“Non-Beam” Triggering at DUNE

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Penn
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DUNE

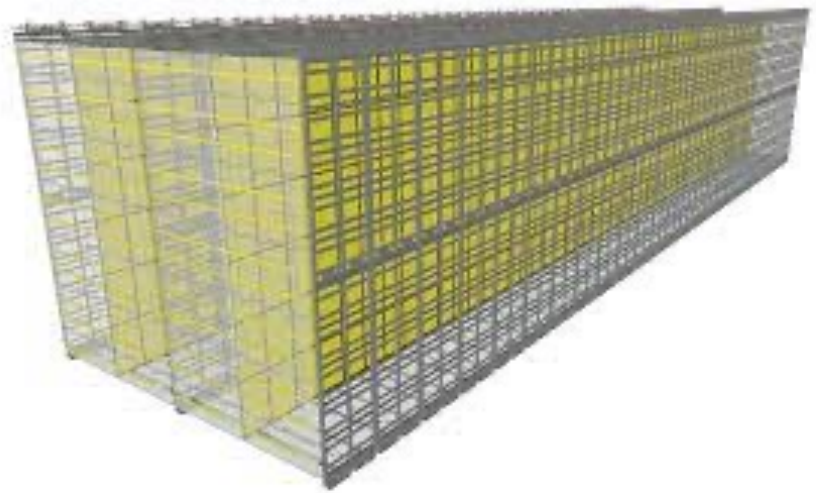
Outline

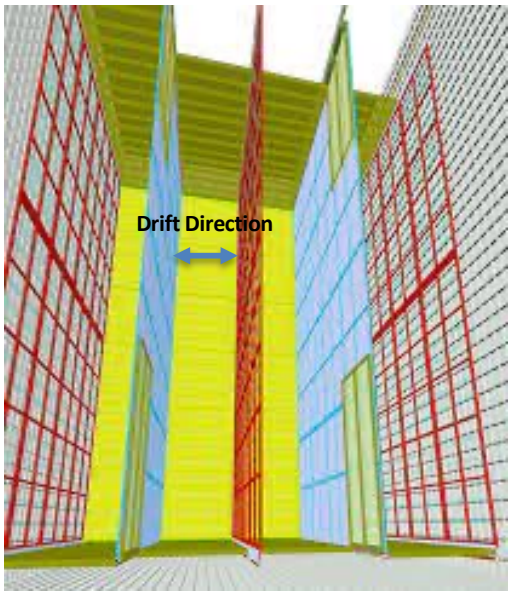
- DUNE Phase I
- Triggering Constraints and Design Considerations
- Performance and Future

DUNE Phase I Far Detector Modules

FD1: “Horizontal Drift”

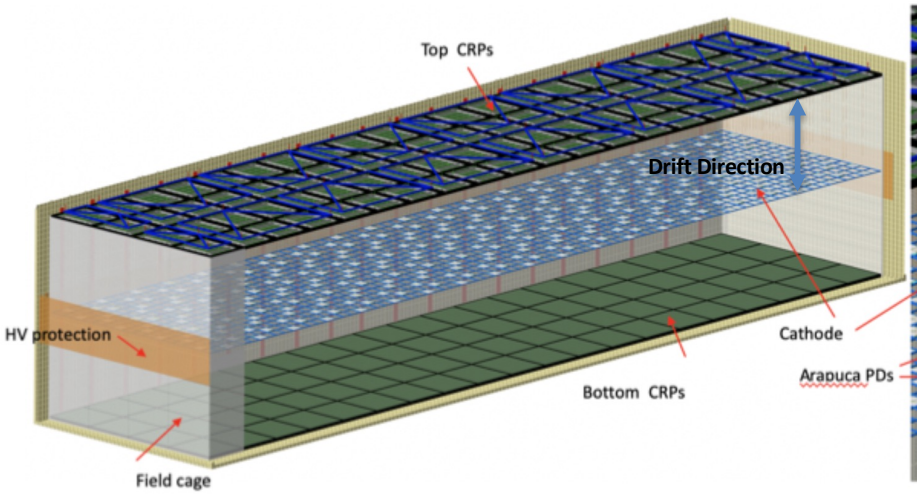
- 4 drift volumes
- 1 collection+2 induction wire planes on each anode (x/u/v) plane=“APAs”
- Photon Detection System (PDS) only on anodes

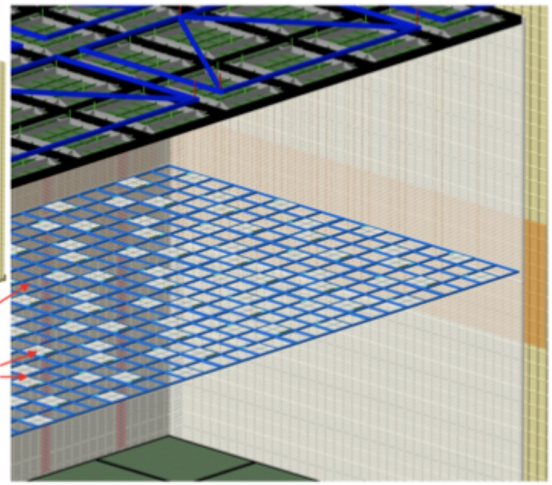




FD2: “Vertical Drift”

- 2 drift volumes
- 1 collection+2 induction “strip” planes on each anode plane=“CRPs” (y/u/v)
- “4π” Photon Detection System (PDS)





"Non-Beam" Triggering

- DUNE Far Detectors (FDs) do not have a "beam" trigger
- Trigger is intended to be as inclusive as possible
  - We expect ~100% efficiency above about 100 MeV
  - Do not use beam information in trigger criteria for these energies
  - (We could if it was useful for some physics topics)
  - Beam and atmospheric ν interactions are each ~1000/10 kt/year
- For low energies (< 20 MeV) criteria become more complex
- Supernova burst triggers are handled very differently
- Near detectors will have a beam-related trigger
- (As do the ProtoDUNEs at CERN)

"Non-Beam" Triggering

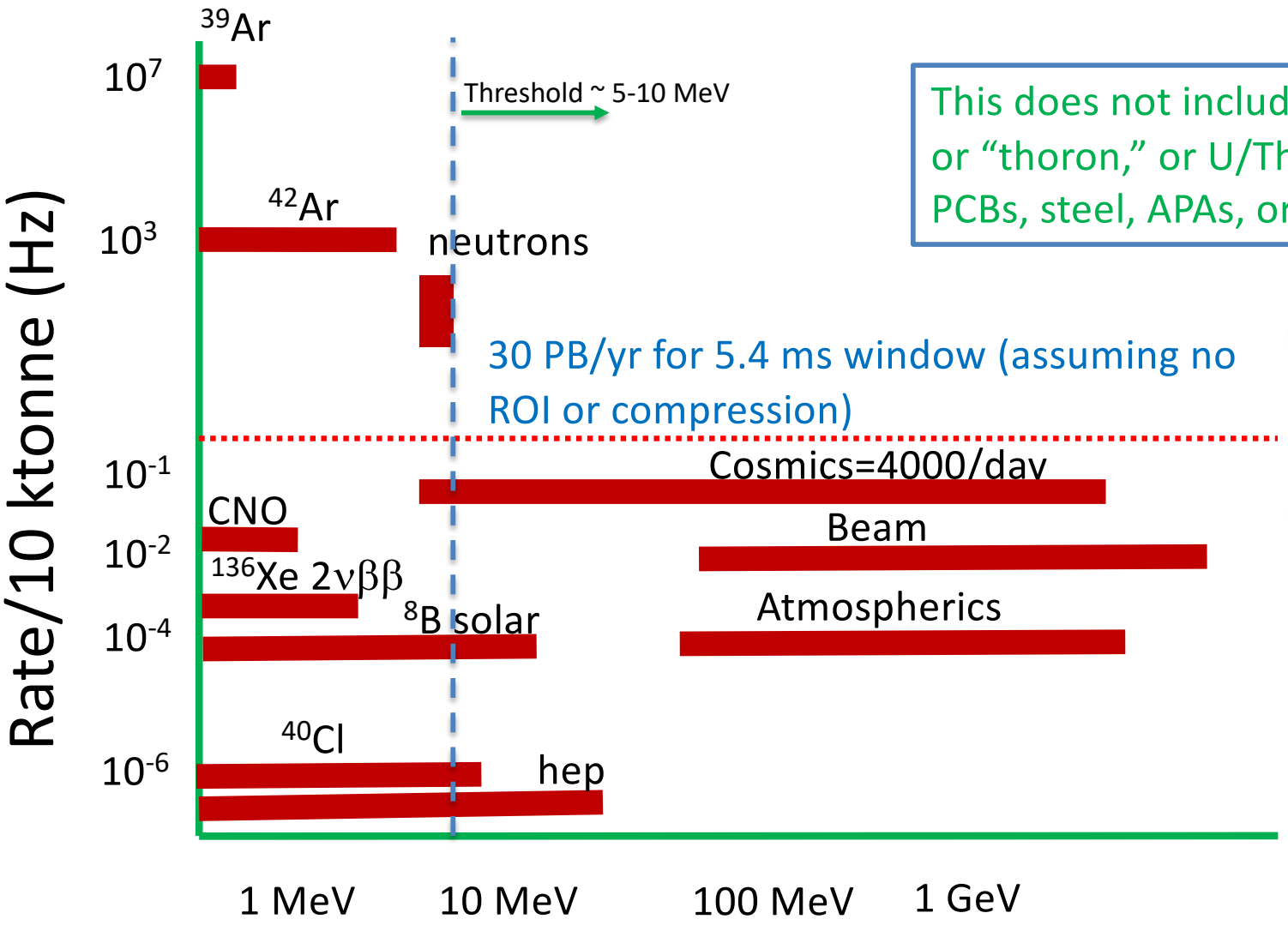
Additional notes:

- LArTPCs are slow enough that trigger is entirely in software
- Front-end buffering can hold up to 10 seconds of *everything*
  - Every ADC sample of every waveform from every TPC channel
- Photon Detection System (PDS) records waveform snapshots
  - Much lower data rate even though system is much faster than TPC

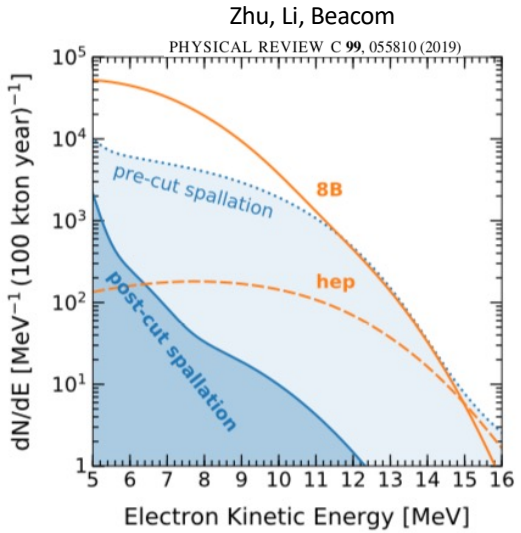
The bottom line:

- Inclusive ~100% eff. high-energy triggers above 100 MeV
- Some exclusivity below 20 MeV is possible if valuable

Background and Storage Limits for Triggering



This does not include unsupported radon or "thoron," or U/Th gammas from cavity, PCBs, steel, APAs, or ^{40}Ar(α,γ)



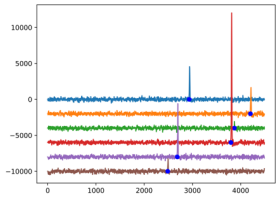
Or spallation

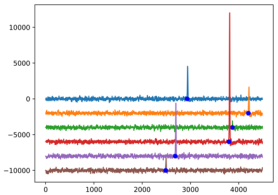
FD Trigger Design Considerations

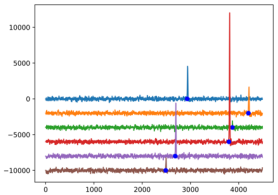
1. *Inclusive*
   - Above 20 MeV we aim to trigger on everything with close to 100% efficiency (there is no “cosmic-ray trigger”)
   - Possible that SOME exclusivity can help with radiologicals
   - A trigger is not an analysis!--We don’t want different algorithms for e.g., CC/NC
2. *Simple*
   - Measuring efficiencies and their uncertainties is complicated
   - Need a reasonable latency so that we don’t run off front-end buffers
   - We never ever want code to ever hang (fewest possible dependencies!)
3. *Hierarchical*
   - Trigger is hierarchical: highest level sees most information
   - This applies to space/time/systems/views/external input
   - Allows for more sophistication downstream where rate is lower
4. *Physics*
   - A trigger that rejects ^{39}Ar by only 1000 doesn’t add any physics

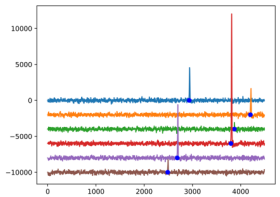
Hierarchical Trigger

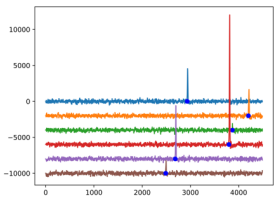
Channel Hit-finding: Trigger Primitives (TPs)

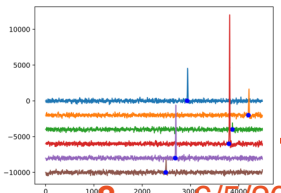




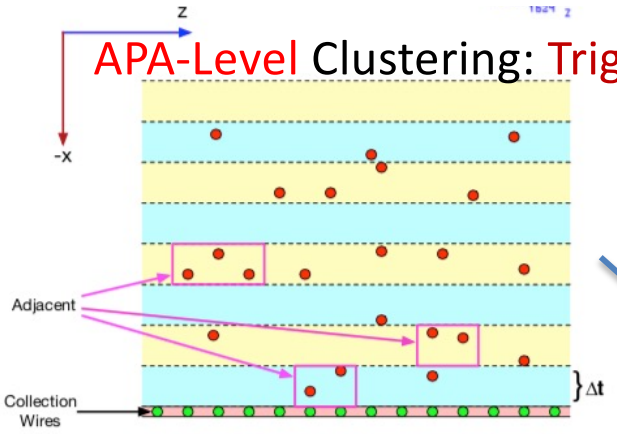


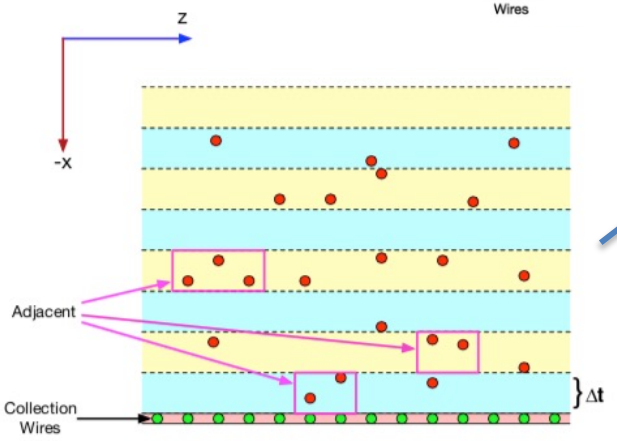




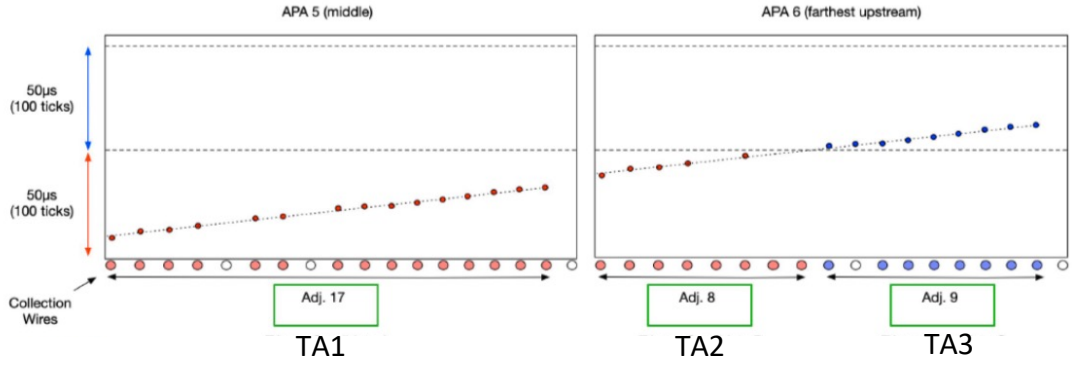


APA-Level Clustering: Trigger Activity (TA)



