gammas

Comparing the result of the **deconvolution** to the **truth**

- **Of the true SS-like events:**
  - 91.5 % are correctly classified
  - 8.5% are incorrectly classified

- **Of the true MS-like events:**
  - 77.4% are correctly classified
  - 22.6% are incorrectly classified

Preliminary Results: simulated ^{208}Tl gammas

Comparing the result of the **deconvolution** to the **truth**

- **Of the true SS-like events:**
    - 91.5 % are correctly classified
    - 8.5% are incorrectly classified

- **Of the true MS-like events:**
    - 77.4% are correctly classified → background-like (unresolved MS) events can be identified and removed from final dataset by this method.
    - 22.6% are incorrectly classified

Conclusion

Goal: Reduce gamma-ray backgrounds in the $0\nu\beta\beta$ ROI by exploiting differences between a background-like and a signal-like S2

The main limitation in our discrimination power comes from **detector effects that smear S2s** leading to a loss of information in the waveform.

- ➔ Developed a detailed **S2 model** to better understand the shape of S2 waveforms in the LZ TPC.
- ➔ The S2 model is then used to **deconvolve detector effects from the S2** to obtain the underlying track, projected along the z-axis.
- ➔ Preliminary studies demonstrate that **the deconvolution algorithm can faithfully classify simulated events**

Looking Forwards:

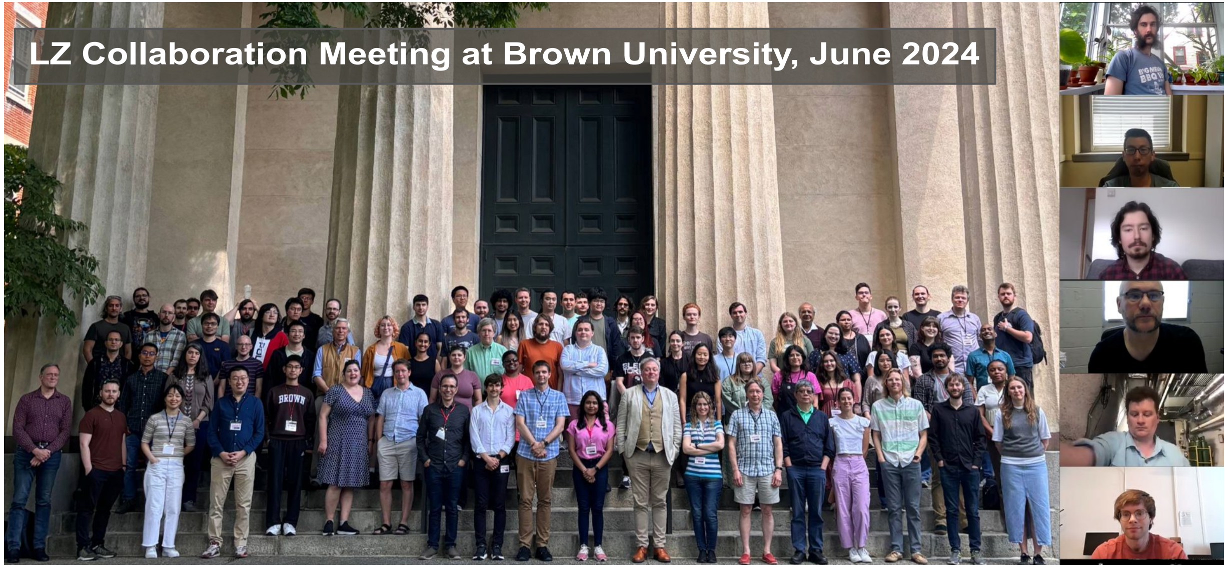
Investigate different methods of classifying signal/background events, in particular **machine learning techniques.**

LUX-ZEPLIN (LZ) Collaboration

38 Institutions , 250 scientists, engineers, and technical staff

@lzdarkmatter

https://lz.lbl.gov/



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- University of Wisconsin, Madison
- University of Zürich

US Europe Asia Oceania

Thank you for your attention!

