DAQ for Hyper-K Water Cherenkov detectors

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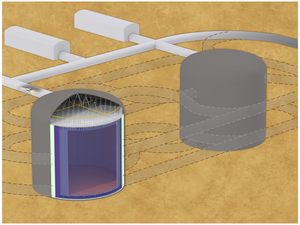
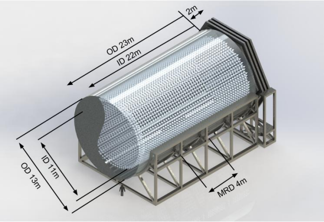
September 22, 2016

Outline

Hyper-Kamiokande & TITUS

- Hyper-Kamiokande (HK) due to start operations ∼2026
  - Two 258 kton (187 kton fiducial) tanks
  - ∼40,000 inner detector 50 cm PMTs per tank
    - 40% inner detector photocoverage
- TITUS: intermediate detector ∼2 km from the J-PARC neutrino beam
  - 2.1 kton fiducial tank
  - ∼3,000 inner detector 30 cm PMTs
  - Gd-doped
  - Magnetised muon range detector(s) (MRD)

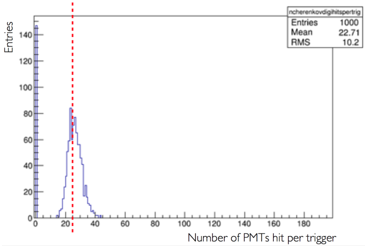




Outline

WCSim: digitizers & triggering

- WCSim is an open-sourced, C++ & Geant4-based simulation code
  - Modular design allows you to choose geometry, PMT type, ...
- There were problems with the dark noise, digitizer, & trigger
  - Trigger efficiency too high at low energy
    - ★ Trigger used raw hits, instead of digits
  - Difficult to perform studies on digitizer/trigger effects



- Rewrote to fix issues, and made it modular
  - A lot of code: +3009, -289
  - Added benefit: can now easily study new triggers (and digitizers)

WCSim: Radioactivity & Geant4.10.1

- Previously, the only 'background' in WCSim was PMT dark noise
- Added ability to simulate radioactive decays uniformly across PMT glass & in the water
  - Can study direct noise & pile-up on physics events
  - Important for low-energy triggering
- Studies in this talk use:
  - 208TI (emits 2.6 MeV γ and e^-'s with 1.5 MeV endpoint)
  - 214Bi (predominantly emits e^-'s with 3.3 MeV endpoint)
  - 40K (emits e^- with 1.3 MeV endpoint or 1.5 MeV γ)
- Upgraded to Geant4.10.1
  - Better neutron capture model
  - Fixes gamma cascade bug

Outline

Data rates in HK 40%

Data source	Event rate	Hits/event	Raw data rate
Dark noise	10 kHz	1 (per tube)	5 GB/s
Low energy backgrounds	10 kHz	25	3 MB/s
Cosmic muons	100 Hz	40,000	50 MB/s
Beam	1 Hz	0	0 MB/s
Calibration	2 Hz	40,000	2 MB/s
Pedestal	1 Hz	40,000	2 MB/s

- Dark noise dominates the raw data
  - Want to reduce this as much as possible, without sacrificing physics
  - Leads to cheaper DAQ system
    - Less hardware: easier to scale
    - Less storage: 5 GB/s = 18 TB/hour = 13 PB/month
    - Less CPU time to reconstruct events / analyse the dataset