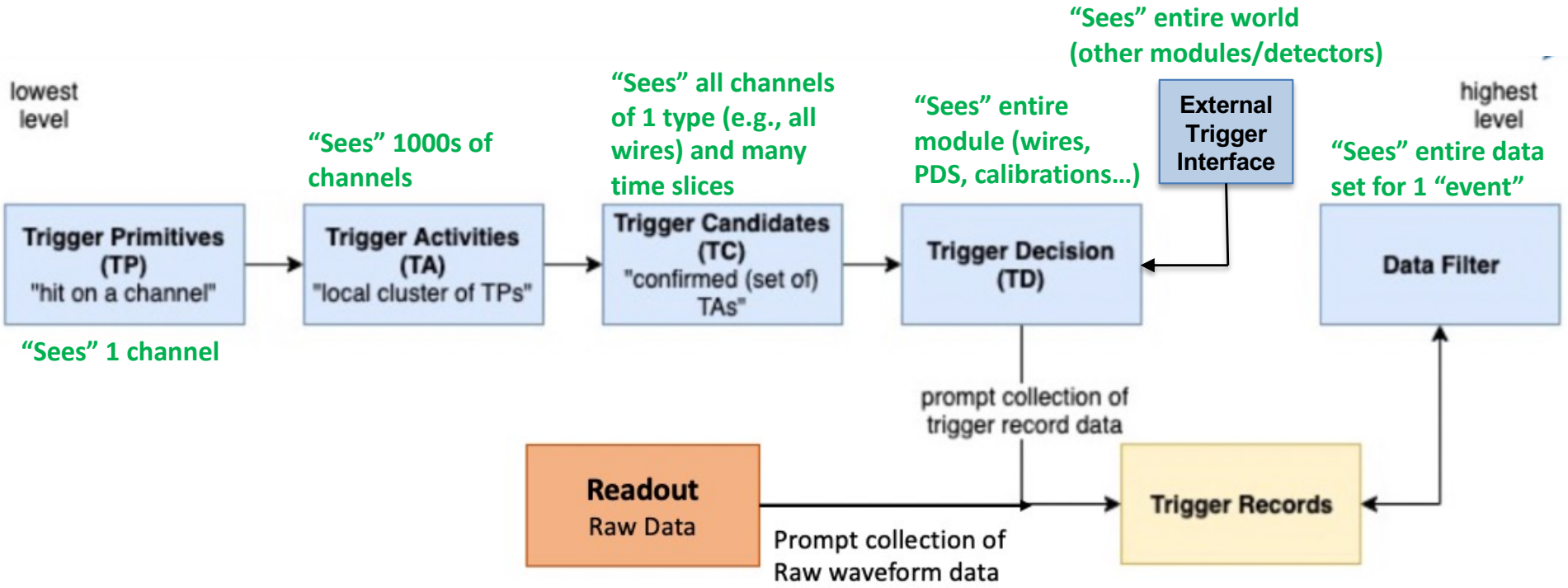


Module-Level Algorithms:
Trigger Candidates (TCs)



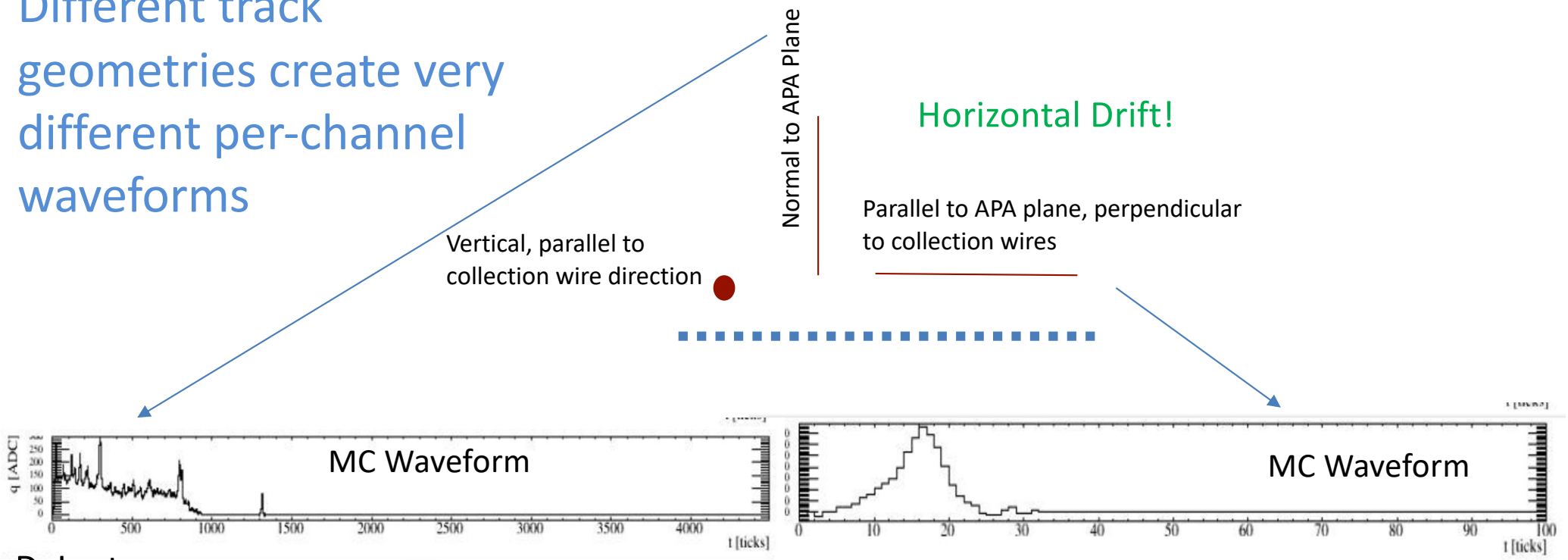
- Threshold for TPs ~ ¼ MIP~250 keV/chan
- Rate is 50-100 Hz per channel
- TA finders view ~2500 channels
- PDS trigger will be very similar

Simplified View

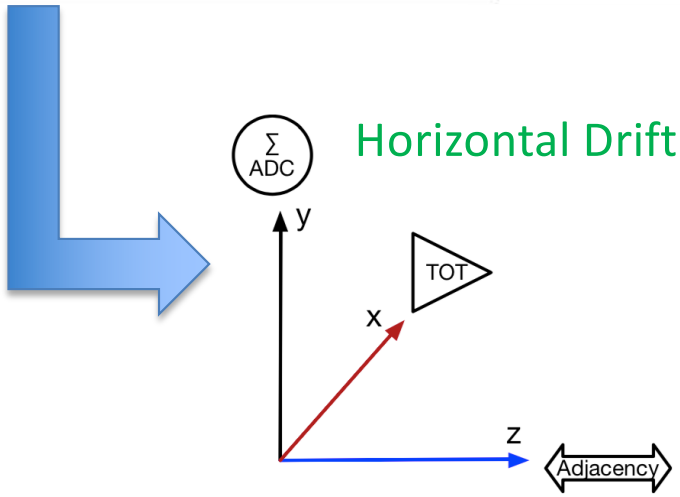


TPC Trigger Primitives (TPs)

Different track geometries create very different per-channel waveforms



D. Last



TPs include "orthogonal" basis of information: integral charge, hit channel time, waveform time-over-threshold

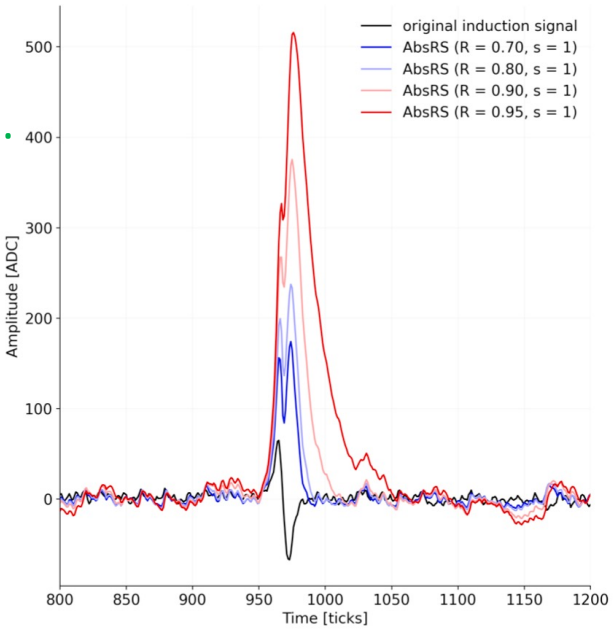
D. Rivera

Induction Channel Trigger Primitives

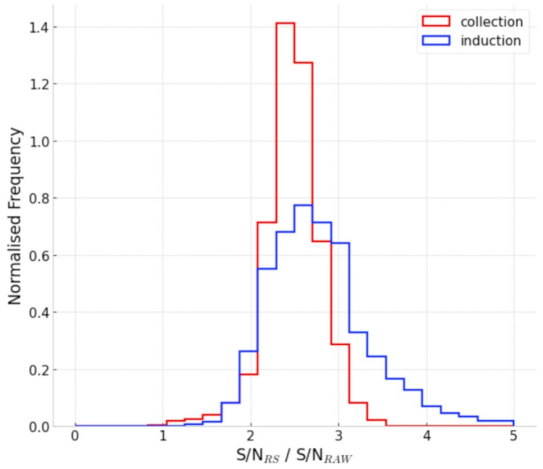
Induction waveforms are bipolar…

$$y_n = R \cdot y_{n-1} + \frac{|x_n|}{s}$$

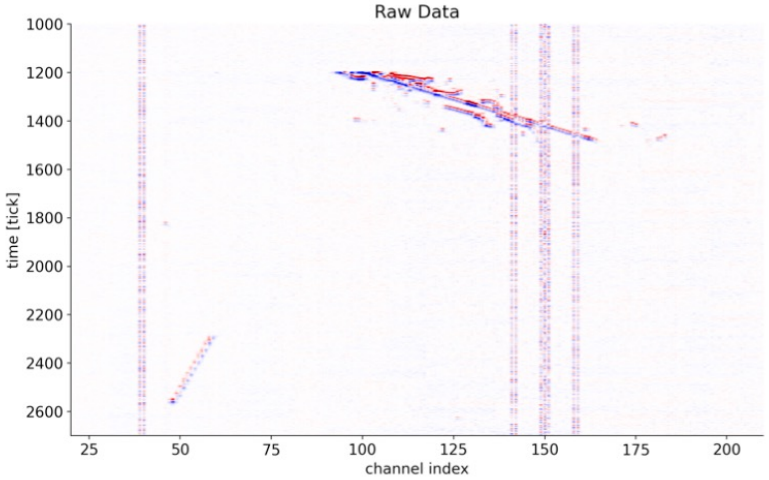
"Absolute value running sum" (like "square-law detection" of RF signals)