Backup Slides

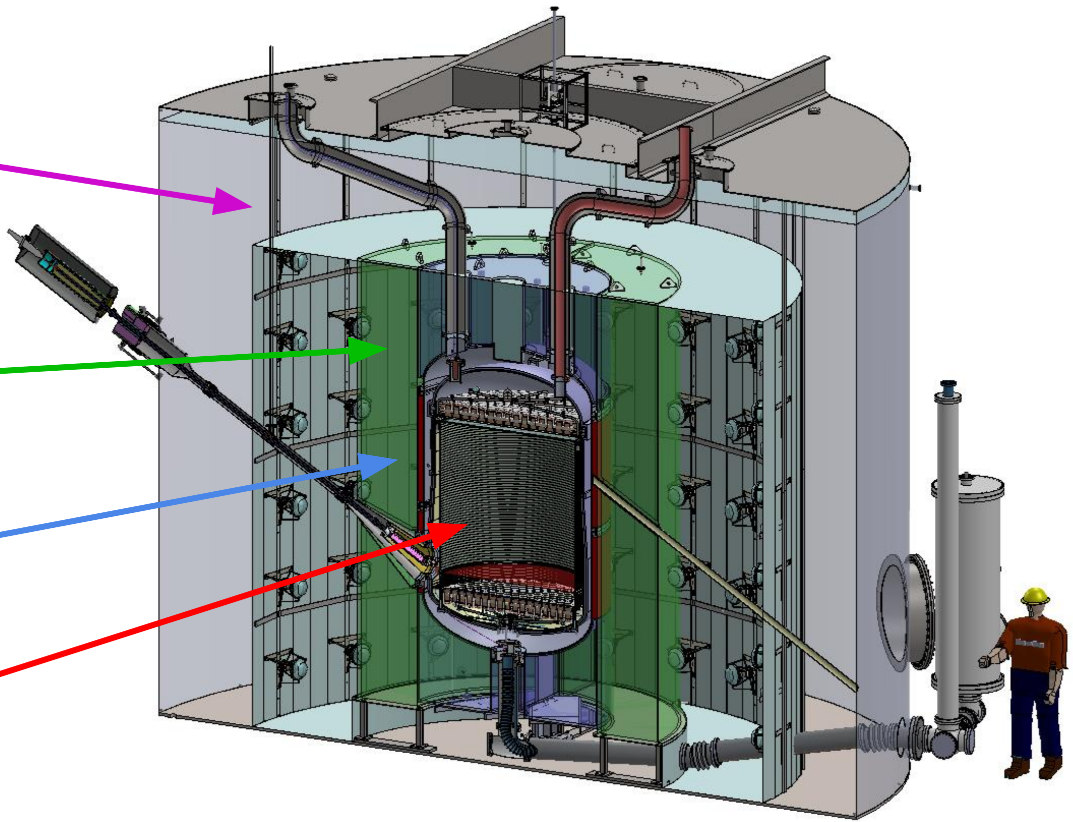
The LZ Detector

138 tonnes of ultra-pure water

Outer **D**etector:
17.5 tonnes of
gadolinium-loaded
scintillator

Skin: 2 tonnes LXe

TPC: 7 tonnes LXe in
active volume.



