Triggering Water Cherenkov Detectors

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20th September, 2018

Outline

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2. Triggering at known time (e.g. beam ν)
3. Triggering at high energy (e.g. atmospheric ν)
4. Triggering at low energy, low rate (e.g. solar ν)
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6. Summary

Triggering basics

Problem

- There is a lot of background in the detector that we don't want to keep
  - e.g. $\sim$5 GB/s dark noise in Hyper-K
    - 13 PB/month isn't cheap
- Trigger to save only the interesting events

But....

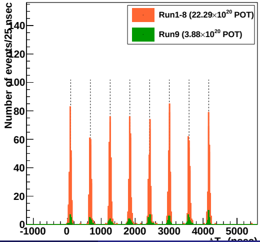
- Anything that doesn't pass the trigger is lost forever

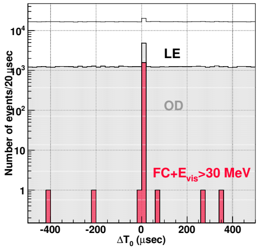
So...

- Need an intelligent trigger that will keep signal with high efficiency and high background rejection

Triggering at known time (e.g. beam ν)

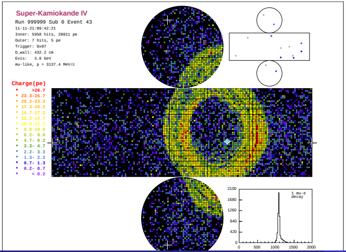
- Open a trigger gate when the physics will appear
- Difficulties
  - Synchronising the clock (can be 100s km)
    - ★ Solutions exist e.g. T2K's Super-K uses GPS
- Alternatively: use some of the triggers discussed later
  - Get high energy physics with high efficiency
  - But possibility to lose some of the low-E physics (e.g. NCQE, Coherent, ...)
- Relatively simple





Triggering at high energy (e.g. atmospheric ν)

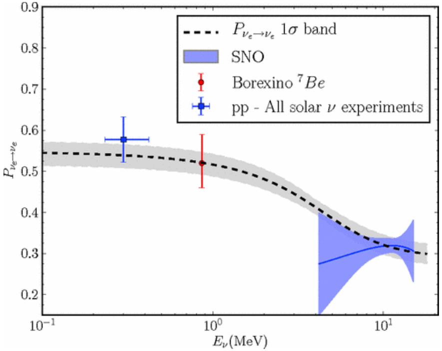
- Count the number of hits in a sliding time window (NHITS)
  - When goes above threshold, issue trigger
- Difficulties
  - Does not work at the lowest energies
    - For Hyper-K, this means E_{electron} of few 10s MeV
    - 44,000 PMTs @ 10 kHZ dark noise = 180 hits in 400 ns
    - $\sim$150 hits for 10 MeV event
  - Doesn't work with events close to wall, directed to nearest wall
    - Defining fiducial volume helps negate this
- Relatively simple



Outline

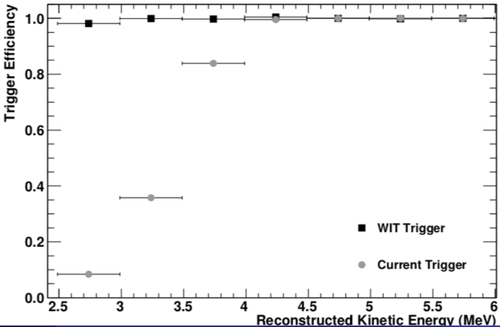
Triggering at low energy, low rate (e.g. solar ν)

- $\mathcal{O}$(10 MeV) electrons & photons are tricky to trigger on
  - From solar ν, supernova ν, neutron capture, ...
  - Number of hits overlaps with dark noise background
  - Radioactivity in water and glass can look like signal
- Need to use complex algorithms
- Important to lower threshold as much as possible



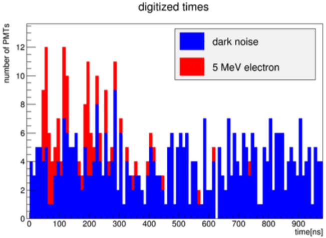
Super-K solar neutrino trigger

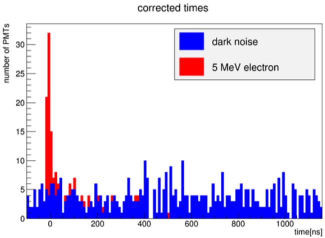
- Efficiency of super low energy trigger is
  - >99% @ 3.99 MeV recoil electron kinetic energy
  - ∼84% @ 3.49 MeV
- Wide-band intelligent trigger (WIT) used to lower threshold to 2.5 MeV
  - Reconstruct vertices in real time
  - G. Carminati, Phys. Procedia 61 (2016) 666-672



