Designing and Testing the JSNS^2 Data Acquisition System Simulation

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Abstract: The JSNS^2 experiment is a direct test of the LSND anomaly. It hopes to find evidence of sterile neutrinos by observing an excess of anti-electron neutrinos detected through inverse beta decay. Simulations of the detector exist, but they lack the trigger system. The addition of the trigger simulation described here improves the accuracy of these simulations and allows them to produce outputs that more closely resemble actual detector data. Several different trigger schemes' abilities to veto cosmic muons were tested with this trigger simulation, the best of which was able to veto 99.6% of cosmic muons.

Motivation:

Neutrinos are the lightest of the known matter particles and come in three flavors. They were long thought to be massless until in the early 2000s it was discovered by the Super-Kamiokande atmospheric neutrino experiment in Japan and the solar neutrino experiment (SNO) in Canada that neutrinos can oscillate between the three flavors and thus can't be massless [1]. However, some experimental data suggest that there may be other flavors that neutrinos can oscillate to which do not interact via the weak force. These non-interacting flavors are known as sterile neutrinos and are not predicted by the standard model. One of the experiments to find such an anomaly is the LSND, which detected a 3.8σ excess of anti-muon neutrinos [2]. It is not clear if this excess is coming from oscillations between unknow neutrino flavors, but if it were this would be evidence of sterile neutrinos.

JSNS^2: The JSNS^2 experiment uses the same neutrino source and neutrino target and interaction as the LSND and will thus be a direct test of the LSND anomaly [3]. It utilizes a detector 24m from the neutrino source that is filled with 17 tons of Gd doped scintillator and lined with 96 inner region photomultiplier tubes (PMTs) as well as 24 veto region PMTs. When a neutrino enters the detector, there is a chance it will interact with a proton via inverse beta decay (IBD). This will produce a positron, which is promptly annihilated producing a flash of light, and a neutron which is captured by the Gd around 30μs later resulting in another flash of light.

The photons from these flashes hit the PMTs that line the detector. When struck, the PMTs produce an analog electronic signal that is sent to the data acquisition system (DAQ) which turns it into digital data [4]. The DAQ does this by first sending the PMT signal to the front end electronics (FEEs). Each FEE receives eight PMT signals and outputs the analog sum of these to the trigger system as well as a high gain and a low gain signal of each channel to the digitizer. The trigger system then tells the digitizer when an event may be occurring in the detector causing it to turn the analog signals it is receiving into digital signals that are stored on a computer.

Fig1

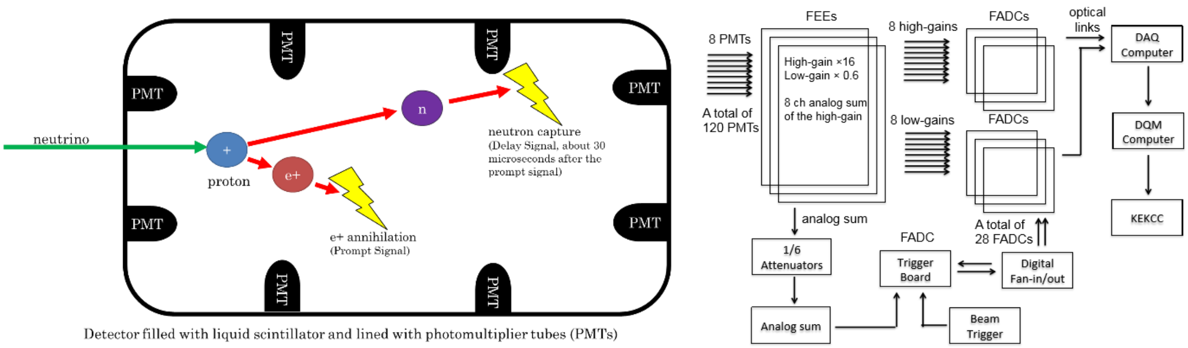


Fig1: A diagram of the JSNS^2 detector and DAQ system as seen in [4]. Neutrinos that enter the detector may interact via IBD which produces two flashes of light that are recorded by the PMTs and sent to the DAQ system. The DAQ system processes these analog signals and turns them into digital data.

Simulation Design:

RAT and the Existing DAQ Simulation: The Reactor Analysis Tool (RAT) is a software package that is used to simulate liquid scintillator detectors like that in the JSNS^2 experiment. It provides a framework for Monte Carlo simulations and analysis by incorporating other software packages, like ROOT and GEANT4, into a framework that also provides additional physics and detector options. The JSNS^2 experiment is currently utilizing RAT extensively and the DAQ simulation has been built entirely inside RAT to make it compatible with all simulations.