The Background Spectrum In The 0νββ ROI → MS vs SS

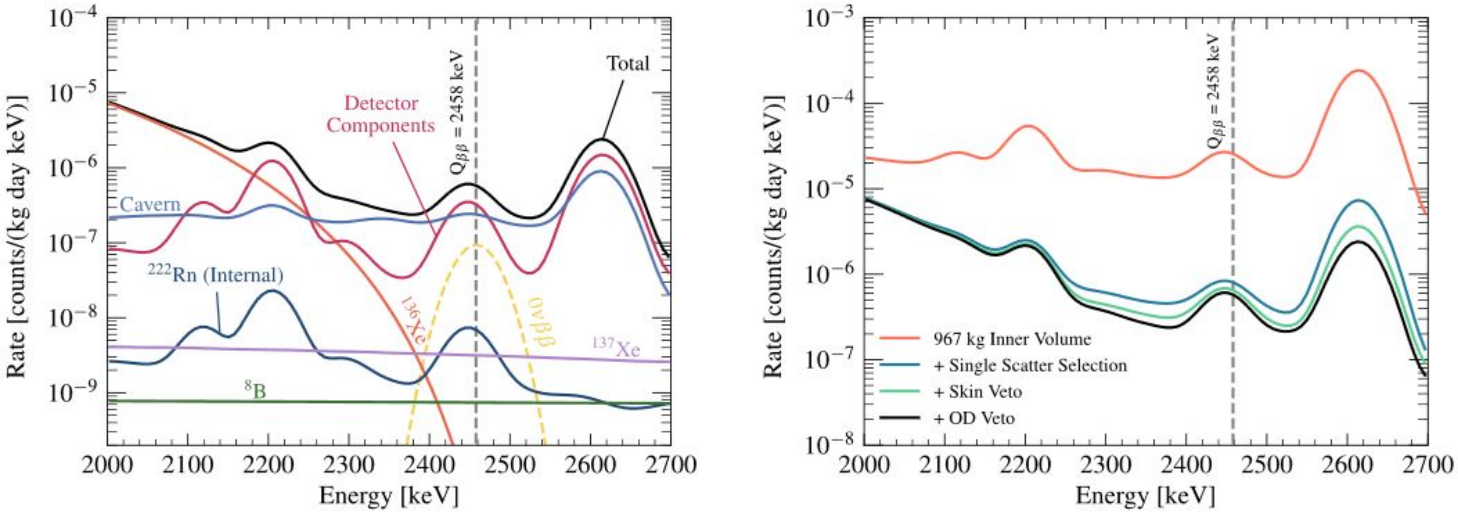
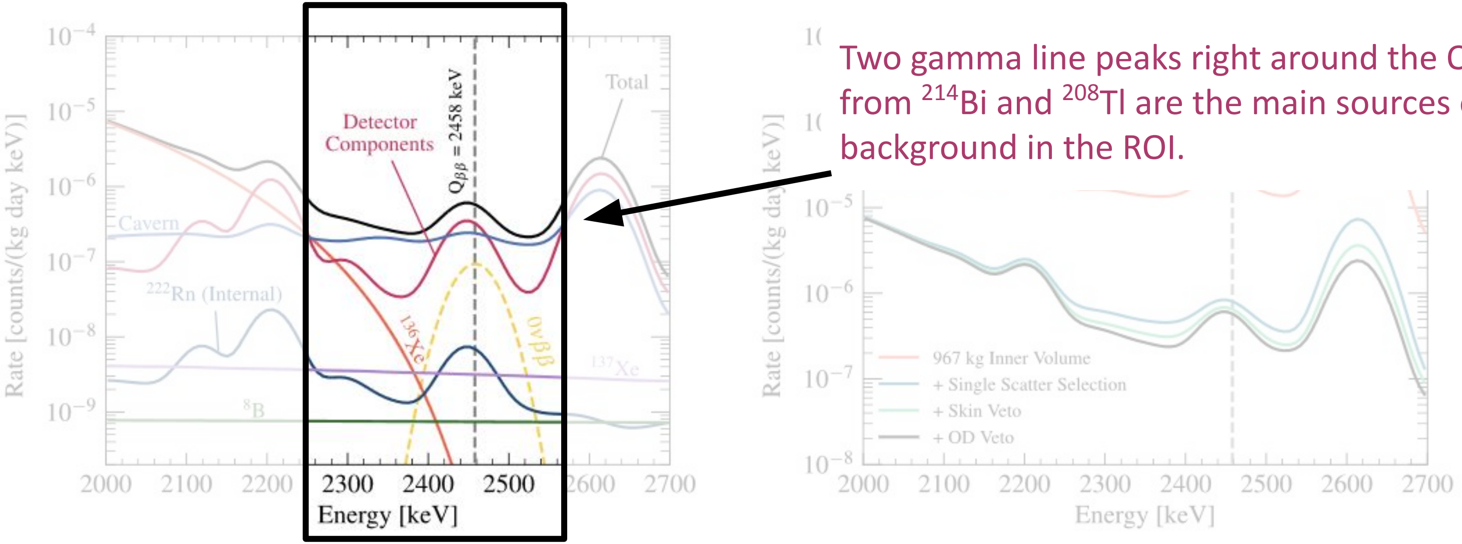


