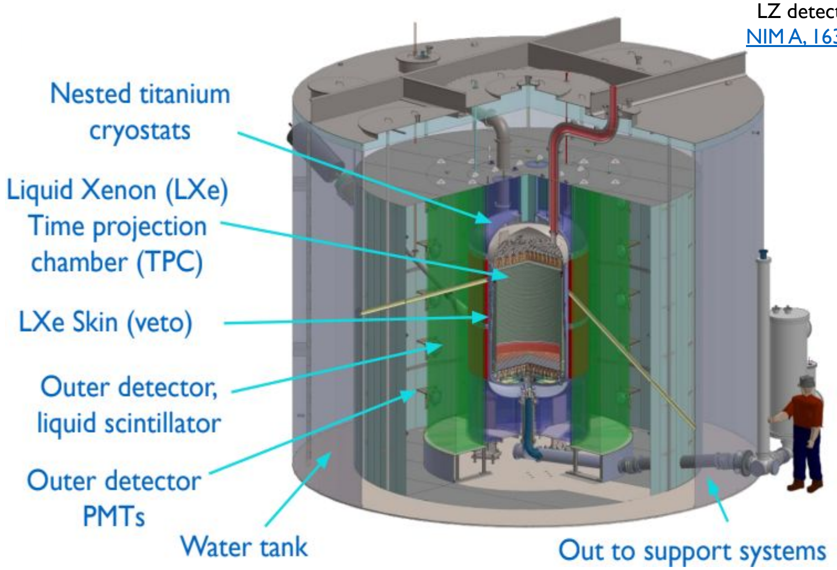
The LUX-ZEPLIN Data Acquisition and Real-Time Monitoring System

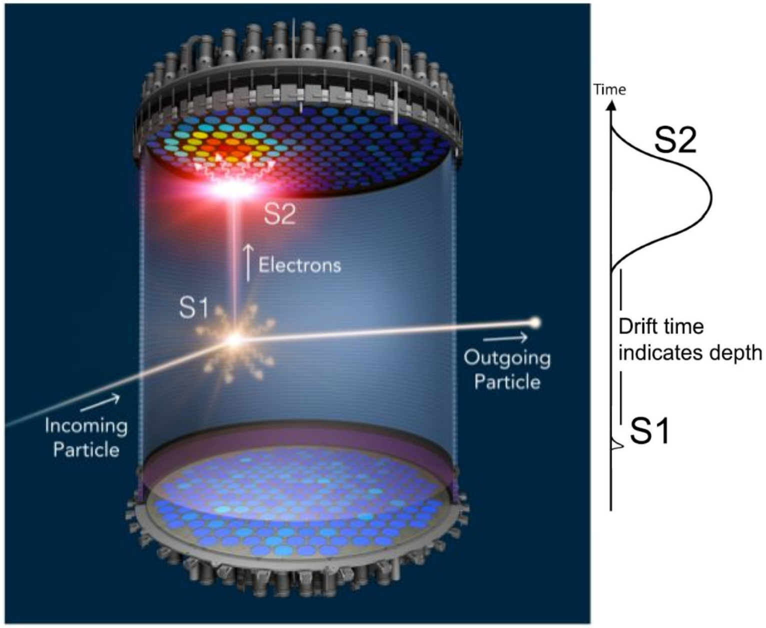
CPAD Conference
WG6: TDAQ and AI/ML
2022/11/30

Dev Ashish Khaitan,
Electronics Systems Coordinator,
on behalf of the LZ Collaboration

The LZ Detector

LZ detector design:
[NIM A, 163047 (2019)](NIM A, 163047 (2019))



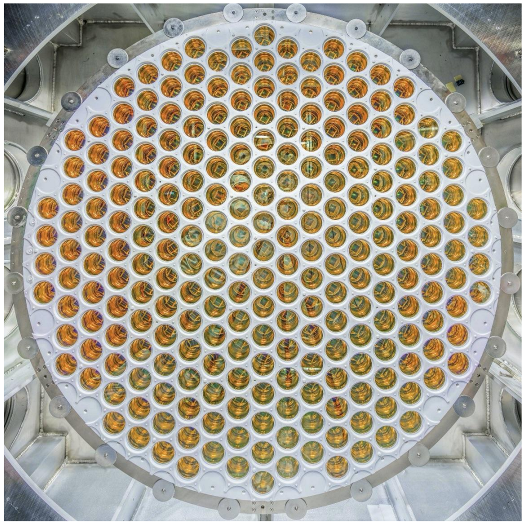


The LUX-ZEPLIN (LZ) Experiment is a direct detection dark matter experiment.

- It is deployed 4850 feet underground at the Sanford Underground Research Facility in Lead, South Dakota.
- LZ completed released its first result in July '22 boasting world leading sensitivity to detect dark matter.
- It's central detector volume is a 7 tonne dual-phase xenon time projection chamber (TPC).
  - We detect scintillation light (S1) and ionization charge from the primary event, which is converted to proportional scintillation (S2) in the gas phase.
  - The detector is fiducialized:
    - Time between S1/S2 and top PMT pattern used to localize event.
    - Using the hit pattern of the S2 light x-y position can be reconstructed.
- The central detector is surrounded by two active veto volumes: a xenon skin and a gadolinium-loaded liquid scintillator. These are surrounded by a passive veto: 230 tonnes of DI water.
- These volumes are instrumented with 745 PMTs.

Dev Ashish Khaitan
dkhaitan@u.rochester.edu
On behalf of the LZ Collaboration

The LZ Data Acquisition System



The LZ data acquisition and sparsification system (DAQ) is responsible for real-time zero suppression and event selection.