The existing version of the DAQ simulation is able to take information from the RAT Monte Carlo simulation and produce an output that looks like the data from the detector. This allows any reconstruction software to be easily tested on data from a RAT simulation. However, the DAQ simulation still has major limitations, including the lack of a trigger system and the inability to record anything but one sampling window starting at the beginning of the simulation. This causes the simulation to record every event to the output .root file and fail to record anything that happens latter that the first sampling window in each event.

Trigger Simulation Code Design: Much of the work I did this summer involved removing these limitations by adding a trigger simulation to the existing DAQ simulation. Most of the code I wrote was implemented by adding three classes to the DAQ simulation, `AnalogSum`, `Trigger`, and `TriggerScheme`. `AnlogSum` inherits from the existing `AnalogSignal` class (which is an abstract base class used to build analog signals) and is responsible for simulating the attenuation and analog sum circuitry that passes the FEEs' signals to the trigger system. `Trigger` also inherits from the `AnalogSignal` class and is responsible for producing the times the `AnalogSum` signal crossed a certain threshold. This class is implemented separately for the various regions of the detector (inner volume, top veto, etc.). `TriggerScheme` is an abstract base class that is used to build various trigger schemes that can be selected from by the user. All of these receive the above threshold times from the `Trigger` class and reject any that do not meet the scheme's criteria. Finally, these times are given to the existing `Digitizer` class which records data to the .root output file at these times (see Fig2). The resulting simulation closely resembles the JSNS^2 trigger system. Its many user tunable parameters allow it to be tested in various situations and modified alongside the actual DAQ system.

Fig2

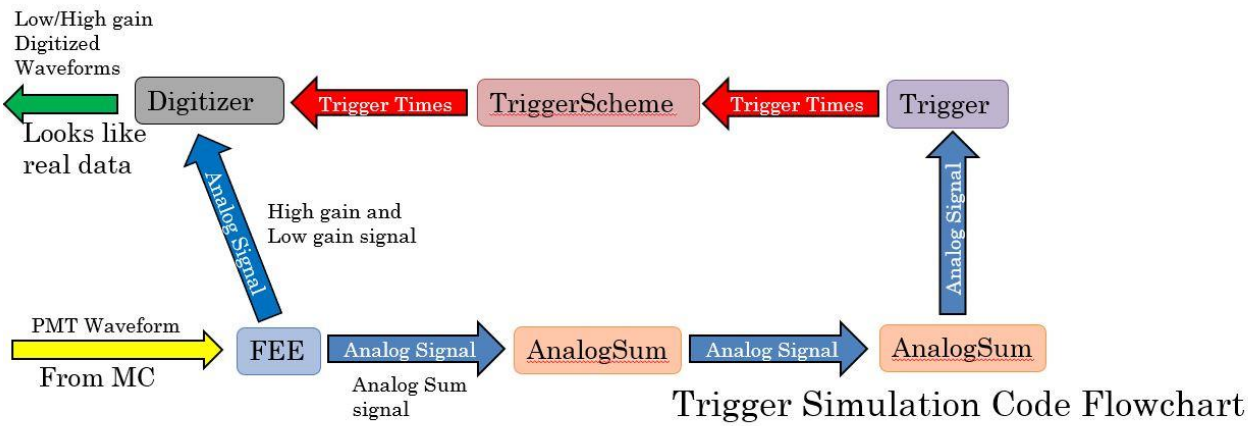


Fig2: A flowchart of the code I added to the DAQ simulation meant to simulate the JSNS^2 trigger simulation. Most of the code of the added code is contained in three classes, `AnalogSum`, which simulates analog sum circuitry, `Trigger`, which finds above threshold times, and `TriggerScheme`, which build the various veto schemes that select trigger times that meet certain criteria.