Aside: Vertex reconstruction

- $<$10 MeV electrons travel only a few cm in water
  - Effectively a point source of Cherenkov light
- Photon time-of-flight correction of hit times will give a peak at vertex
  - Dark noise background is random and will remain flat
- Radioactive background concentrated at tank walls
  - Can cut on vertex position to remove this





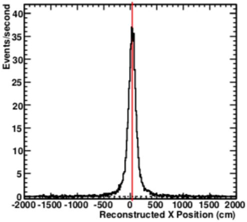
Super-K solar neutrino trigger

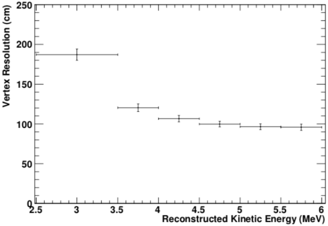
1. Pre-trigger
   - Require 11 hits ($\sim$2 MeV) above dark noise background ($\sim$12 hits) in 220 ns window
   - Reduces background by $\sim$70%
2. STORE (Software Triggered Online Reconstruction of Events)
   1. Fnd list of 2 PMT correlations
      - ⋆ Hit time for each PMT must be $\leq$ time of flight separation between PMTs
   2. Look at 4 PMT correlations
      - ⋆ Time residuals of all four hits in each combination must be zero at its associated point
   3. For fiducial vertices, look for coincidences of all hit PMTs
      - ⋆ If no coincidence in fiducial volume, event rejected

   - Reduces background by another $\sim$30%

Super-K solar neutrino trigger

3. Clusfit
   - Fast vertexing algorithm
     - ★ Removes isolated hits (dark noise, reflected/scattered light)
   - If no coincidence in fiducial volume, event rejected
4. BONSAI (Branch Optimization Navigating Successive Annealing Iterations)
   - Maximum likelihood fit to timing residuals of Cherenkov signal & background
   - If largest-likelihood hypothesis is in fiducial volume, event stored





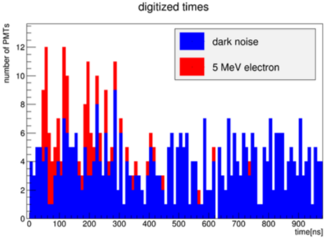
Super-K vs Hyper-K

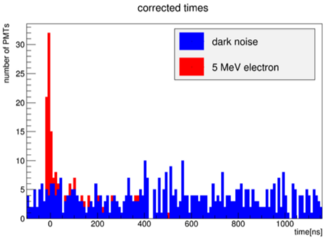
	Super-K	Hyper-K
Max direct light travel time (ns)	$\sim$220	$\sim$400
NPMTs	$\sim$11000	$\sim$44000
PMT dark rate (kHz)	$\sim$5	$\sim$10
Noise hits in trigger decision window	$\sim$12	$\sim$180
NHITS per MeV	$\sim$6	$\sim$ 15

- Hyper-K swamped by dark noise
  - Require fast algorithms

Hyper-K low energy trigger: test-vertices

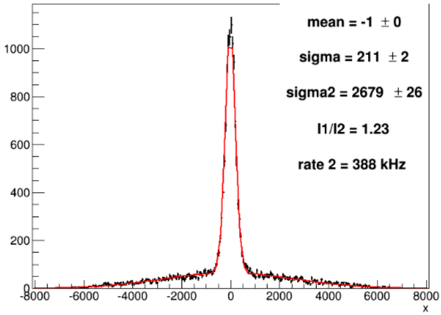
- Time-correct all hits to all vertices on a fixed 5 m grid
  - Shrink time window from 400 to 20 ns
  - Reduces dark noise
- Look for a peak above threshold
- Algorithm returns vertex position(s)
  - Gives a chance to reject non-fiducial vertices that are radioactivity-dominated

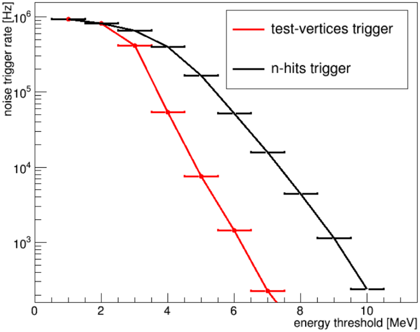




Hyper-K: Test-vertices performance

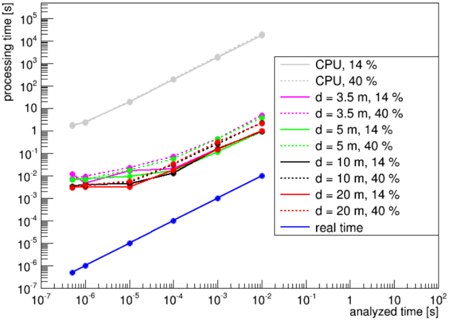
- Left: vertex resolution $= \frac{1}{2}$ grid spacing
- Right: Kinetic energy threshold defined as 90% signal efficiency
  - Test-vertices trigger lowers threshold by 2 MeV