How SK triggers: NHITS

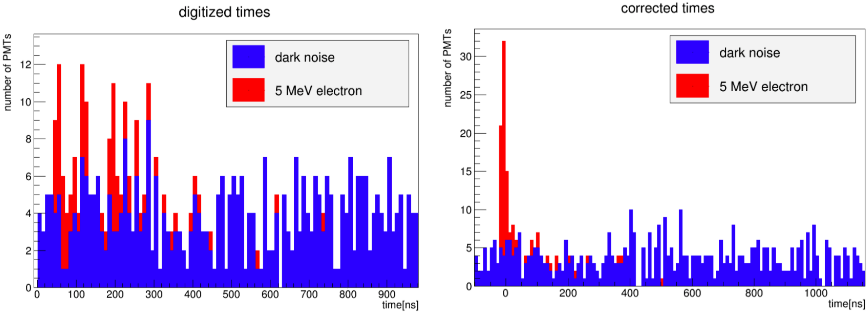
1. Count number of hits in a sliding time window
   - Window size $\approx$ max light travel time across detector
2. If NHITS $>$ threshold, issue trigger
3. If NHITS $>$ a lower threshold, perform full reconstruction to decide to trigger

	SK	HK 14%	HK 40%
Max light travel time (ns)	200	400	400
NPMTs	11146	14728	44028
PMT dark rate (kHz)	4.2	8.4	8.4
Noise hits in trigger decision window	$\sim$9	$\sim$49	$\sim$148

- There are so many background hits in HK 40%!
- Are there clever ways to trigger without performing full reconstruction?

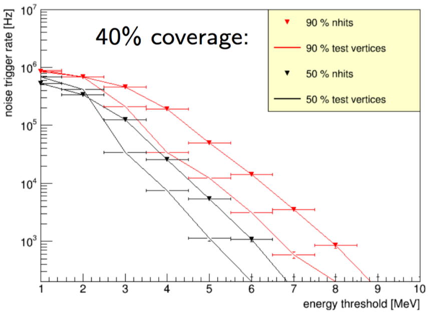
Test-vertices trigger

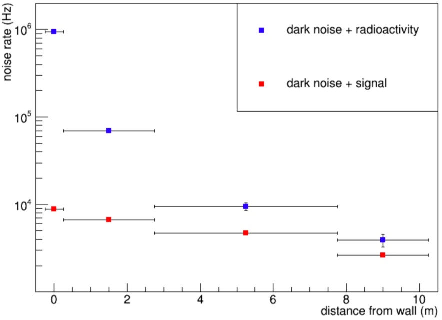
- Populate detector with cylindrical array of test-vertices ($\Delta L = 5$ m)
- For each vertex, apply photon time-of-flight correction, then proceed with NHITS-like trigger
  - Reduces trigger time window: 400 ns $\rightarrow$ 20 ns
  - $\sim$vertex reconstruction to kill dark noise
    - ★ 5 MeV e^- vertex resolution: position 2.1 m; time 13 ns



Test-vertices trigger performance

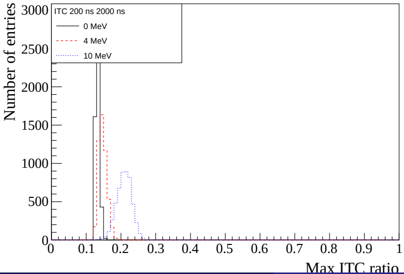
- Process in real-time on $\sim$100 GPUs
  - Currently <\$400,000 (should become cheaper)
- For a given noise trigger rate, the test-vertices algorithm lowers the trigger threshold by $\sim$1 MeV
- Can cut PMT radioactivity by rejecting events with reconstructed vertices at detector edges
  - Suppress 87% PMT radioactivity with 30% total volume loss

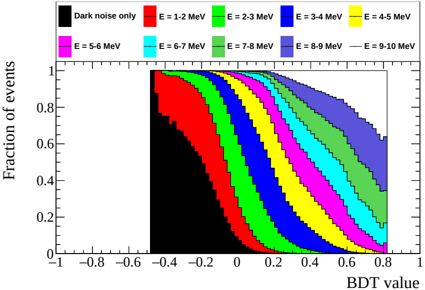




Other trigger ideas

- In time channel ratio (ITC)
  - Cut on ratio of hits in two 'small' and 'large' time windows
  - May be useful for SK, but not for 40% HK
- Multivariate trigger (TMVA)
  - Use lots of variables
  - Promising with MC
    - ⋆ 90% dark noise rejection @ 92% 3–4 MeV efficiency
  - But…trigger systematics may be horrendous
    - ⋆ Use as a testing ground for new variable ideas