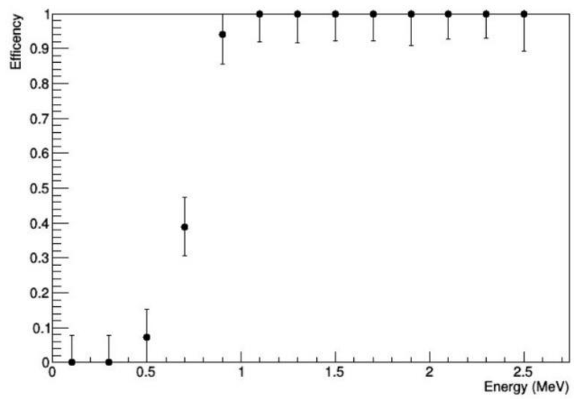
Testing and Simulations:

Initial tests of the trigger were performed by simulating high energy electrons with varying energy and location within the detector volume. This allowed me to test how the efficiency of the trigger depends on the energy of an event and the number of photoelectrons (PE) produced by that event. As expected, as both quantities increased, so too did the efficiency of the trigger (Fig3). These results show that the trigger simulation is working properly and can be used to test the performance of various trigger schemes.

Fig3

Efficiency vs Energy

Efficiency vs. Number of PE



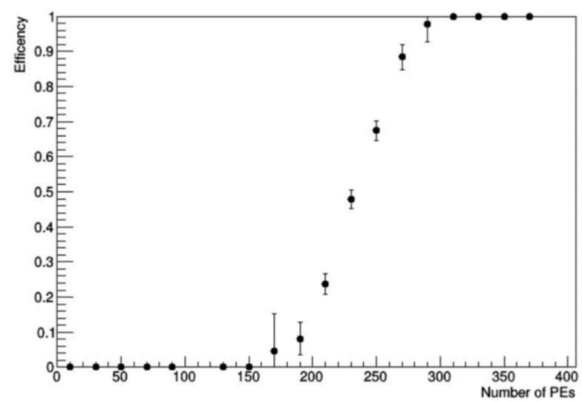


Fig3: (left) The efficiency of the trigger is plotted against the energy of the event for a simulation of 500 e- with 0 to 2.5MeV. (right) The efficiency of the trigger is plotted against the number of photoelectrons produced by each event for 1MeV e-. In both cases the e- were placed randomly within the inner detector volume. The behavior seen here indicates that the trigger simulation is behaving as expected.

Testing Proposed Trigger Schemes: One of the functions of the trigger system is to filter out cosmic muons. The Cosmic-ray Shower Library (CRY) is known to accurately simulate these events and can be easily used to produce outputs for RAT. I used this library alongside the trigger simulations to test several trigger scheme's ability to successfully capture IBD events among cosmic muons. The IBD event was placed within the first 9000ns of the simulation to imitate the window opened by the beam trigger and the muons were allowed to occur within the first 300,000ns to allow them to interfere with both the prompt and delay events. All IBD events were placed randomly within the detector and the muons were placed in the location they hit the detector according to CRY. A description of the trigger schemes I tested can be found in Table1 and a description of the metric I used to analyze performance can be found in Table2.

Table1

No Veto	No veto trigger, all triggers are accepted.
Veto	Triggers from the entire veto region are used to reject triggers from the inner detector region. The inner detector signals are delayed by 50ns to assure the veto signal arrives first when both are triggered. The inner threshold and the veto threshold are ~1Mev.
Top Veto	Same as Veto, but the top veto region is used instead of the entire veto region.
Sterile	Prompt and delay events are trigger separately. The prompt event has a ~18Mev threshold and must occur in 9000ns after the beam trigger (assumed to be first 9000ns of simulation). Delay triggers must occur 100,000ns after the prompt trigger and have a ~5MeV threshold. Both events can be vetoed by the veto trigger on the entire veto region with threshold ~1MeV but only the prompt signal has a time delay of 100ns.
Top Sterile	Same as Sterile, but the top veto region is used instead of the entire veto region.
Delay Sterile	Same as Sterile, but the delay signal also has a 100ns time delay.
Top Delay Sterile	Same as Top Sterile, but the delay signal also has a 100ns time delay

Table1: A description of the various trigger schemes that were tested.