FIG. 3. Background energy spectrum in the inner 967 kg volume: contributions from the main background sources (left) and effect of successive selection cuts used in the analysis (right). More details regarding the analysis can be found in the text. The ^{60}Co, ^{238}U-late chain and ^{232}Th-late chain backgrounds from the detector components are combined into a single curve on the left plot but are treated independently in the sensitivity analysis. The dashed yellow line in the left plot represents the expected signal spectrum for ^{136}Xe $0\nu\beta\beta$ decay, considering a half-life of 1.06×10^{26} y (see Sec. IV), and it is not included in the total spectrum. The spectra are smeared using the energy resolution function of LUX [31], scaled to be 1.0% at $Q_{\beta\beta}$.

[1] D. S. Akerib and others, 'Projected sensitivity of the LUX-ZEPLIN experiment to the 0νββ decay of ^{136}Xe', Phys. Rev. C, vol. 102, no. 1, p. 014602, 2020, doi: 10.1103/PhysRevC.102.014602.

The Background Spectrum In The 0νββ ROI → MS vs SS

Two gamma line peaks right around the $Q_{\beta\beta}$ value from ^{214}Bi and ^{208}Tl are the main sources of background in the ROI.



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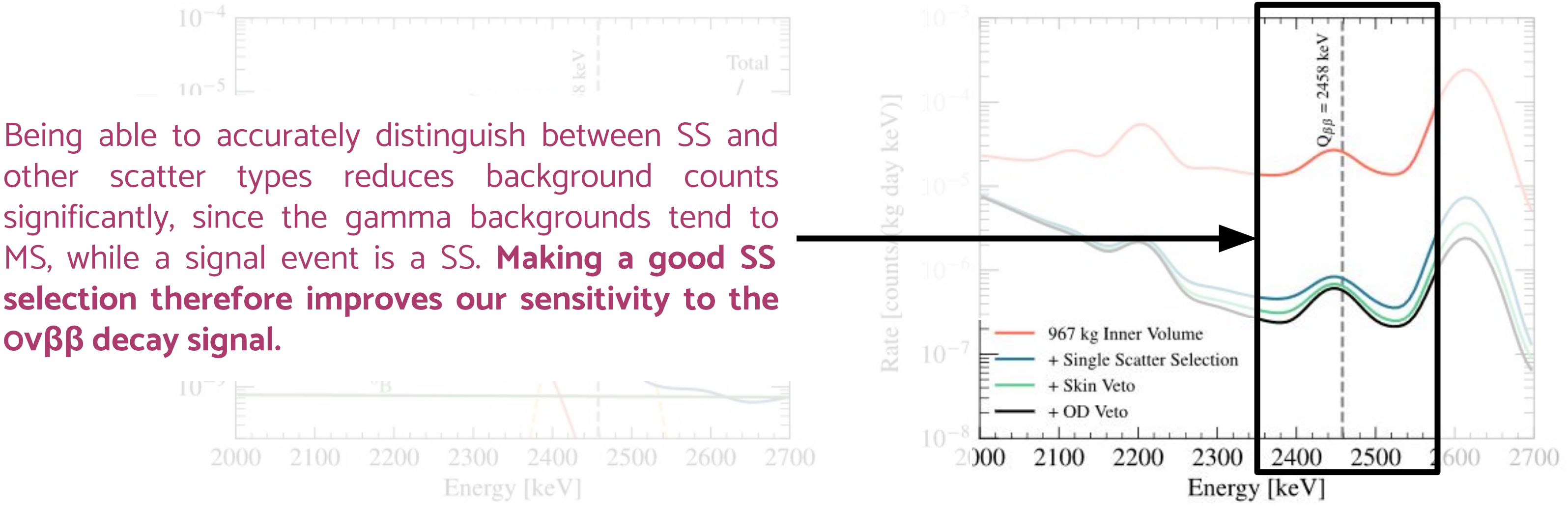