- The entirely custom hardware and firmware gives us great flexibility to meet the needs to our experiment.
- One of the many unique aspect of this system is the integrated approach to data acquisition and system health monitoring.

The LZ DAQ is based on the functionality provided by the 32-channel digitizers (DDC-32) and Logic boards.

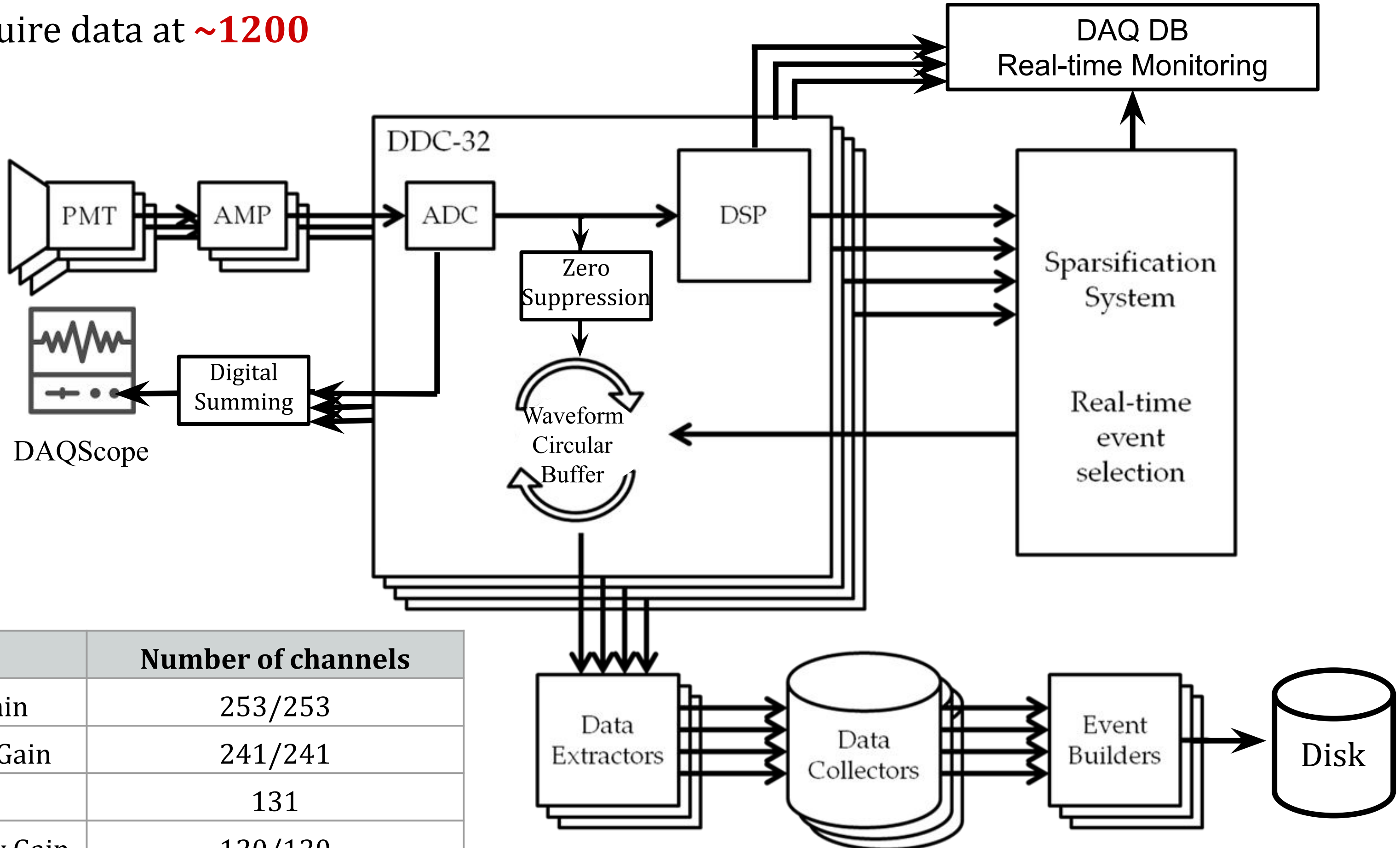
- Boards designed by Wojtek Skulski (SkuTek Instrumentation, https://www.skutek.com/).
- These boards have a Kintex-7 Field Programmable Gate Array (FPGA) and a microBone single-board computer.
- The firmware and software for the DAQ was developed in-house by Eryk Druszkiewicz.

Dev Ashish Khaitan
dkhaitan@u.rochester.edu
On behalf of the LZ Collaboration

The LZ Data Acquisition System

We can stably acquire data at **~1200 MB/s**.

During LZ's first science campaign, the DAQ had a livetime ~97%.