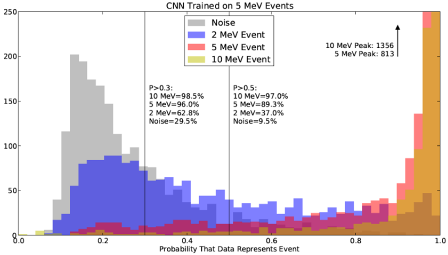
Hyper-K: Test-vertices performance

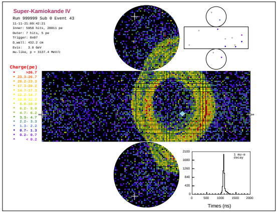
- Implemented on GPU
  - $\mathcal{O}(10^4)$ times faster than a CPU



Hyper-K convolutional neural network

- Use pattern recognition to distinguish signal from background
  - Hyper-K is large camera
    - ★ PMTs = pixels
    - ★ Charge = greyscale value
- Lancaster MPhys student implemented this
  - Using off-the-shelf CNN algorithm
  - Currently neglecting top/bottom endcaps (to be extended)
- Promising results using just the barrel region
  - 89% efficiency @ 5 MeV; 9.5% dark noise acceptance

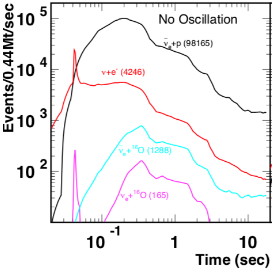


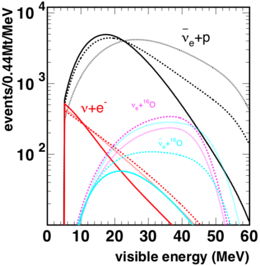


Outline

Triggering at low energy, high rate (e.g. SN ν)

- For a typical galactic supernova @ 10 kpc expect 100s of events
  - 52,000$\sim$79,000 at Hyper-K
    - Range from SN models & oscillations
- These occur in $\sim$10 seconds
  - Most within the first second
- Energy $\mathcal{O}$(10 MeV)
- The SN may be too far away to give a positive trigger
  - Buffer data to wait for external trigger (e.g. from SNEWS)





Super-K SN trigger

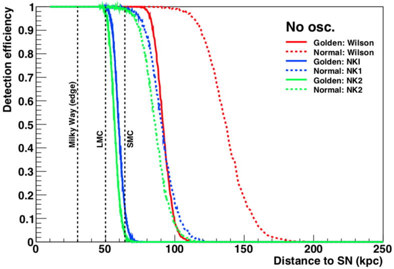
1. Reconstruct event vertex position, direction, & energy on SN monitor machine
2. Select events with $E > 7$ MeV in fiducial volume
   - Remove cosmic ray muons & their decay electrons
3. Count number of reconstructed events in 20 seconds previous (N_{cluster})
4. Analyse vertex distribution: it should be uniform in volume
   - Background: e.g. spallation events form a line/plane distribution
5. Cut on N_{cluster} with volume-like requirement determines when experts analyse events
   - Automated phone calls, emails, alerts to SNEWS etc.

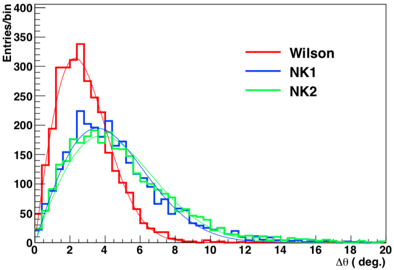
- Takes just a few minutes from detection to alert

Astropart.Phys. 81 (2016) 39-48

Super-K SN trigger

- Almost 100% efficient at Large Magellanic Cloud
- SN direction also calculated using likelihood fit
    - Direction resolution a couple of degrees





Summary

- Known time & high energy physics are relatively simple to trigger
  - e.g. atmospheric ν, beam ν, proton decay
- Low energy, low rate require intelligent algorithms
  - 3 levels of vertex reconstruction in Super-K
  - Hyper-K exploring vertexing and CNN on GPUs
- Low energy, high rate requires buffering of data
  - Few minutes for self-triggered; potentially longer for external trigger