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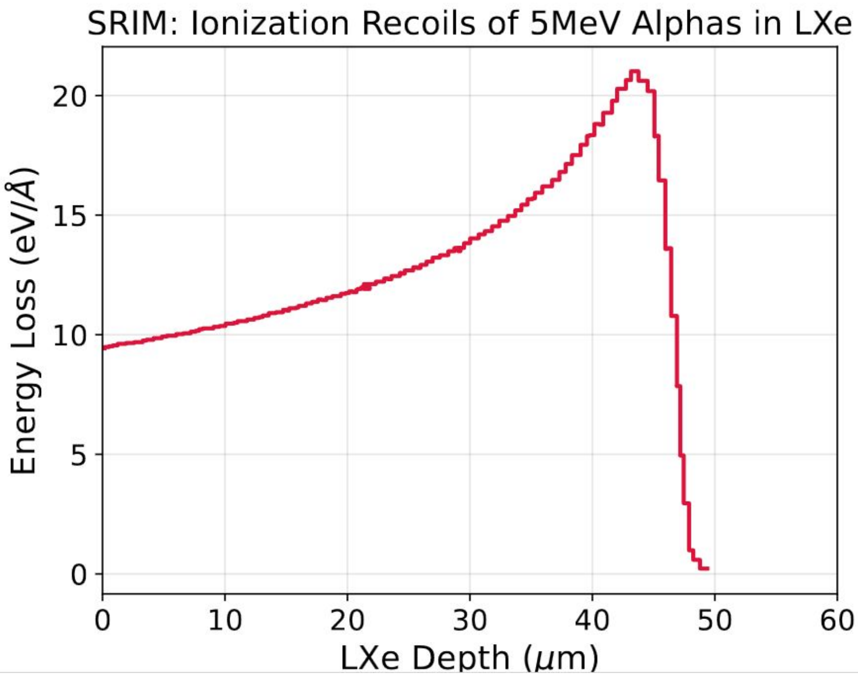
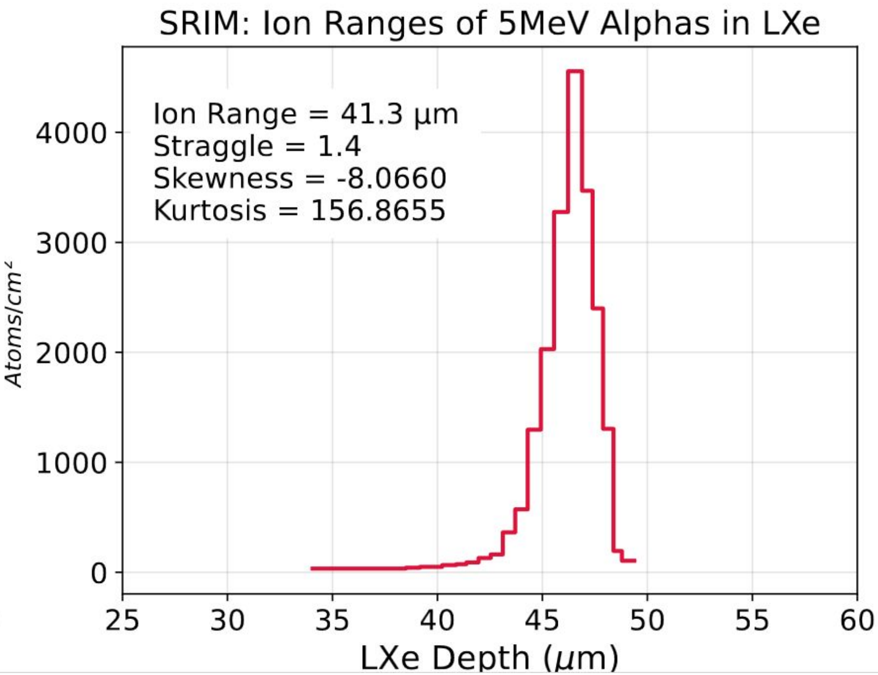
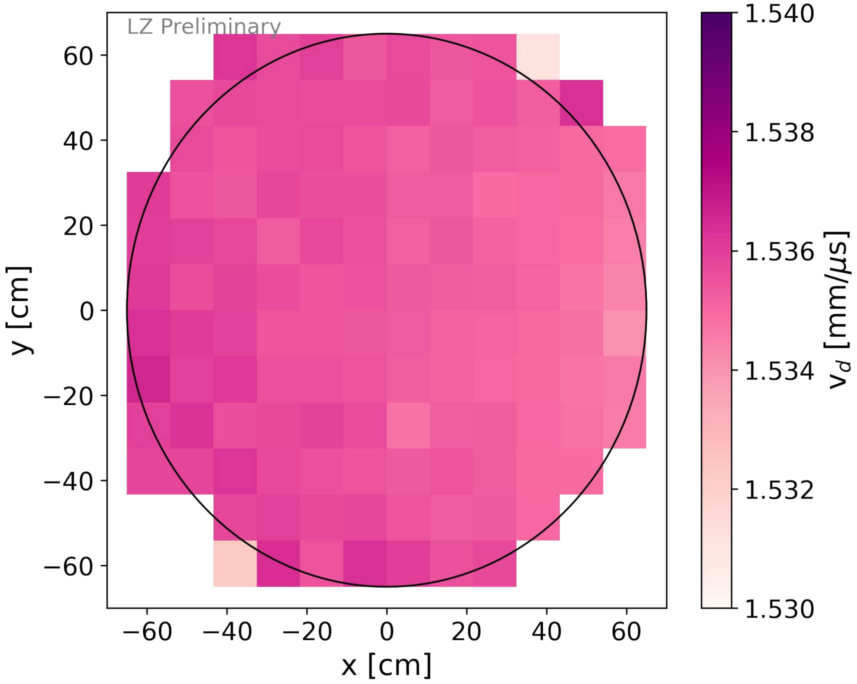
Alpha Decays as Point-Sources