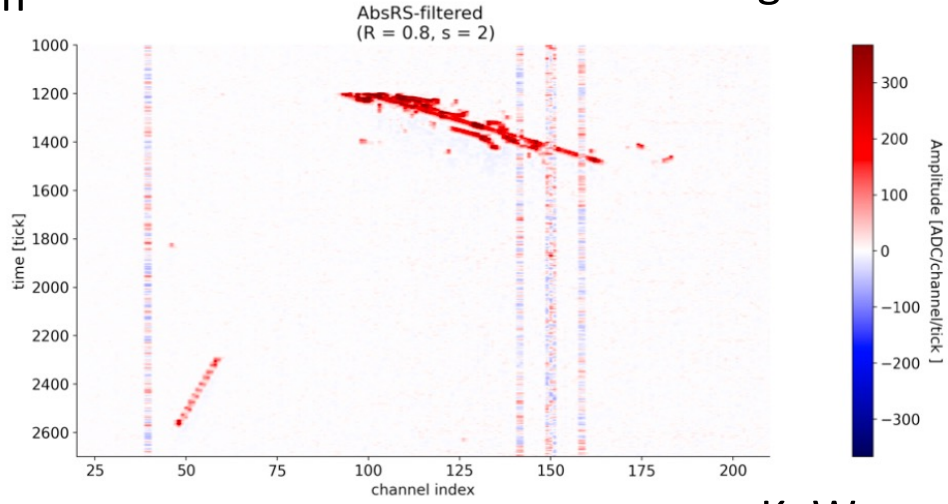
Improved Signal/Noise



Before Absolute Value Running Sum



After Absolute Value Running Sum



K. Wawrowska

Trigger Activities (TAs)

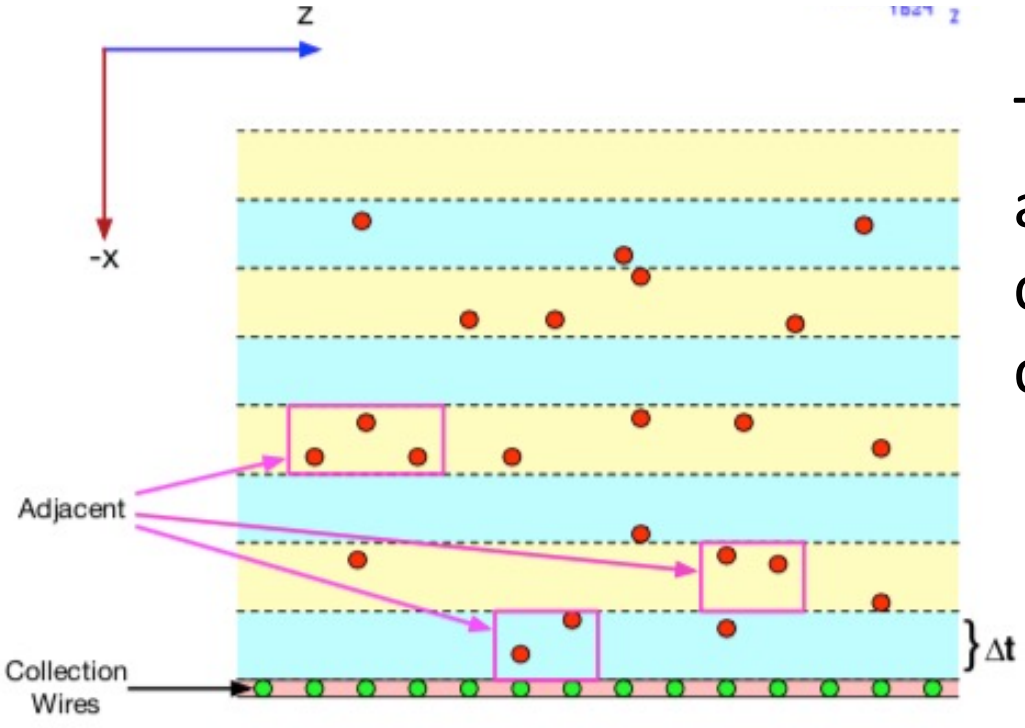
- Goal is to find *local* (in channel/detector space) activity
  - E.g., a single APA or CRP, or set of X-ARAPUCAs
- Multiple concurrent algorithms possible
  - Low-energy TPC (e.g., SN neutrino interactions)
  - High-energy TPC (atmospheric neutrino, proton decay…)
  - Low-energy PDS
  - High-energy PDS
  - (etc.)
- Algorithms need to be able to handle ~250 kHz of TP inputs
- Needs to be robust against noisy, dead, or missing channels

High Energy Trigger Activity

Example: Clustering and Cutting

Cannot simply sum up all charge---in 10 ktonnes and a full drift, this is about a GeV of charge.

Clustering then cut on number of adjacent channels, total charge, max charge, max time-over-threshold, etc.



D. Rivera

Thresholds is set conservatively assuming 5.4 ms readout of *all* channels had data rate < 25% of cosmic data rate (High-E events only)

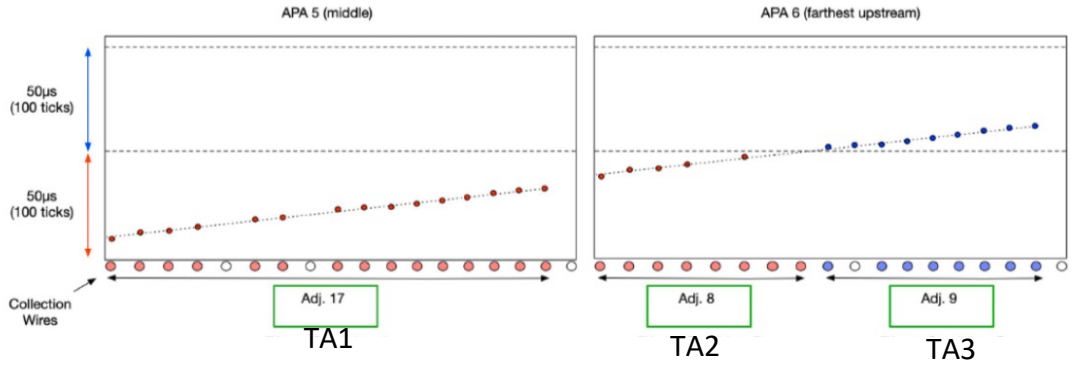
Radiological rate acceptable with:

- N_{adj} >= 8 wires
- Cluster charge sum > 7000 ADC counts
- Max integrated wire charge > 6500 counts
- Max time-over-threshold >= 45 ticks

For high-rate Low E events, we would not save all channels—lower threshold possible

Trigger Candidates (TCs)
Larger Scope

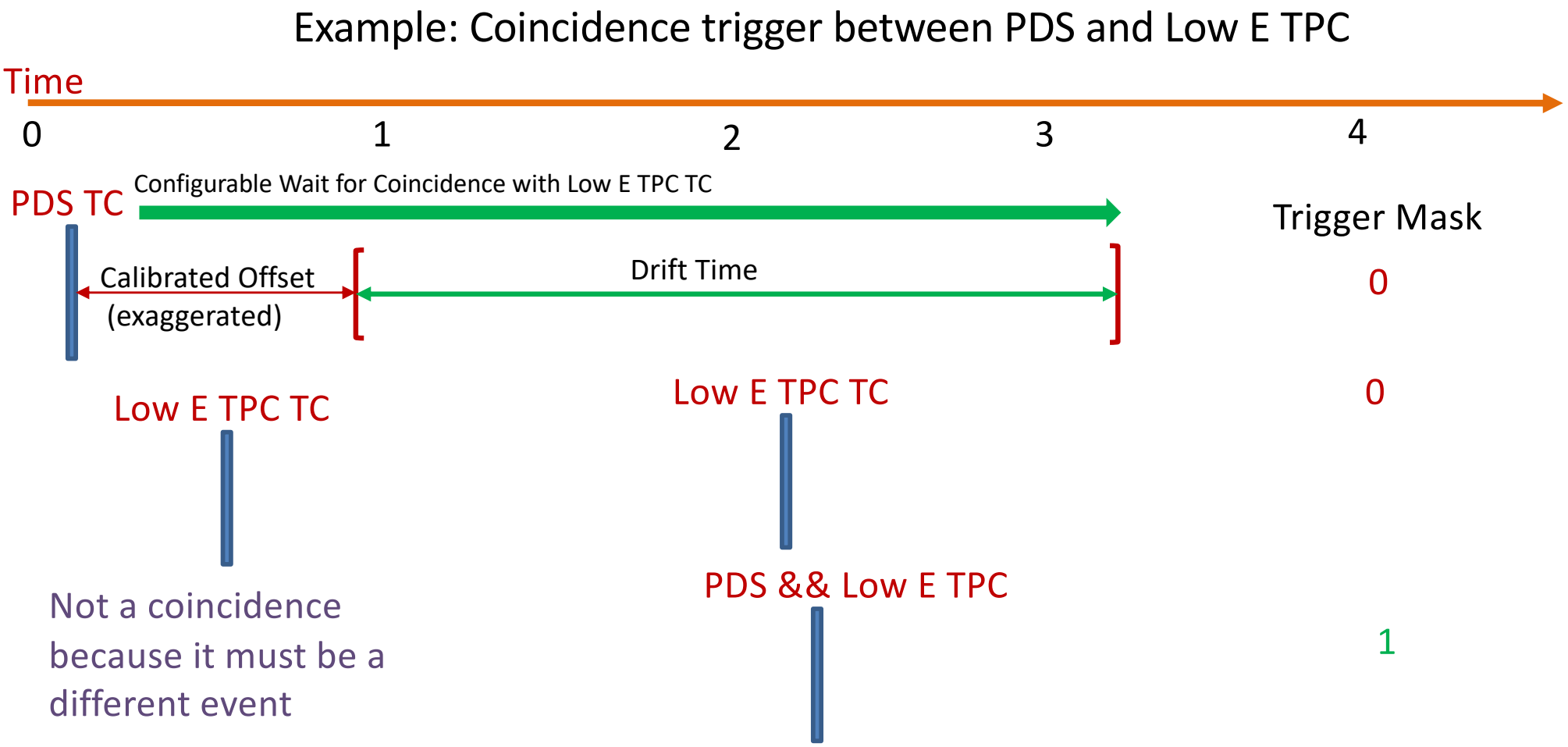
- Entire module of single system (e.g., all wires)
- Can look for spatial correlations between TAs
  - Horizontal muons crossing multiple APAs (ProtoDUNE)



