LZ Dark Matter Experiment: Fiducial Volume Optimisation

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Motivation

In the forefront of experimental research on dark matter (DM), direct detection experiments are leading efforts in proving the existence and identifying the nature of DM. Despite constituting 84.5% of all the total mass, DM detection has proven to be one of the scientific challenges of the century.

To reduce background noise the experiments are carried out far underground, under heavy shielding. To further suppress background originating from the detector's components and surroundings, a cut in the volume of the detector that is capable of recording an event (active detector) is applied. The optimisation of this fiducial volume maximises the selected active material while minimising the background noise present in it.

The LZ Detector

The heart of the LZ (LUX-Zepelin) experiment consists of a new generation time projection chamber (TPC) containing 7 active tonnes of liquid Xenon (LXe). Non-relativistic collisions occurring between incoming particles and the LXe nuclei create both a bundle of photons and free electrons. Electric fields within the TPC drift the electrons to the surface (skin) and extract them from the LXe, releasing additional scintillation light. [1]

For each recoil distinct signatures are recorded by the PMT arrays at the two ends of the TPC. The timing and pattern of the signals is used to reconstruct the position and energy of a recoil. Monte-Carlo software allows for events to be simulated and then used to study the predicted back-ground noise and reconstruction efficiency.

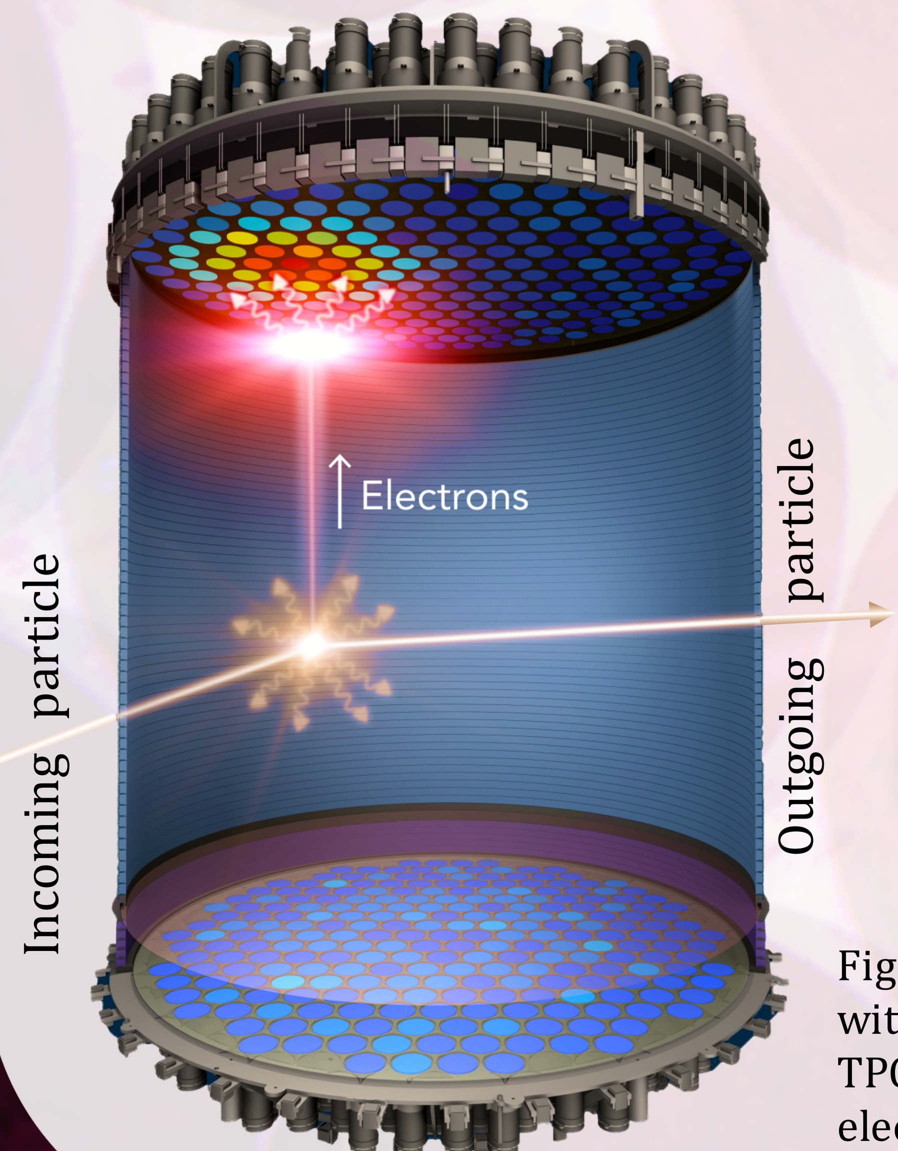
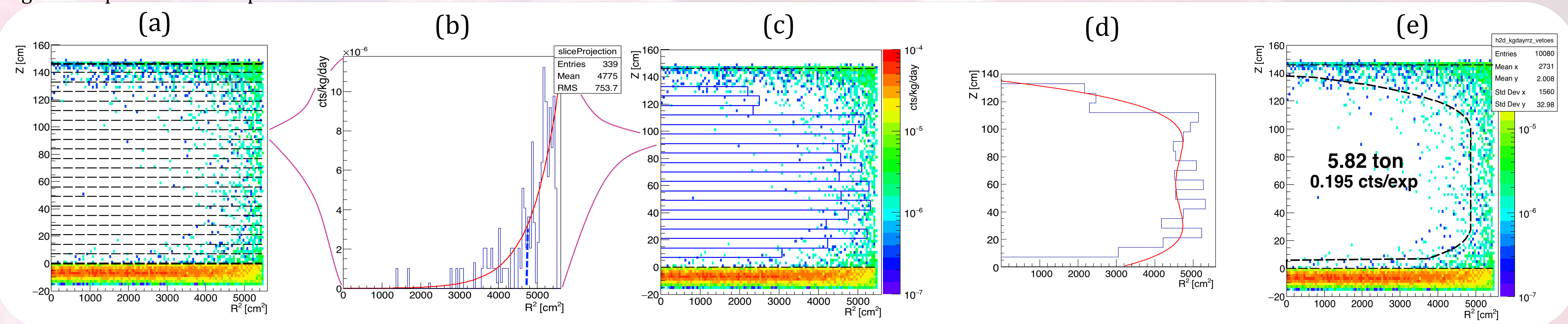