Alpha decays are **point-sources** to good approximation (combination of well-defined range and bragg peak.).

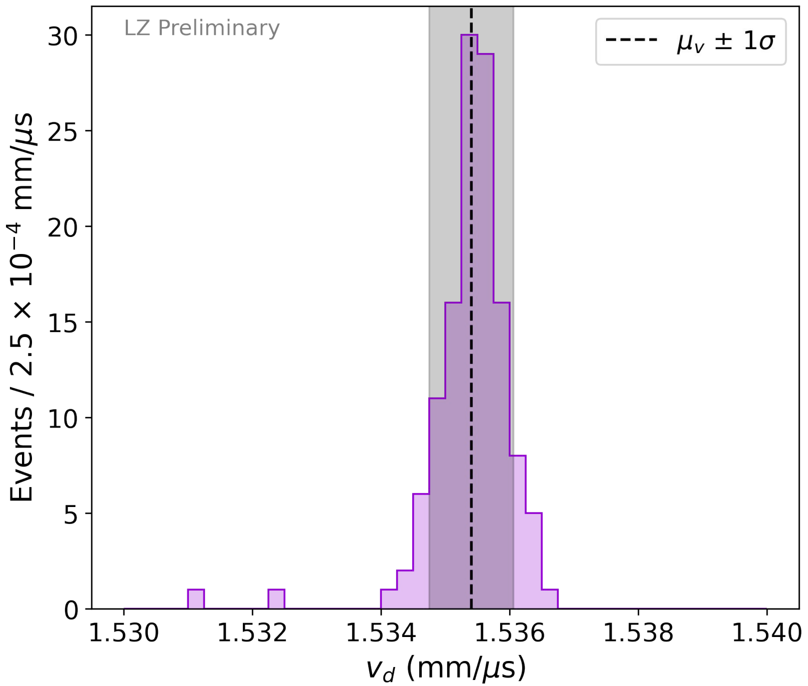




Drift Velocity Measurement