- Can look for time correlations between TAs
  - Supernova bursts
  - Spallation neutrons from cosmic-ray that misses active volume
  - Low energy NC interactions that lead to gammas+neutrons
- High-energy TAs are simply “promoted” to TCs

DUNE FD Module Level Trigger Logic

- MLT "sees" all systems, channels, and large blocks of time
- Makes Trigger Decisions based on Trigger Candidates→ Leads to a Trigger Record to disk
- TCs from different systems come at different times;
  we merge them if readout windows overlap



Data Filter

Data Filter:

- Operates on full triggered data:
  - All TPC+PDS information in a particular time window
- Can remove entire events
- Can remove parts of an event (e.g., ROI selection of ”hit” channels)
- Can tag event classes for online or nearline analysis pipelines
- Data Filter has ~1 minute to process an event
  - Potential for aggressive fiducialization, flash-matching, energy estimation…
- Can handle different triggered event classes differently

External Trigger Interface

- Allows inter-module triggering
  - SN burst trigger in one module will trigger another
  - Can require coincidences between modules
  - Can add event criteria (e.g., $N_{FD1}+N_{FD2}>N_{thresh}$)
- Can take input from other local detectors
  - LZ? Theia? nEXO?
- Can take input from non-local detectors
  - Delay must be << 10 seconds

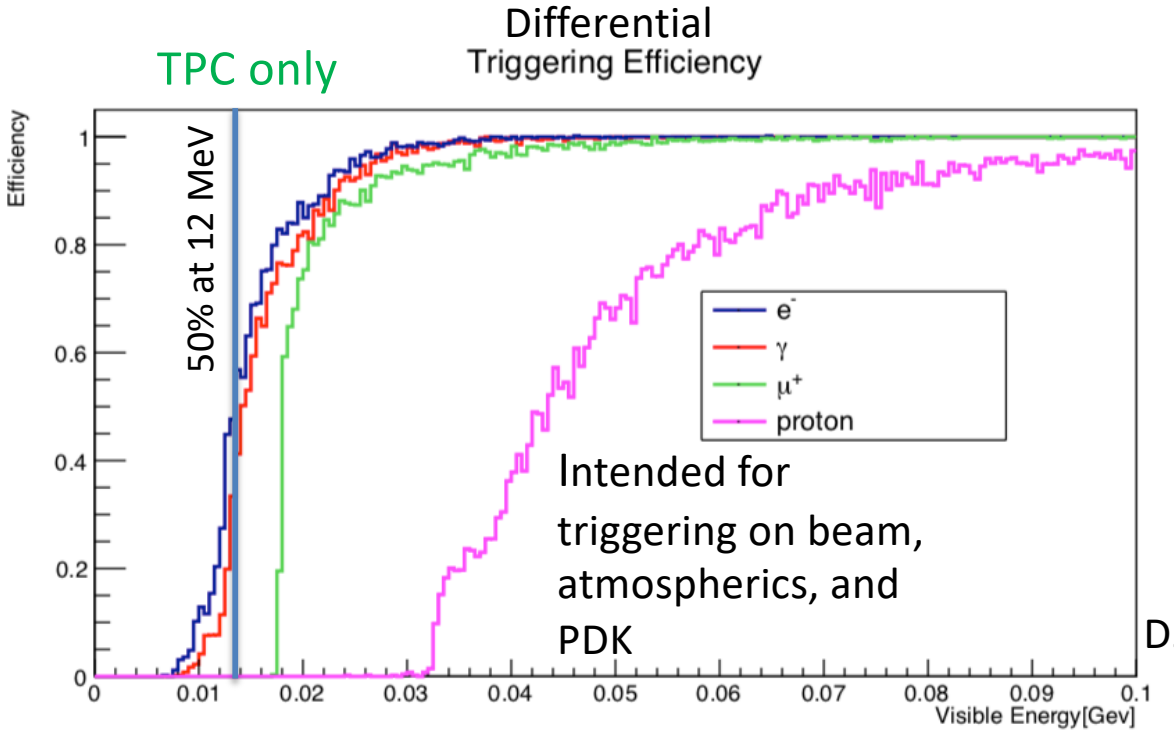
Data Selection Output

- Stream of trigger primitives (x/u/v and PDS)
  - TPC threshold ~250 keV
  - PDS thresholds 1-2 pe
  - Record time, charge integral, peak, time-over-threshold
  - **Triggerless** (other than channel thresholds)
- SN Burst data: 100 seconds of *everything*
  - Target fake rate of 1/month
- Nominal "Trigger Records"---typically single interactions/decays
  - Limited by total storage requirements
  - Size of each Trigger Record depends on ROI selection (if any)
  - Strictest ROI likely on lowest energy data

Note: Supernova Burst Neutrinos are collected by all 3 paths; second path collects *everything* but time to analysis is longer than others.

High-Energy Trigger Efficiency

TPC only

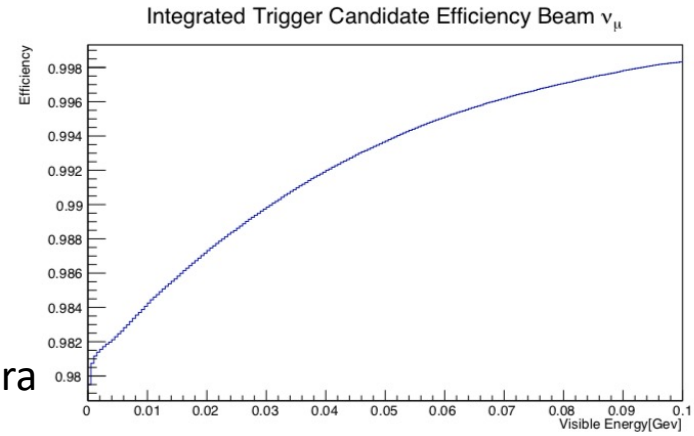


Intended for triggering on beam, atmospherics, and PDK

D. Rivera

- Integrated efficiency ϵ_I is given by :

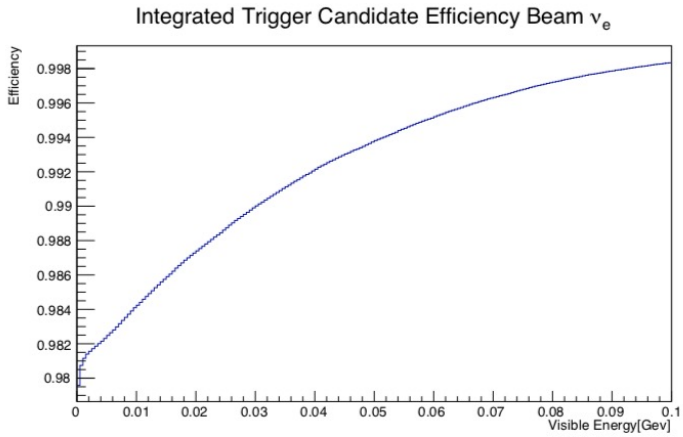
$$\epsilon_I(E_{vis}) = \frac{\int_{E_{vis}}^{\infty} n_{trig}(E)dE}{\int_{E_{vis}}^{\infty} n_{evt}(E)dE}$$



Threshold is set by background rate!