Outline

DAQ design

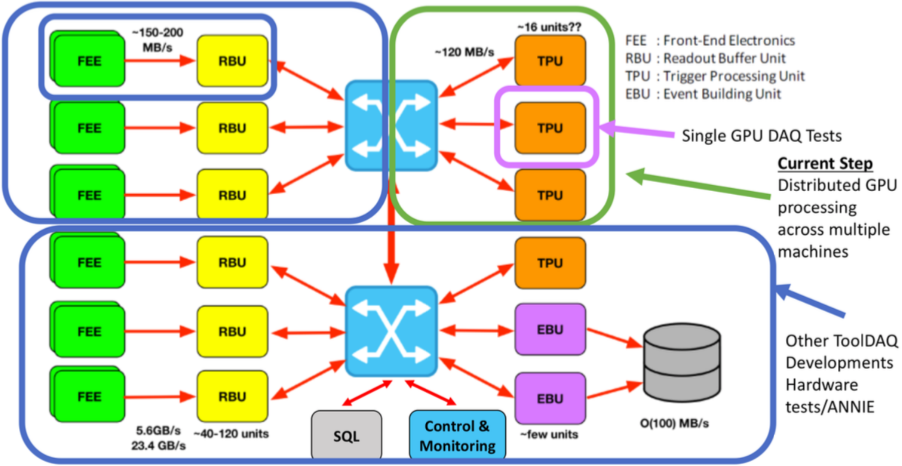
Use physics studies & prototype measurements to design the DAQ

1. Event rates and triggering
2. Detector readout requirements
3. Data storage
4. Functionality
5. Detector monitoring

Key aspects

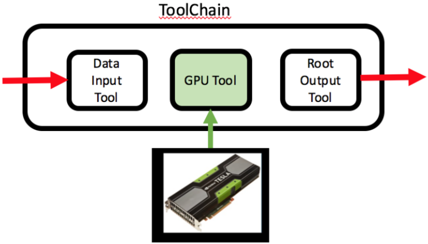
1. Raw data rate
   - In particular raw data rate in the event of a local supernova
2. Triggered event data rate
   - This depends on where the triggers are implemented
     - Firmware of the electronics and/or in the DAQ computer
3. Triggered architecture
   - What firmware etc will we use.

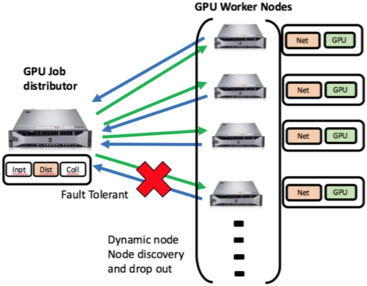
DAQ reference design



DAQ framework

- Many options for a DAQ framework
  - `artdaq`, `MIDAS`, written ourselves, ...
- Currently doing tests using `ToolDAQ`
  - Developed in UK for HK as a fault-tolerant, lightweight, DAQ framework
  - Currently being used by the ANNIE experiment
  - Designing HK & intermediate detector layout





Summary

- Improved `WCSim`
- Studying some new trigger algorithms for HK 40%
  - Test vertices lowers energy threshold by ∼1 MeV
  - ITC ratio doesn't help in high-photocoverage tank with high-noise PMTs
  - Using TMVA for new ideas
- TITUS *should* be easier
  - Fewer lower-noise (smaller) PMTs, but more cosmics
  - Will perform detailed studies when a combined near detector design has been chosen
- Have a baseline DAQ hardware design
- Weighing up pros & cons of different DAQ frameworks
  - Including our bespoke code (`ToolDAQ`)