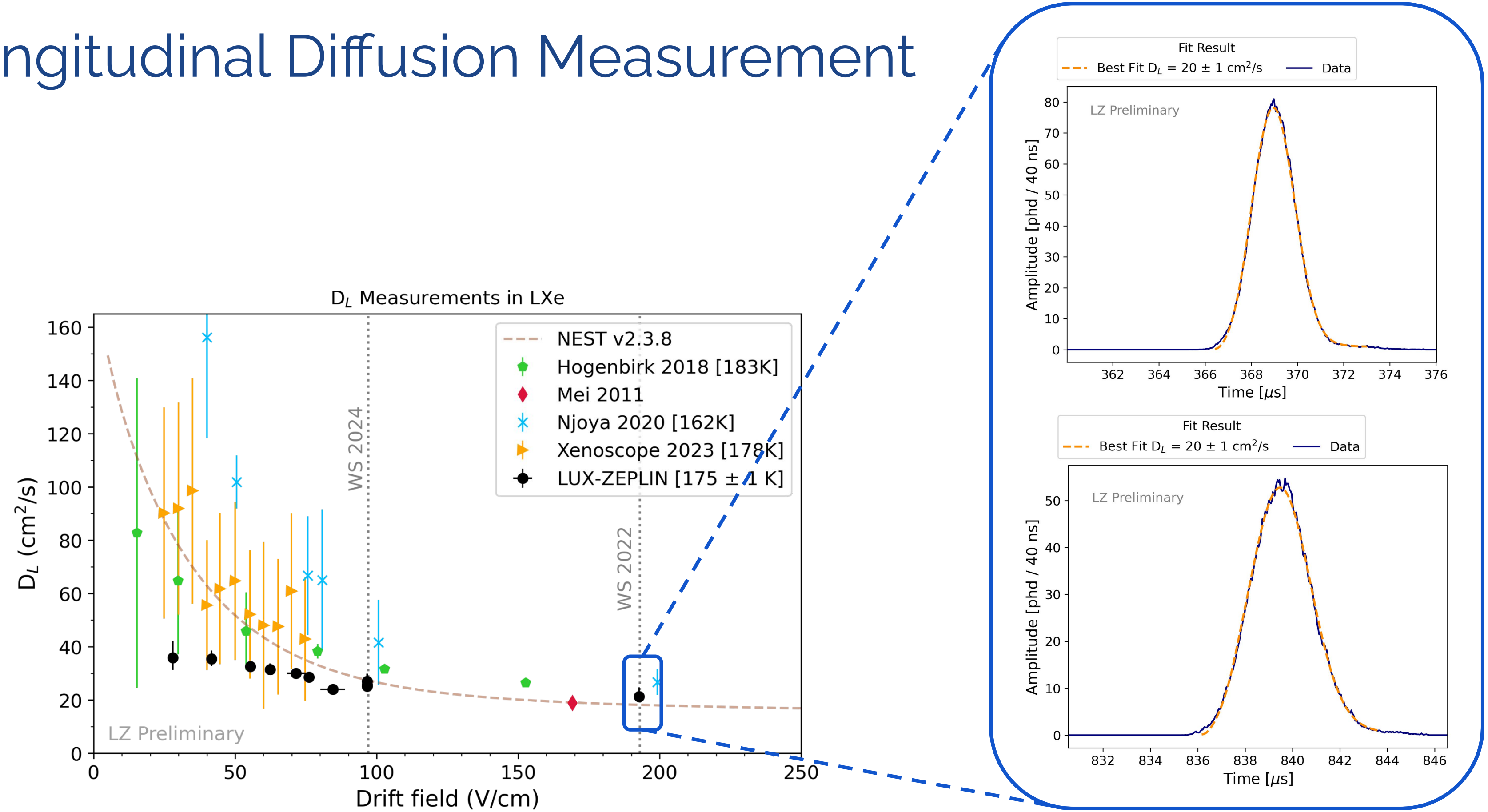


Spread of the drift velocity measured as a function of (x,y), used to determine the spatial dependence of the drift velocity.