The trigger is intentionally *inclusive*

but different species have different topologies and thus different efficiencies



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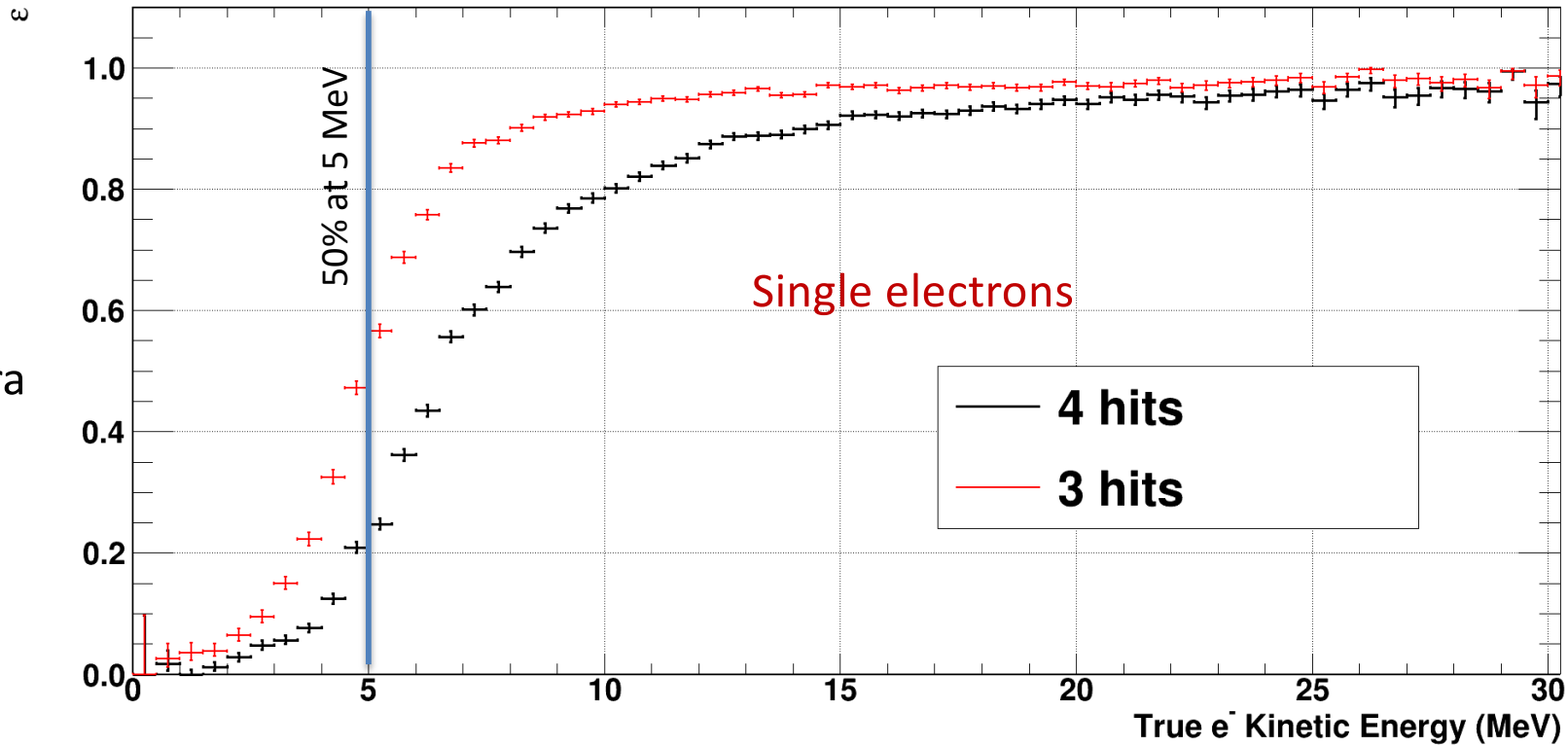
Low Energy Trigger Efficiency

Using just clustering and total charge but no time-over-threshold:

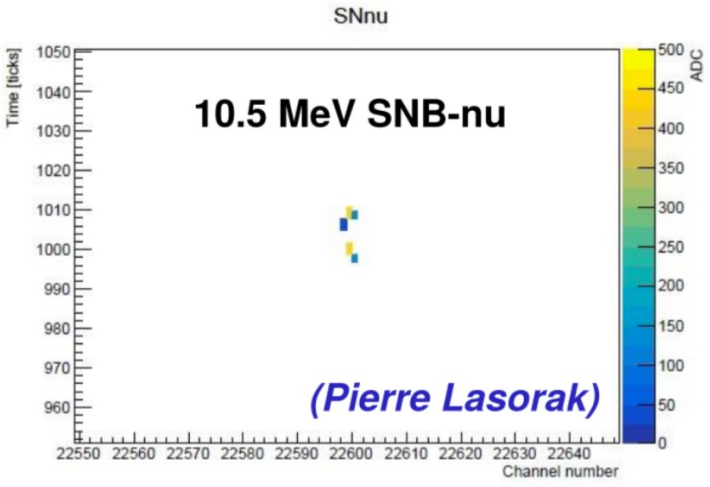
T. Bezerra

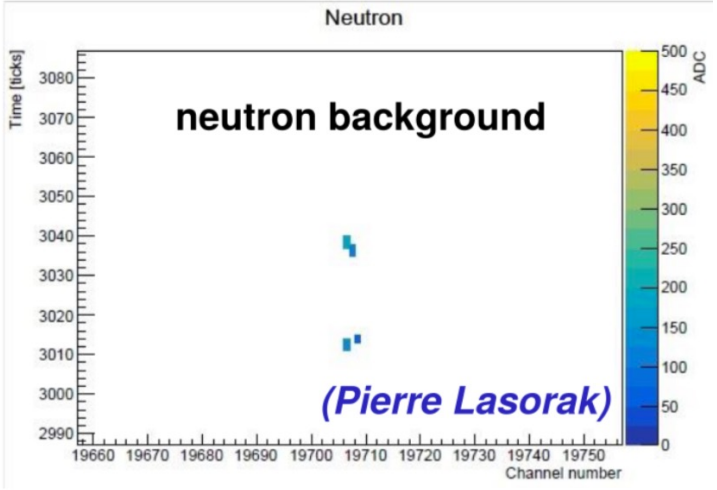


At 3 hits/trigger activity cluster rate from backgrounds ~10 Hz

Low Energy Trigger Efficiency

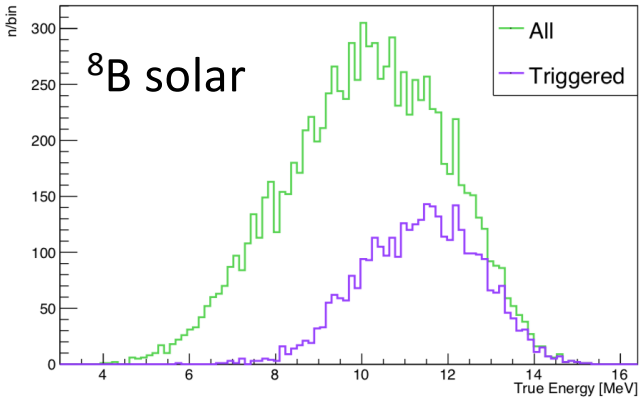
Event topologies can help reject backgrounds at trigger level:



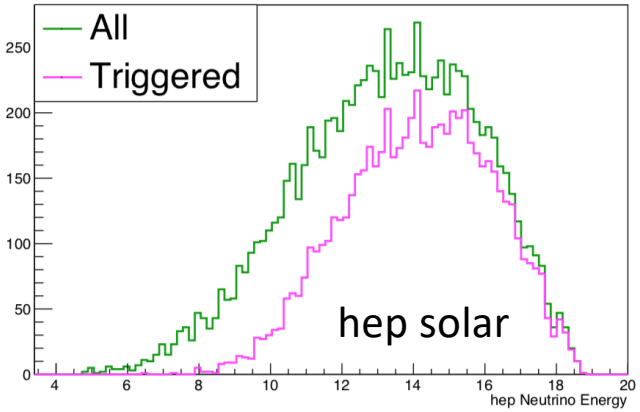


E.g., simple 2D length cut:

$$\mathcal{L} = \sqrt{(adj_{max} * 5mm)^2 + (TOT_{max} \times v_{drift})^2}$$



Total trigger rate ~ 3 Hz



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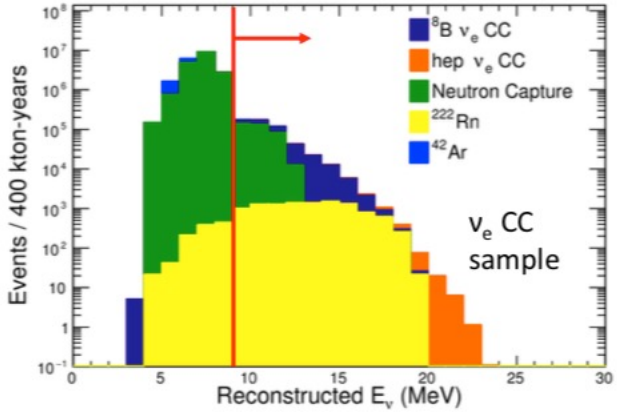
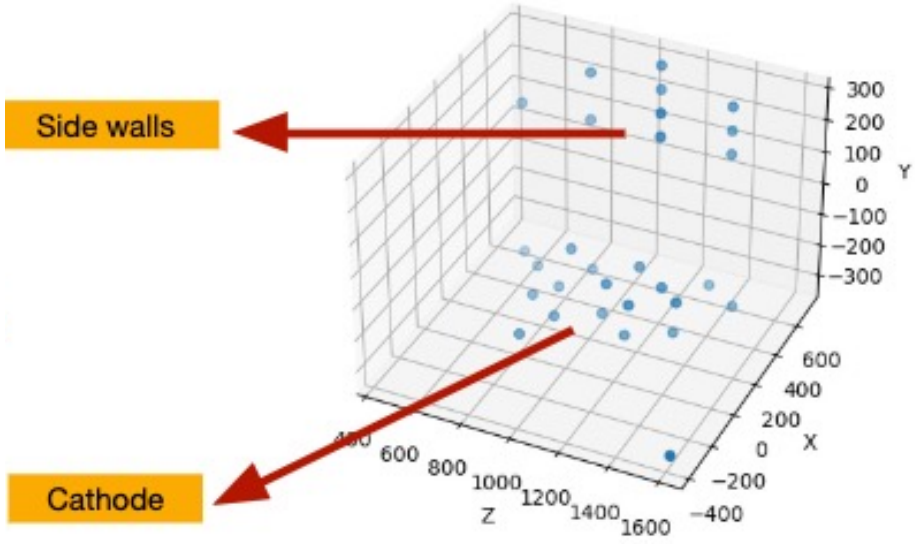


D. Pershey

Low Energy Trigger Efficiency

- Timing and topological information even in photon hits
- Combination of photon triggers with TPC triggers can allow fiducialization to remove neutrons and cavity gamma-rays

Photon hits in Vertical Drift Module



J. Crespo-Anadon, P. Barham

"Natural" place for this is in Module Level Trigger logic and Data Filter

Low Energy Trigger Rates

Region-of-Interest (ROI) Readout

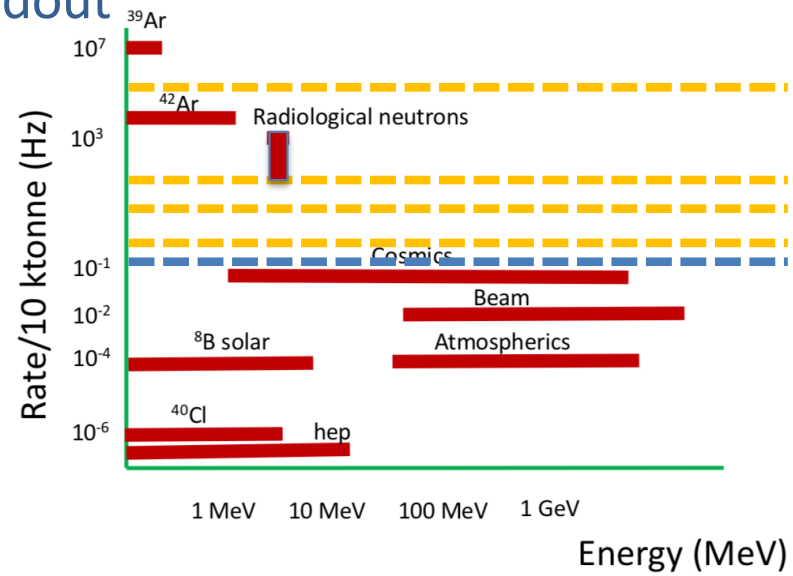
- High-Energy: Record ~5ms of every channel's waveform
- Low-energy would quickly fill up entire disk allocation
- Move to region-of-interest data selection for these events

Can have a higher trigger rate if data/trigger is smaller:

1. Halve readout window
2. Write out only APAs with trigger activity (TA)
3. Use a much narrower readout (100 μs) window around hits ("zero suppression")
4. Fully localize TA and use 100 μs window for readout

Table 2:

Data Reduction Approach	Event Size (Uncompressed)	Max Trigger Rate	Enabled Physics
Nominal	6.075 GB	0.078 Hz	Beam, NDK, Atm.
2.7 ms Readout Snapshot	3.3075 GB	0.156 Hz	Unknown
APA-Localization (Cosmics)	0.243 GB	1.95 Hz	*hep* solar ν
APA-Localization (Low-E)	0.041 GB	11.7 Hz	^{8}B solar ν, neutrons,Rn
Zero Suppression	0.040 GB	12.0 Hz	^{8}B solar ν, neutrons,Rn
TA Localization +Zero Suppression	14.6 kB	32.5 kHz	^{42}Ar, ^{40}Cl, *pep* solar ν?



Of course, ROI can depend on type of Trigger Candidate

Phase II?

FDs not defined yet, but…

- If FD3 and/or FD4 look like FD2, only change is more inter-module triggering
- If FD3 and/or FD4 have higher photo coverage, might allow lower trigger threshold
- If FD3 and/or FD4 are pixelized, might run them triggerless
  - Pixel data is a lot like trigger primitives (not full waveforms)
  - Same is probably true for "ARIADNE" optical readout
  - But would like to do inter-module triggering so still might want a trigger
- If FD3 and/or FD4 is water-based liquid scintillator or similar…
  - Could run triggerless but want to leverage << 1 ns timing to trigger other FDs
  - This trigger might go through "Hardware Signals Interface" (HSI)

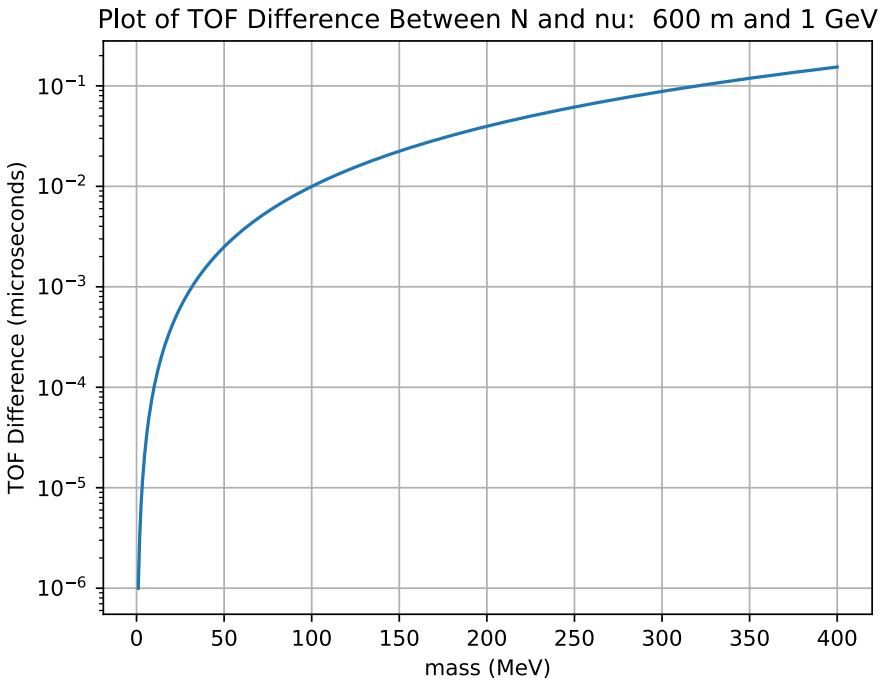
Ultimately, though, likely little change to overall architecture

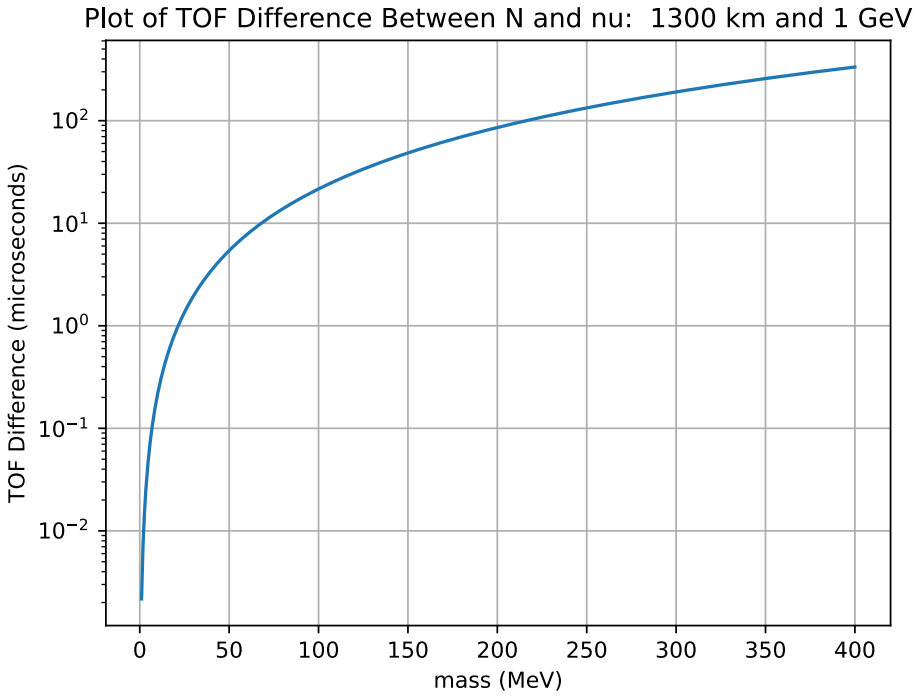
Summary

- DUNE FD trigger is very flexible
- Hierarchical design increases information at each level
- At high-energies, expect near 100% efficiency
- Low-energy triggering constrained by backgrounds
- But many opportunities for pushing lower