Group	Number of channels
TPC Top High/Low Gain	253/253
TPC Bottom High/Low Gain	241/241
Skin High Gain	131
Outer Detector High/Low Gain	120/120
Fast Sensors	24
External Triggers/PMTs	13
Dummy Monitoring	20
Total	**1416**

46 x DDC-32 Digitizers

16 x Data Collectors

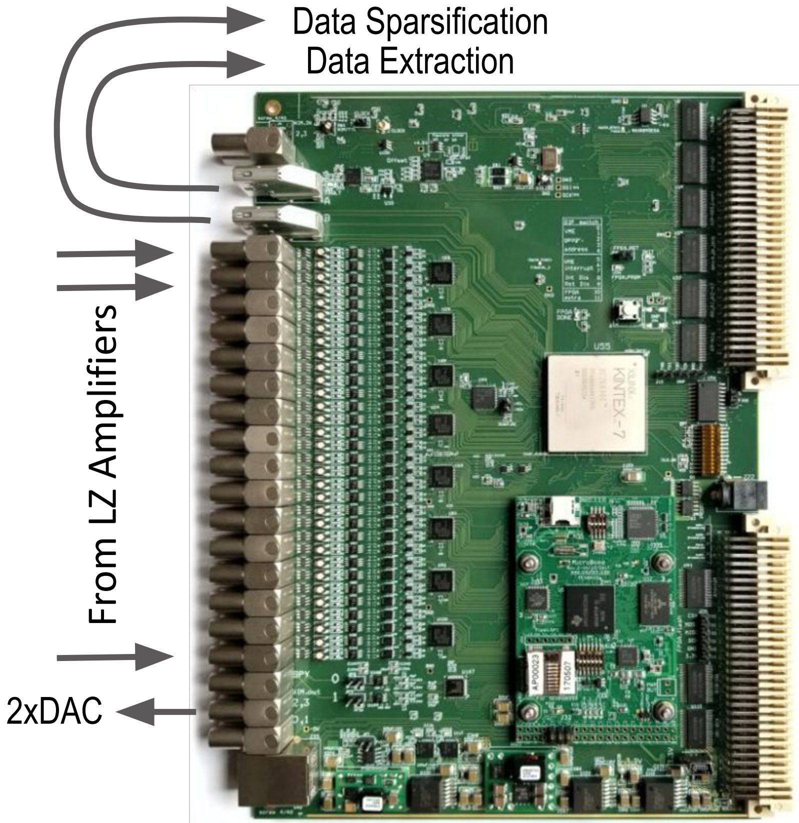
6 x Data Sparsifiers

16 x Data Extractors

2 x Master Logic Boards

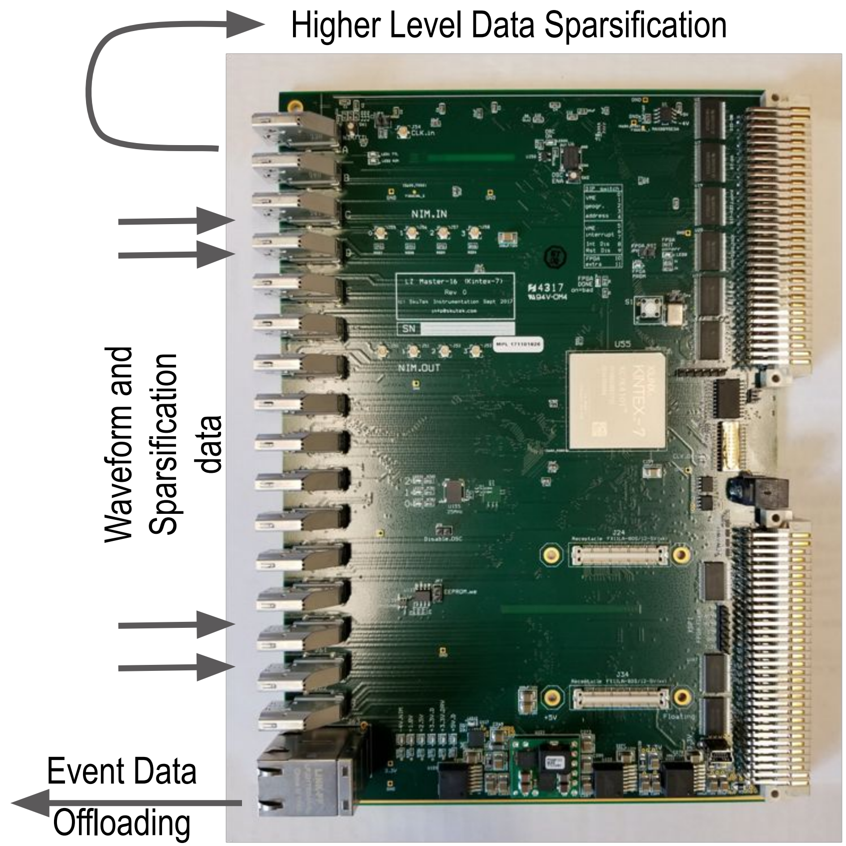
32-channel Digitizer and Logic Board

- Boards designed by Wojtek Skulski (SkuTek Instrumentation, https://www.skutek.com/)
- The entire firmware/software was developed in-house by Eryk Druszkiewicz (UofR) for LZ.



32 ADC digitization channels:

- 14-bit resolution @ 100 MHz sampling
- 2V input range with +/-1V adjustable baseline



16 custom HDMI serial links:

- 3.2 Gbps downstream and 800Mbps control channels
- One FPGA driven 1 Gbit Ethernet offloading link

- Kintex 7 Xilinx FPGA and AM3358 running Linux with Ethernet and RS-232.
  - **Digital signal processing is carried out on the Kintex 7 FPGAs.**
- Fully remotely programmable and virtual JTAG accessible.

Digital Signal Processing

The FPGAs are continuously processing data to provide zero suppression, event selection and signal chain health monitoring.

- We use the Pulses Only Digitization (POD) algorithm for zero suppression.
  - Based on the trigger time, the Data Sparsification Master defines an event window.
    - PODs derived from the raw waveforms, within the event window are recorded to disk, when collecting zero suppressed data.