Backups

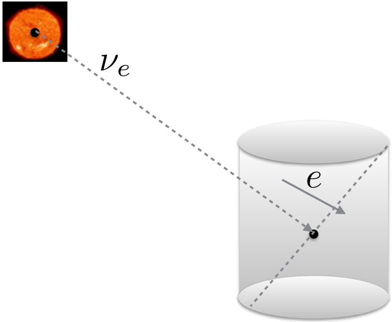
TMVA trigger training variables

- For each event
  - Take 1000 ns from the first physics hit
    - Noise-only: use a small offset
  - Calculate each of the following 26 variables:
- NHITS
- β_{14} (see slide 20)
- Solar anisotropy ratio (see slide 21)
- RMS of hit times
- Mean & RMS of:
  - Charge
  - Hit PMT position (θ, r, z)
  - Angle between each pair of hits ((0,0,0) is the third position)
    - θ, $\cos(\theta)$, $P_2(\theta)$, $P_3(\theta)$, $P_4(\theta)$, $P_5(\theta)$ (see slide 20)
  - Solar anisotropy distance (see slide 21)

SNO β variables

- Take cosine of angle between each pair of hits
  - Use detector centre as third point
- Use Legendre polynomials: $\beta_k = \langle P_k(\cos\theta_{ij}) \rangle \,; i \neq j$
  - $P_0(x) = 1$
  - $P_1(x) = x$
  - $P_2(x) = \frac{1}{2}\left(3x^2 - 1\right)$
  - $P_3(x) = \frac{1}{2}\left(5x^3 - 3x\right)$
  - $P_4(x) = \frac{1}{8}\left(35x^4 - 30x^2 + 3\right)$
  - $P_5(x) = \frac{1}{8}\left(63x^5 - 70x^3 + 15x\right)$
- $\beta_{14} = \beta_1 + 4\beta_4$ used for selecting signal @ SNO
  - Good separability
  - Ease of parameterisation of the Gaussian-like distribution
- May need to account for the cylinderical geometry
  - e.g. separate out the endcaps from the sides

Solar anisotropy



- Split the detector in two equal halves
  - Use known direction to Sun & detector centre to define plane
- *e* direction correlated with ν_e direction
  - Expect more hits on PMTs opposite the Sun

- *Solar anisotropy ratio*
  - Ratio of NHITS in forward/background halves
- *Solar anisotropy distance distribution*
  - Signed perpendicular distance of each PMT to the plane
- Won't work for other low energy events, but...
  - Supernovae: dedicated trigger
  - Neutrons: correlated in time/space with other events

Backups

5 TMVA trigger

6 DAQ design

DAQ design

1. Event types and triggering
   1. Successfully access the majority of physics of interest.
   2. Have the ability to handle event rates.
   3. Discard non-physics events using a trigger.
   4. Sufficient local storage/processing to deal with events from a local supernova.

DAQ design

2. Detector readout requirements
   1. Handle incoming data from multiple compartments.
   2. Deal with cross-compartment triggers.
   3. Readout rate will depend on where the triggers are implemented i.e. in electronics firmware or on a backend system.
   4. Design includes a setup such that if one node fails it will automatically run on another node. Investigate cloud like setup?

DAQ design

3. Data storage
   1. Transfer of data from the DAQ machines to disk.
   2. Transfer of data offsite.
   3. Run numbering scheme.

DAQ design

4. Functionality
   1. Should be easy to use for non-experts.
   2. Have the ability to run compartments independently (e.g. for calibration).
   3. Read out of additional calibration information.

DAQ design

5. Detector monitoring

1. Successfully access the majority of physics of interest.
2. Have the ability to handle event rates.
3. Discard non-physics events using a trigger.
4. Sufficient local storage/processing to deal with events from a local supernova.
5. Near time checks will have to be made on the incoming data to ensure that the detector is performing satisfactorily.
6. Monitoring of electronics/PMTs e.g. temperature, voltage etc. This should use a separate readout stream to the data.