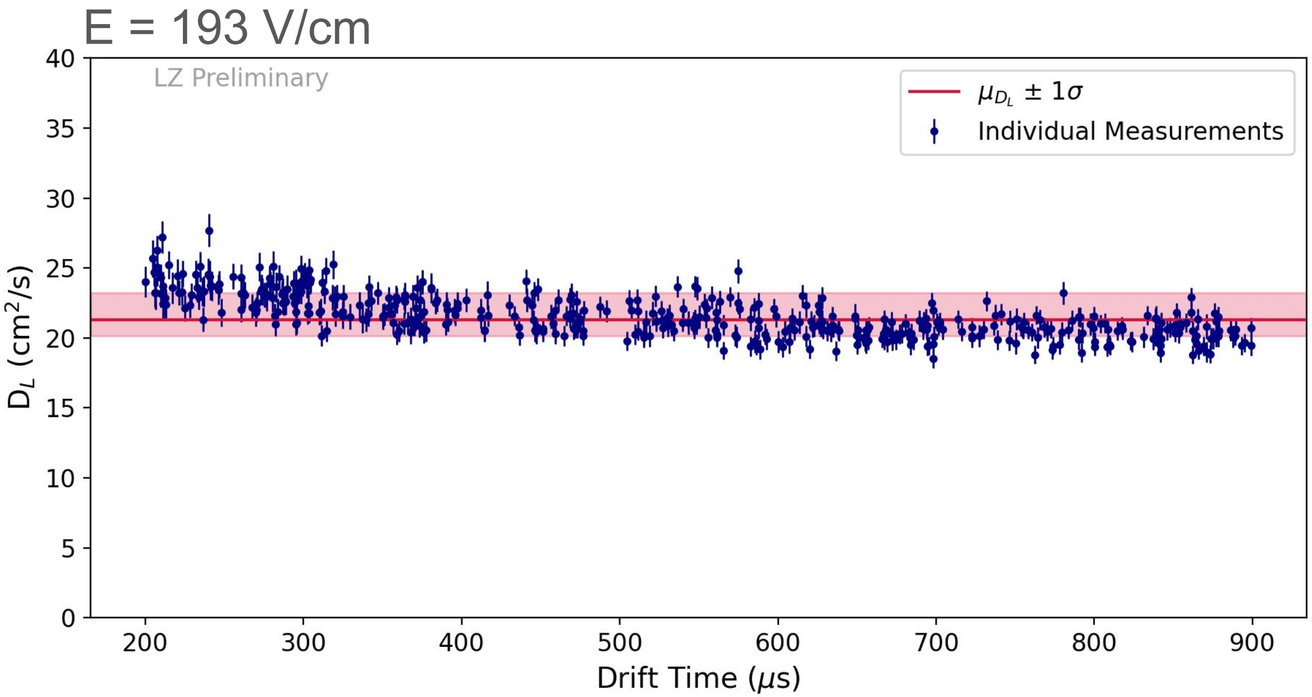
1-D projection of the plot on the left.

Longitudinal Diffusion Measurement



Some more examples S2-model fits on WS-2022 S2s from waveforms at the top of the detector and bottom of the detector.

Longitudinal Diffusion Measurement



Shows the spread of the individual D_L measurements made based on waveforms from the WS-2022 data set. The drift-time dependence of the measurement is hypothesised to be due to the temperature gradient of 2K between the bottom of the TPC and the LXe Surface. Both the statistical spread of the data & tilt are accounted for in total uncertainty on the D_L measurement.