- The raw waveforms are convolved with S1- and S2-filters.
  - Either an S1- or an S2-filter response is used to include channels in a trigger decision.
  - Another set of S1- and S2-filters responses are used to monitor for system stability.
    - These rates are recorded to a database (DB) to provide monitoring and alarming ability.
    - This also provides of pulse rates for each the channel.

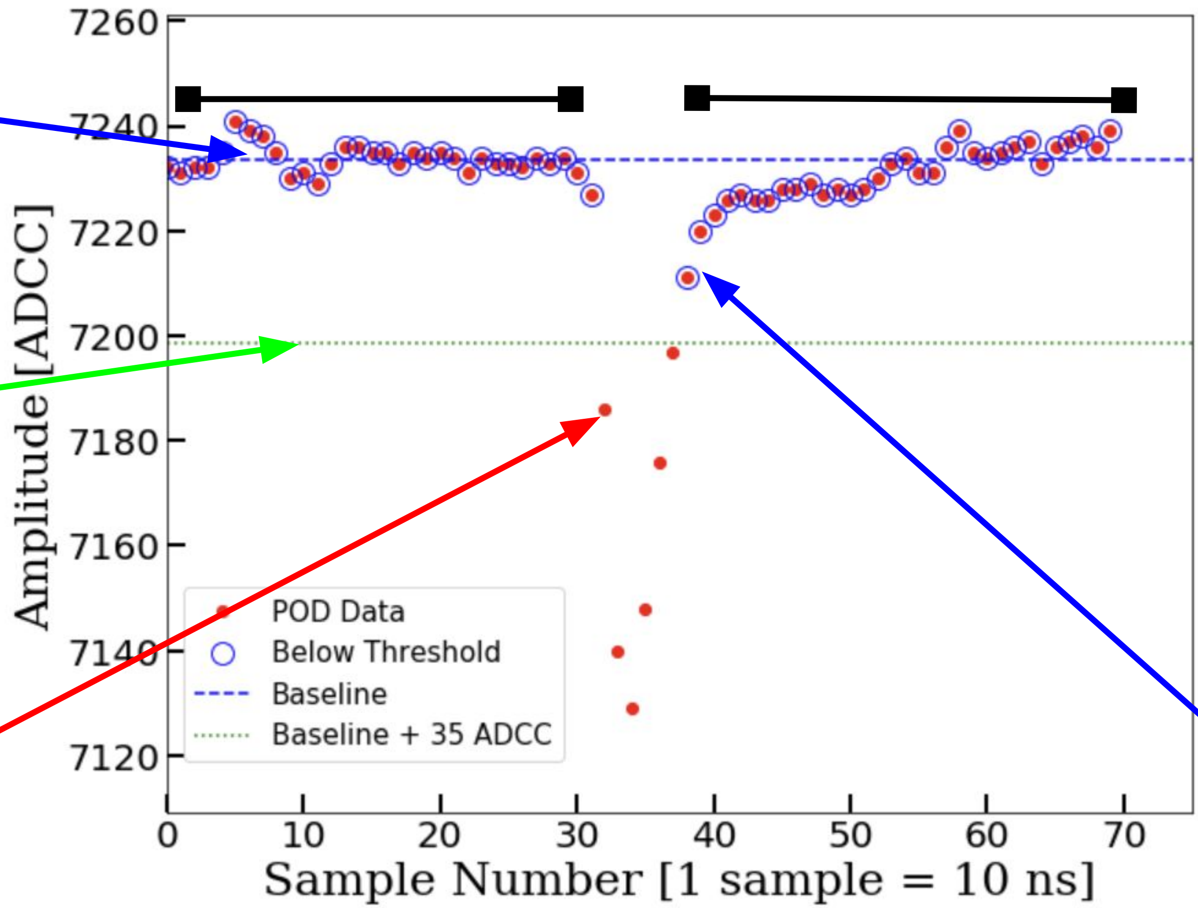
- A digital sum of raw waveforms from selected channels is routed to an oscilloscope.
  - This provides non-intrusive signal chain monitoring.

Anatomy of a POD

1. The FPGA calculates a rolling average of 32 samples.

2. For each channel a threshold, based on the previous 32 samples, is applied to the next sample.

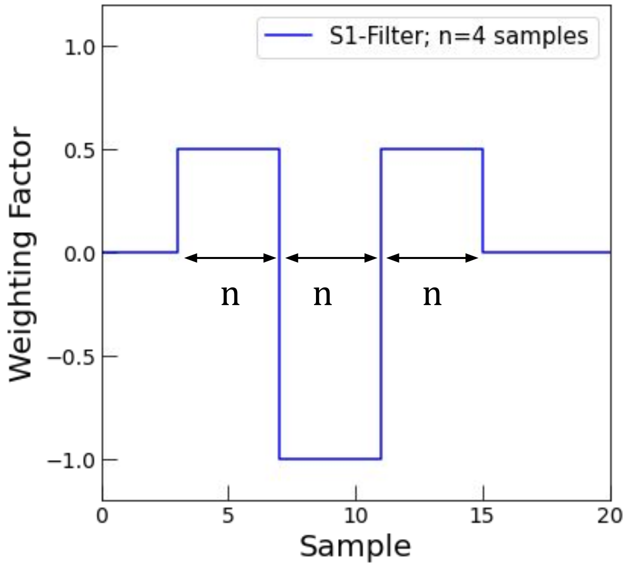
3. If the sample crosses the threshold
-> **This defines the start of the POD.**