Figure 1: Scattering of a DM particle with the target nucleus inside the TPC producing photons and free electrons. [2]

Optimisation algorithm

Due to high cylindrical symmetry of the TPC, the algorithm operates in a projection of the cylindrical polar coordinates. The primary sources of background noise are the PMTs, cryostat and TPC shell. Because of incredibly high self-shielding properties, background noise is not able to penetrate far beyond the edges of the LXe. Background noise is measured in counts per unit exposure, defined as the product of the effective target mass (kg) and the live time of the experiment (days). An upper threshold on this parameter yields an upper bound for the fiducial volume (0.2 cts/exp for nuclear recoils (NR)).

Figure 2: Optimisation steps.



(a) The cylind. projection of the TPC is separated into slices between the ca-thode (Z=0cm) and the LXe skin (Z= 148cm).

(b) In each slice, a cut is applied when the upper threshold defined is reached in the cts/exp contained in the slice.

(c) The highest and lowest points are selected by defining a condition on the minimum slice length.

(d) The remaining trimmed slices are smoothed out and an analytic function is fitted to them.

(e) If a predefined level of tolerance is not reached, run parameters are adjusted accordingly and the algorithm repeats.

Sensitivity

Using the events simulated within the fiducial volume, we can produce predictions for the outcome of the sensitivity analysis of the LZ experiment. This analysis searches for recoils of LXe atoms caused by a DM interaction. Recoils are expected to be distributed uniformly within the TPC and their rate depends on the different physical models (i.e. WIMPs, Axions ALPs etc). The absence of signal allows us to exclude regions in parameter space.

To improve sensitivity:

- Increase fiducial mass
- Improve statistical analysis tools
- Allow for longer exposure

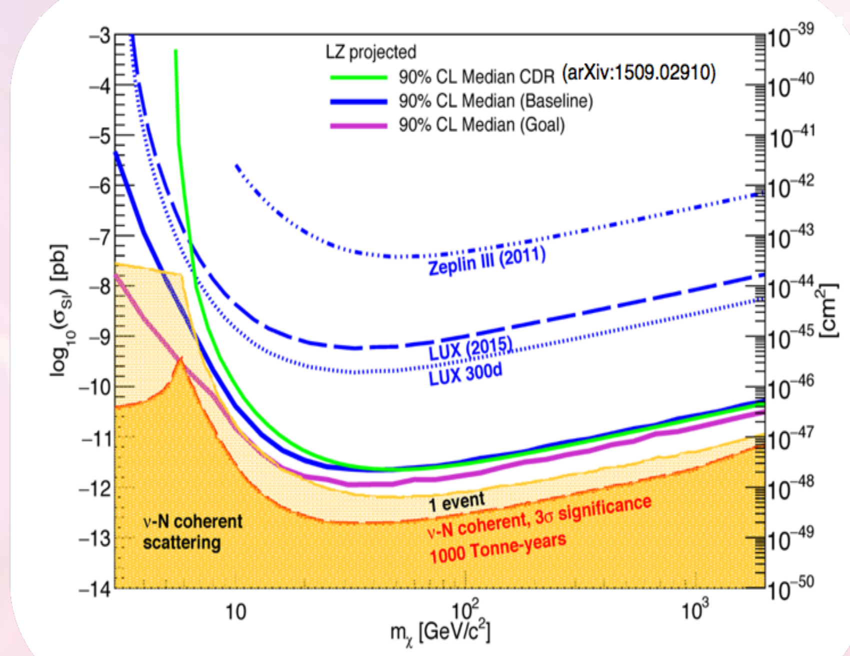


Figure 3: Projected 90% confidence sensitivity for LZ for WIMP-nucleon cross section.

Conclusions

The use of a sophisticated tool for the optimisation of the fiducial volume has a very significant role when processing experimental data. While applying the same threshold of 0.2 cts/exp NR, the results are as follow:

- LZ collab. fiducial mass prediction: 5.6 tonnes
- Optimised fiducial mass (Figure 2): 5.8 tonnes

This small difference in the optimised fiducial volume implies that a greater effective volume can be available to the analysis while keeping the background noise unchanged. This would yield an increase in sensitivity and largest exclusions in the parameter theories of physical models.

References

[1] LZ Conceptual Design Report. LZ Collaboration. arXiv:1509.02910
[2] "SLAC Gears Up For Dark Matter Hunt With LUX-ZEPLIN". 2016. Web. 20 July 2016.

Background Image: View from the bottom PMT holder of the LUX detector. Photo by C. H. Faham