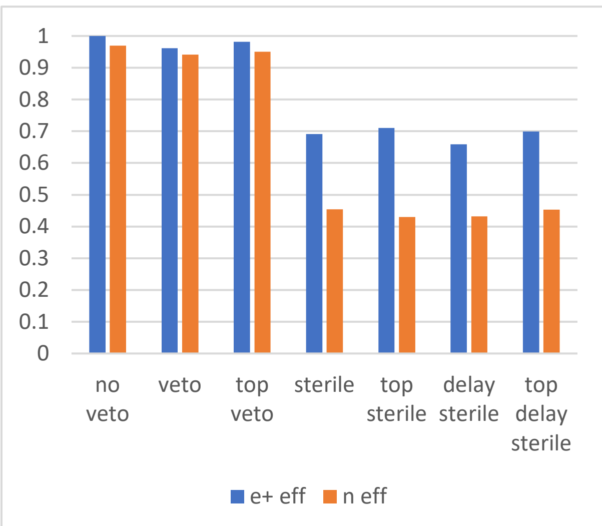
Table2

Metric	Description
e+ efficiency	Fraction of prompt positron annihilations triggered
n efficiency	Fraction of delay neutron captures from the IBD triggered
muon efficiency	Fraction of cosmic muons that caused a trigger
right delay rate	Fraction of events with two triggers and a neutron capture from the IBD as the second trigger
wrong delay rate	Fraction of events with two triggers and something other than a neutron capture from the IBD as the second trigger

Table2: A description of the parameters used to evaluate the performance of each trigger scheme.

Results:

Fig4



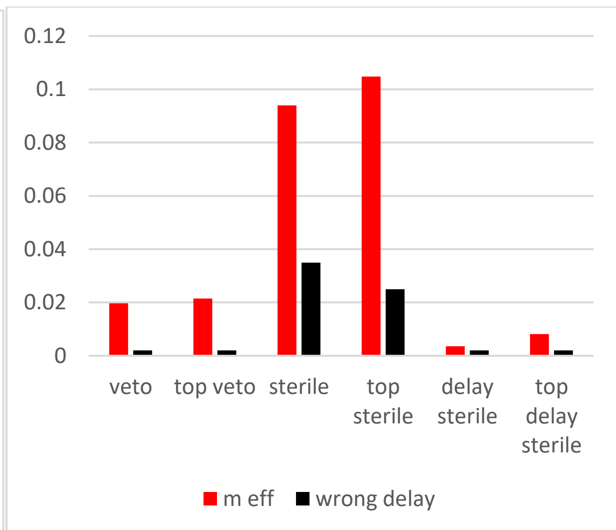


Fig4: (left)The e+ and n efficiency of various trigger schemes and (right) the muon efficiency and rate at which a muon imitates a neutron. These results come from simulations ~1500 IBD events and comic muons which hit the detector at ~4kHz. The IBD events are distributed uniformly within the detector volume and uniformly in the first 9000ns of the simulation. Cosmic muons are placed according to the CRY simulation and are allowed to occur within the first 300,000ns so that they can interfere with both the prompt and delay events.

The sterile trigger schemes have a much higher threshold and thus see a lower e+ and neutron efficiency than the veto trigger schemes. This drop in performance may have been pushed artificially high by the fact that the IBD events were distributed uniformly within the detector. This is not the most realistic approximation and it may be producing more events than expected on the edges of the detector that fail to trigger.

Utilizing the entire veto region instead of the top veto region made only a marginal increase to the performance of the trigger. This can be seen by comparing any of the veto schemes that use the entire veto region to their top veto region counterpart.

The sterile trigger without the time delay on the delay signal triggered on about 10% of muons compared to about 2% for the veto schemes and 0.4% for the sterile trigger schemes with the delay. This is likely due to muons being able to cross the delay threshold before the veto threshold and be accepted by the trigger. This caused the trigger to record the wrong delay event, in which the prompt event was an e+ annihilation but the delay event was a muon, more often than the other schemes. It recoded these events 3% of the time, compared to less than 0.5% for all other schemes. Thus, should the JSNS^2 experiment decide to use the sterile veto scheme for collecting the bulk of its data, it should strongly consider adding a time delay to both the prompt and delay signals to increase the trigger's ability to filter out muons.

References:

[1] S. M. Bilenky. 2012. "Neutrino. History of a unique particle." arXiv:1210.3065

[2] A. Aguilar *et al.* (LSND Collaboration). "Evidence for neutrino oscillations from the observation of $\overline{\nu_e}$appearance in a $\overline{\nu_\mu}$ beam" PRD 64, 112007

[3] S. Ajimura, *et al*. 2017. "Technical Design Report (TDR): Searching for a Sterile Neutrino at J-PARC MLF (E56, JSNS2)." arXiv:1705.08629

[4] J. S. Park, *et al.* 2020. "The JSNS2 data acquisition system." arXiv:2006.00670

[5] RAT documentation. https://rat.readthedocs.io/en/latest/overview.html

[6] CRY documentation. https://nuclear.llnl.gov/simulation/main.html