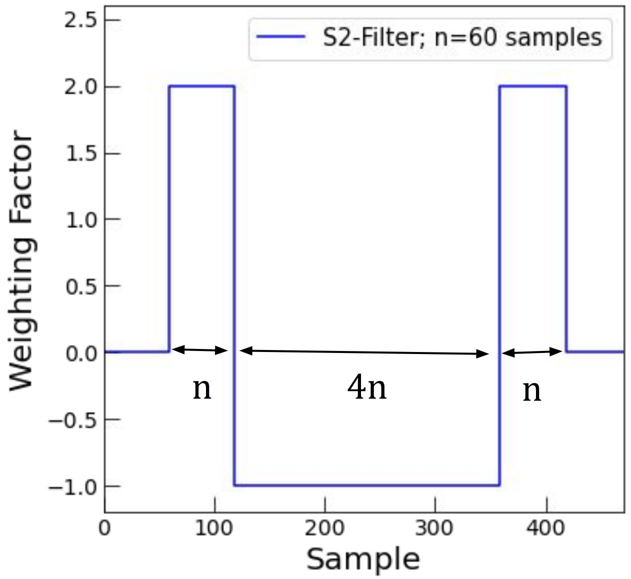


4. When a sample goes below the threshold
=> **This defines the end of the POD.**
These samples start to be used for the rolling average.

5. We record 32 sample pre- and post- the above threshold region.
=> **This entire waveform is called a POD.**

S1- and S2-Filter



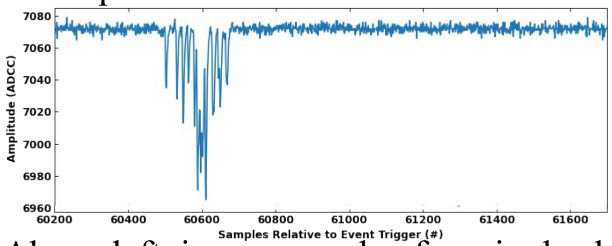


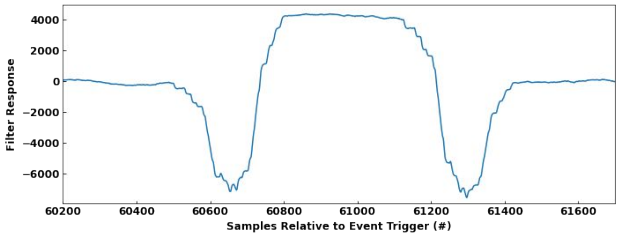
We convolve PMT signals with the S1- and S2-Filters to calculate a proxy for area.

- This provides the ability to make an area-threshold trigger decision and provides real-time feedback on activity in the detector.

The S1- and S2-filters are double Hogenauer filters.

- They have different main and side lobe widths, matched to the expected S1 and S2 signals.
  - The S1 signals are from scintillation in the detector. They are typically <100 ns.
    - Seen in all three detector volumes.
    - The S1-filter width (n) can be tuned between 1 and 16 samples.
  - The S2 signals are electroluminescent signals. These signals are typically < 5 us.
    - Seen only in the TPC.
    - The S2-filter width (n) can be tuned between 1 and 128 samples.
- The main and side lobes have different weighting factors.
- These filters provide baseline subtraction and a response proportional to the pulse area.





Above left, is an example of an single channel’s response to an S2 signal of 15 phd.

- It’s S2-filter response is shown on the right.

Dev Ashish Khaitan
dkhaitan@u.rochester.edu
On behalf of the LZ Collaboration

Event Selection

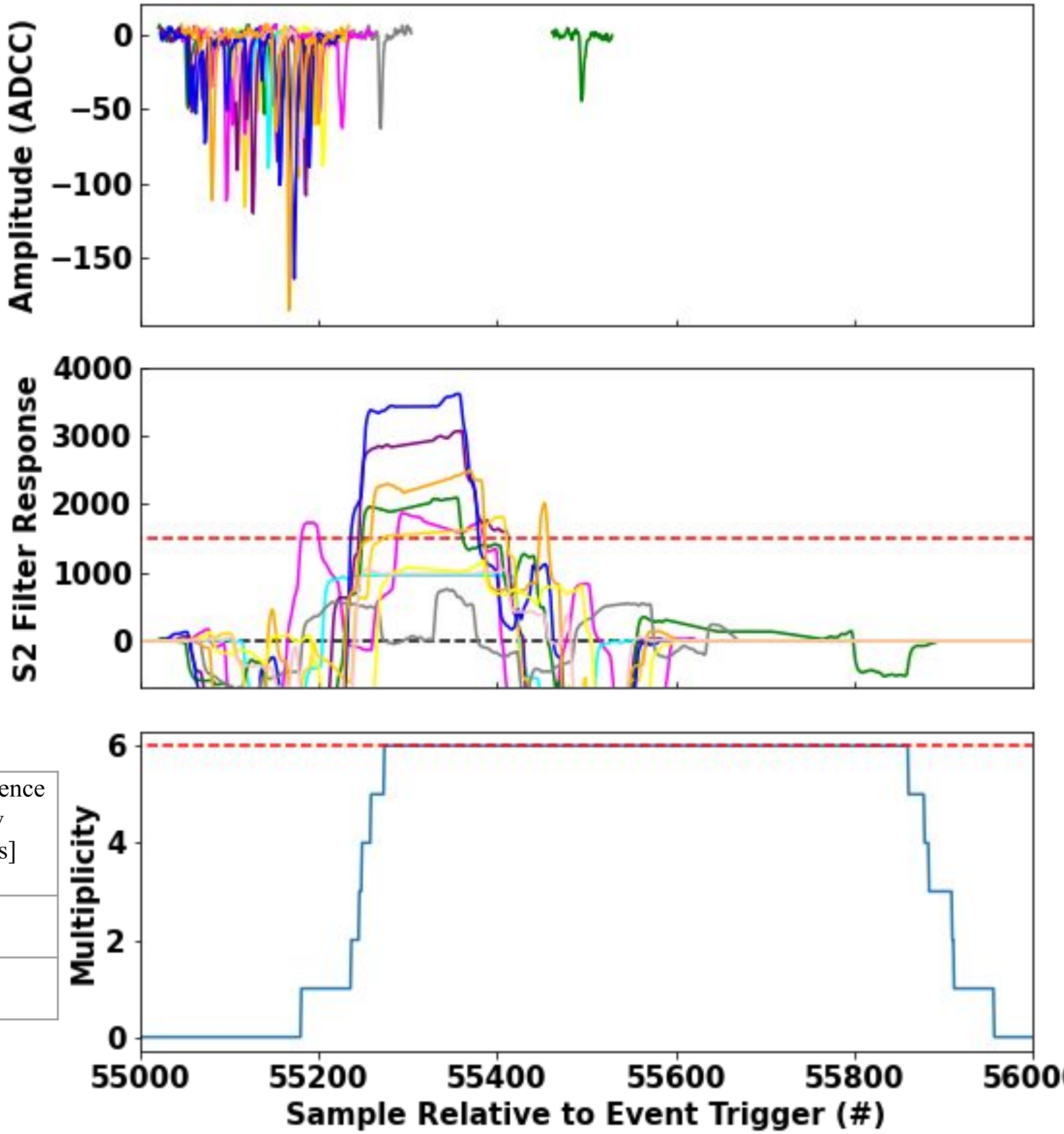
We select events to record to disk by employing detector response based and external triggers.

- Detector response based decisions require a number of channels to cross either an S1/S2-filter response threshold within a coincidence window.
- External triggers sources are the GPS system, Xe LED system, OD optical calibration system, DD-n calibration system, etc.

During LZ's first science campaign we used:

- A TPC S2-filter trigger,
- An OD S1-filter trigger,
- A 1 Hz GPS trigger, and
- A 4 Hz Random trigger.

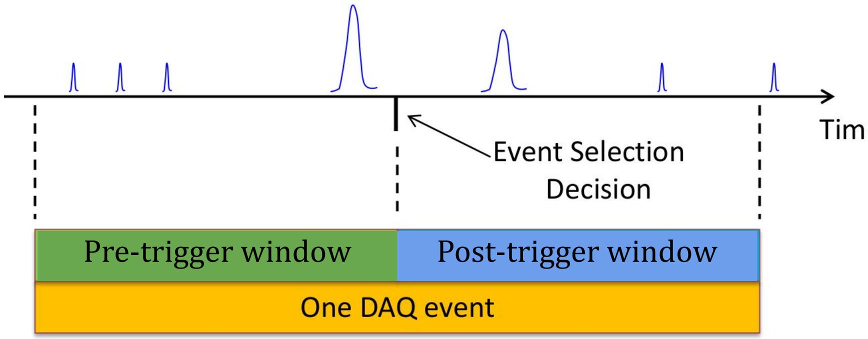
Trigger	Channels	Filter Width [samples]	Main lobe/ Integration width [samples]	Threshold [ADCC]	Multiplicity	Coincidence Window [samples]
TPC S2-filter	All Top TPC HG	61	244	1500	6	500
OD S1-filter	All OD HG	15	15	3000	15	32



Event Selection

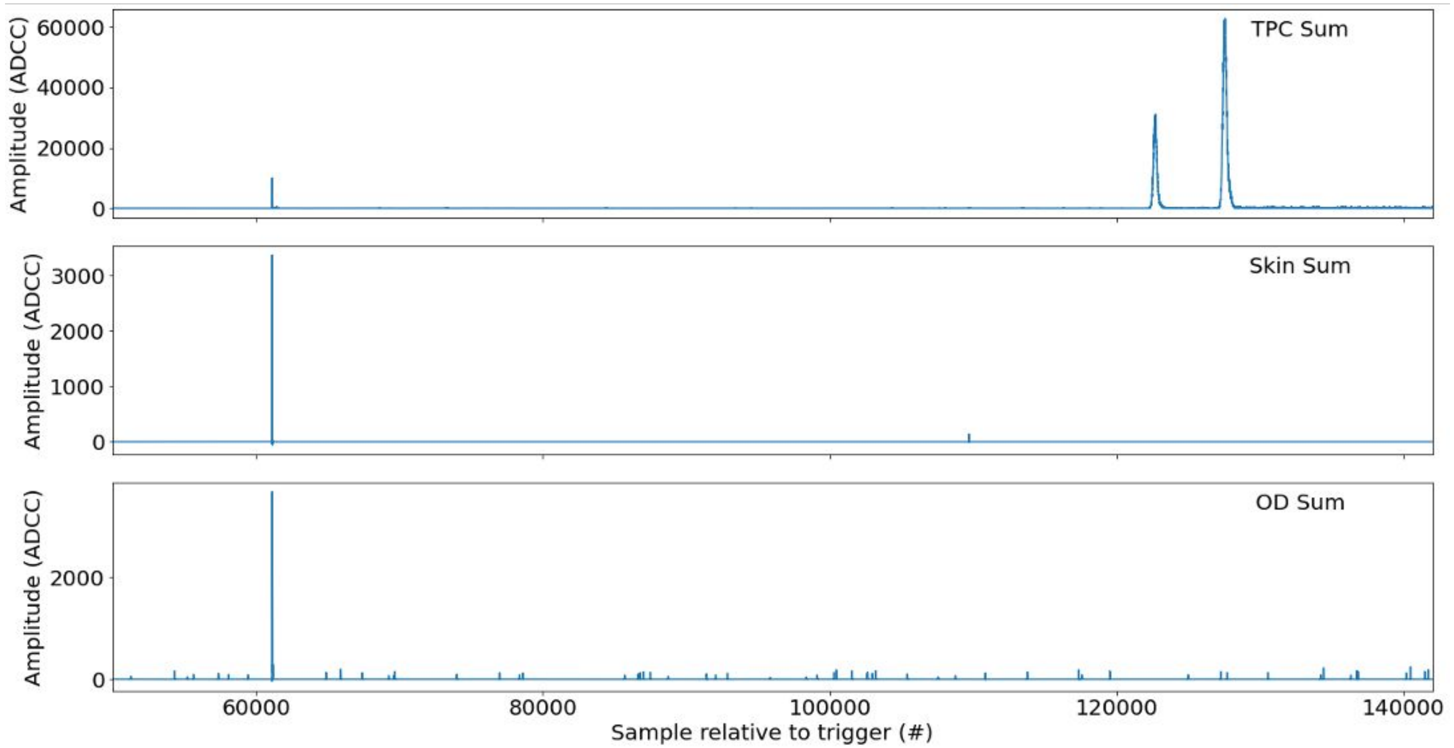
When a trigger is received, an event window of 2 ms pre-trigger and 2.5 ms post-trigger is defined.

- Regardless of the trigger source, we capture data from all channels.
- There is no hierarchy in triggers.
  - The first arriving trigger defines the event window.
  - We record which trigger caused the event and which triggers would've happened in the post-trigger window.



DD-n calibration event triggered on the DD-n external trigger.

A coincident signal is visible in all three detector.



Dev Ashish Khaitan
dkhaitan@u.rochester.edu
On behalf of the LZ Collaboration

Signal Chain and Detector Monitoring

The rate of S1- and S2-filter threshold crossings are monitored for stability.

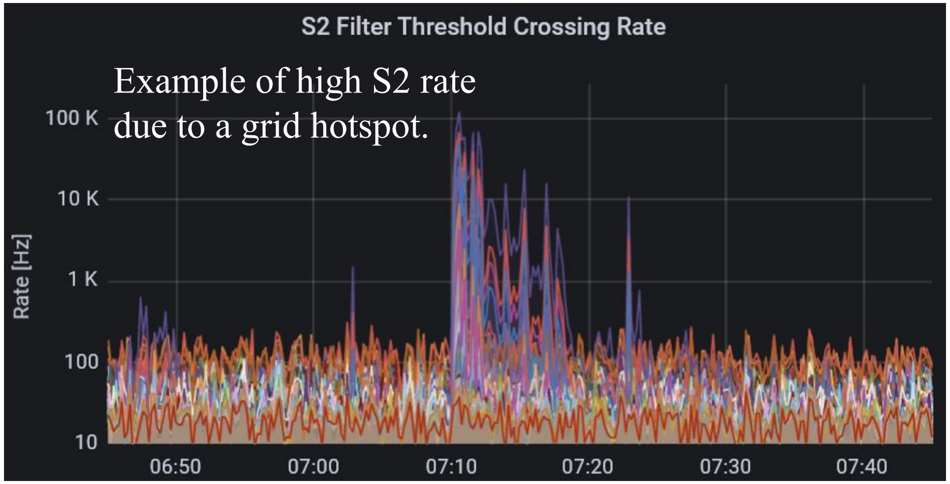
- Individual rates provide information if the PMT or signal chain is experiencing issues.
  - Daily checks on these rates are carried out.
- Grouped rates provide information on the health of the detector.
- During the first science campaign, we excluded periods of high rates due to spurious activity.

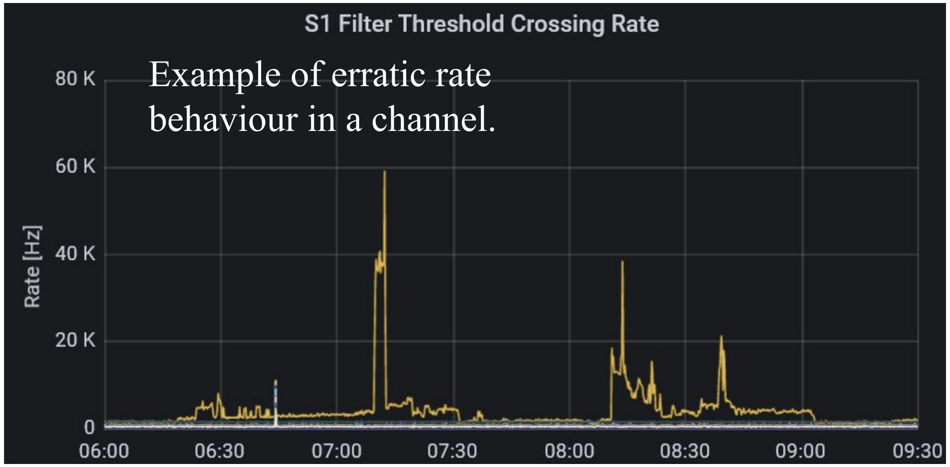
We record the rate of S1- and S2-filter threshold crossings in a database (DB) for each channel.

- During the first science campaign, we reported the average ~13-14x0.25 second measurements.
  - These rates are recorded every 10 seconds.
  - If any of the individual measurements saturates the 16 bit counter the maximum value is reported for that interval.
- For the next science campaign, these counters will have >90% livetime.

The HG channel S1-filter responses are included in our slow control system.

- Alarms have been defined and enabled on rates.

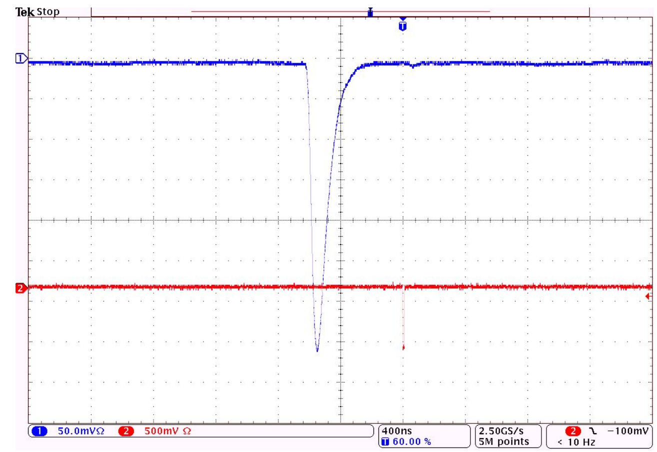


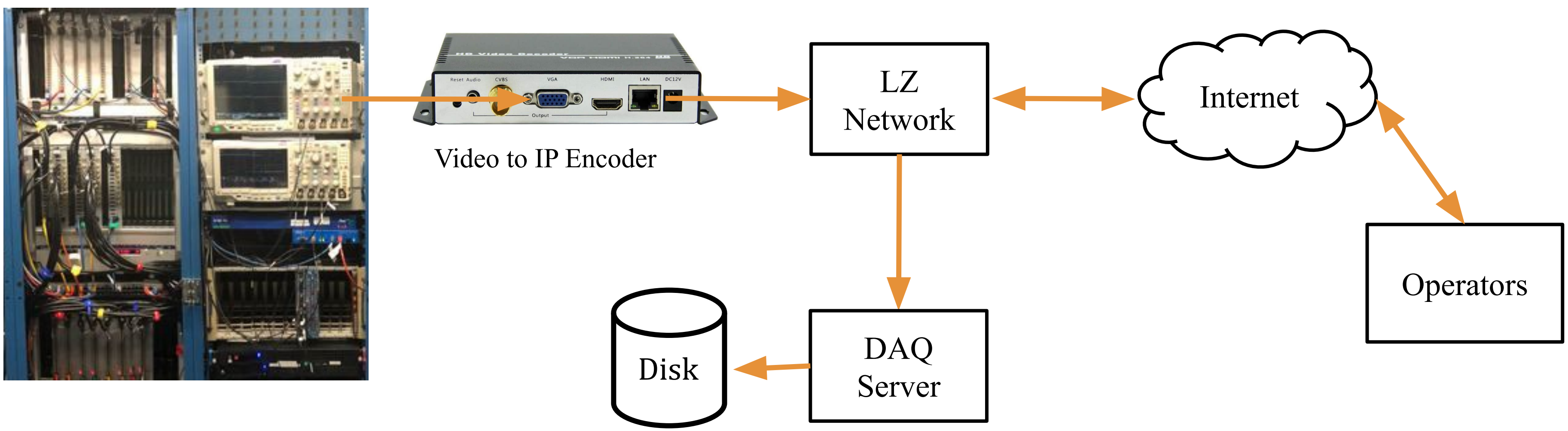


DAQScope

The DAQ system allows an operator to look at any one or sum of selected PMT signal channels on a Tektronix oscilloscope with remote controls and video streaming.

- Configuration of the scope and channels to be displayed is done via a custom Run Control interface.
- Multiplexing and summing is done digitally, thus there is no need to unplug or replug physical connections.
- The channels displayed are at full 100 MHz sample rate with no zero-suppression.
- The stream can be viewed via a streaming media player like VLC.
  - We also record the stream to disk on the DAQ Server.





Summary

The LUX-ZEPLIN (LZ) Experiment is a direct detection dark matter experiment.

- The detector volumes are instrumented with 745 PMTs.
- The LZ DAQ is responsible for zero-suppression and event selection.
  - This system has been used by LZ to achieve world leading sensitivity.
  - The LZ data acquisition and sparsification system is built around the functionality provided by Kintex-7 FPGAs.
    - The entirely custom hardware and firmware gives us great flexibility to meet the needs to our experiment.
    - One of the many unique aspect of this system is the integrated approach to data acquisition and system health monitoring.

With the right team, we have built, commissioned and implemented an entirely custom DAQ system.

- The Rochester-built DDC-32 digitizers (http://skutek.com) were designed by Wojtek Skulski.
- The firmware and software for the LZ DAQ was developed by Eryk Druszkiewicz of the Rochester LZ group.
- I led the installation, commissioning, and operation of the LZ Electronics and DAQ systems.

Thank You!

Dev Ashish Khaitan
dkhaitan@u.rochester.edu
On behalf of the LZ Collaboration

The LZ Collaboration

35 Institutions: 250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Wisconsin, Madison

US UK Portugal Korea Australia


LZ Collaboration Meeting – September 8–11, 2021

Thanks to our sponsors and participating institutions!

U.S. Department of Energy Office of Science

Science and Technology Facilities Council

Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

Institute for Basic Science

Dev Ashish Khaitan
dkhaitan@u.rochester.edu
On behalf of the LZ Collaboration