Backups

TOF Comparison



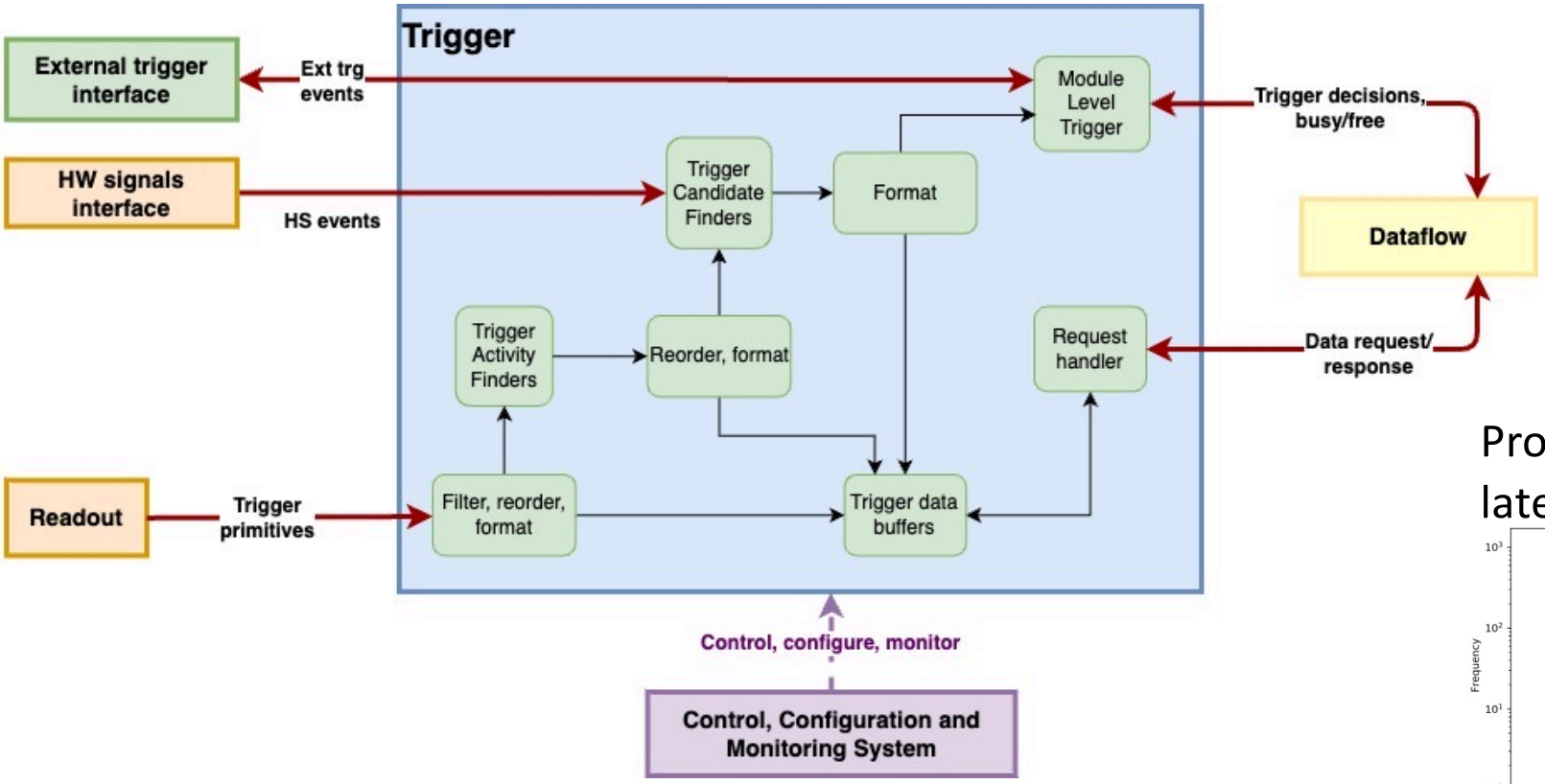


Cosmic pileup in 100 μs window=4×10^{-6}/spill

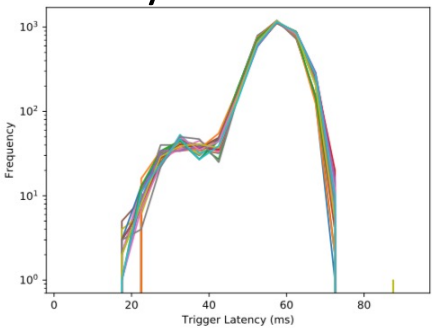
Trigger Flow Diagram

~20 servers/module

(no GPUs or other acceleration)



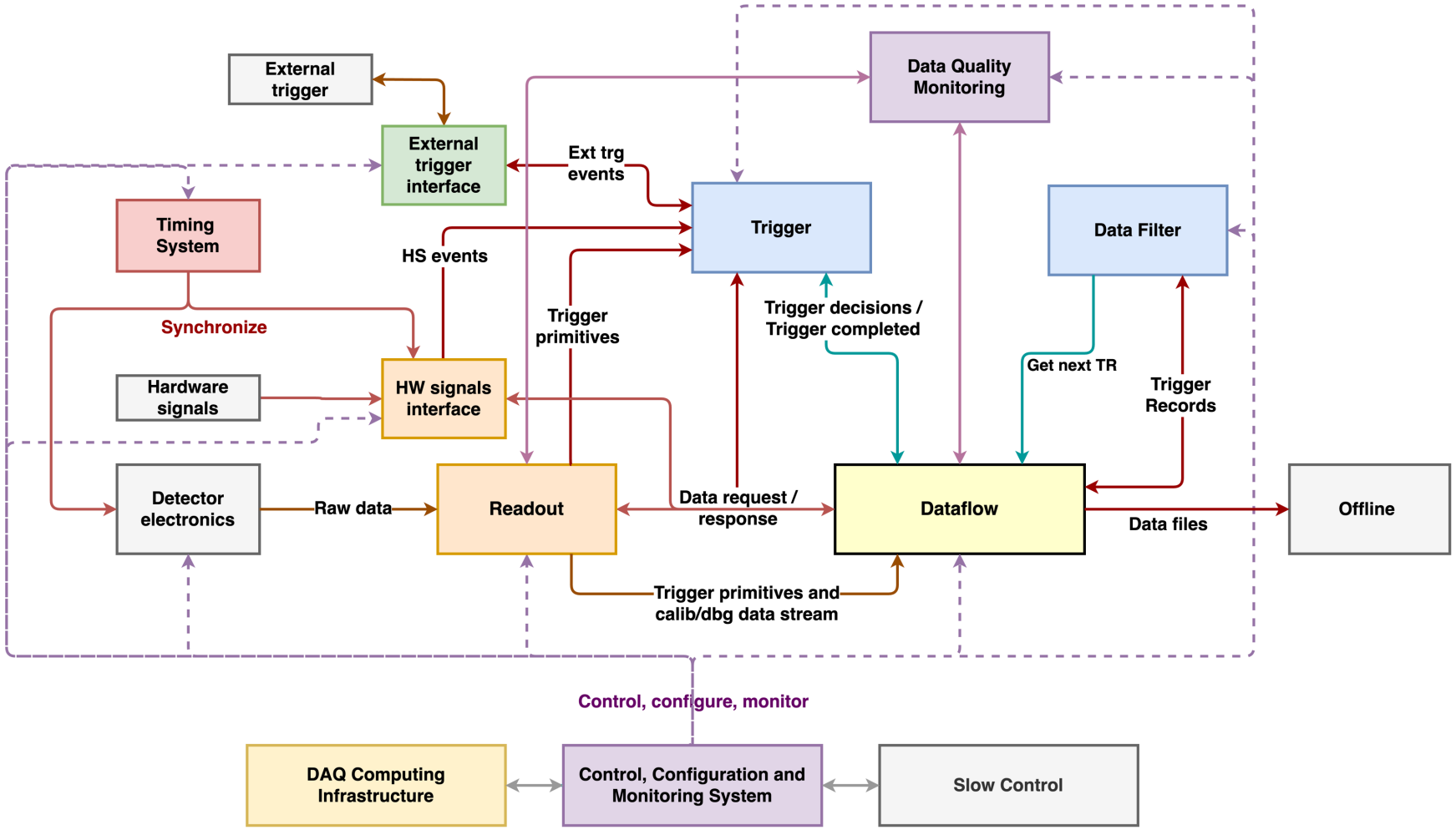
ProtoDUNE I trigger latency



A lot of the complexity is in dealing with a realtime system---
Making sure things are in time order, dealing with problematic channels, etc.
We do not expect algorithms to take much time.

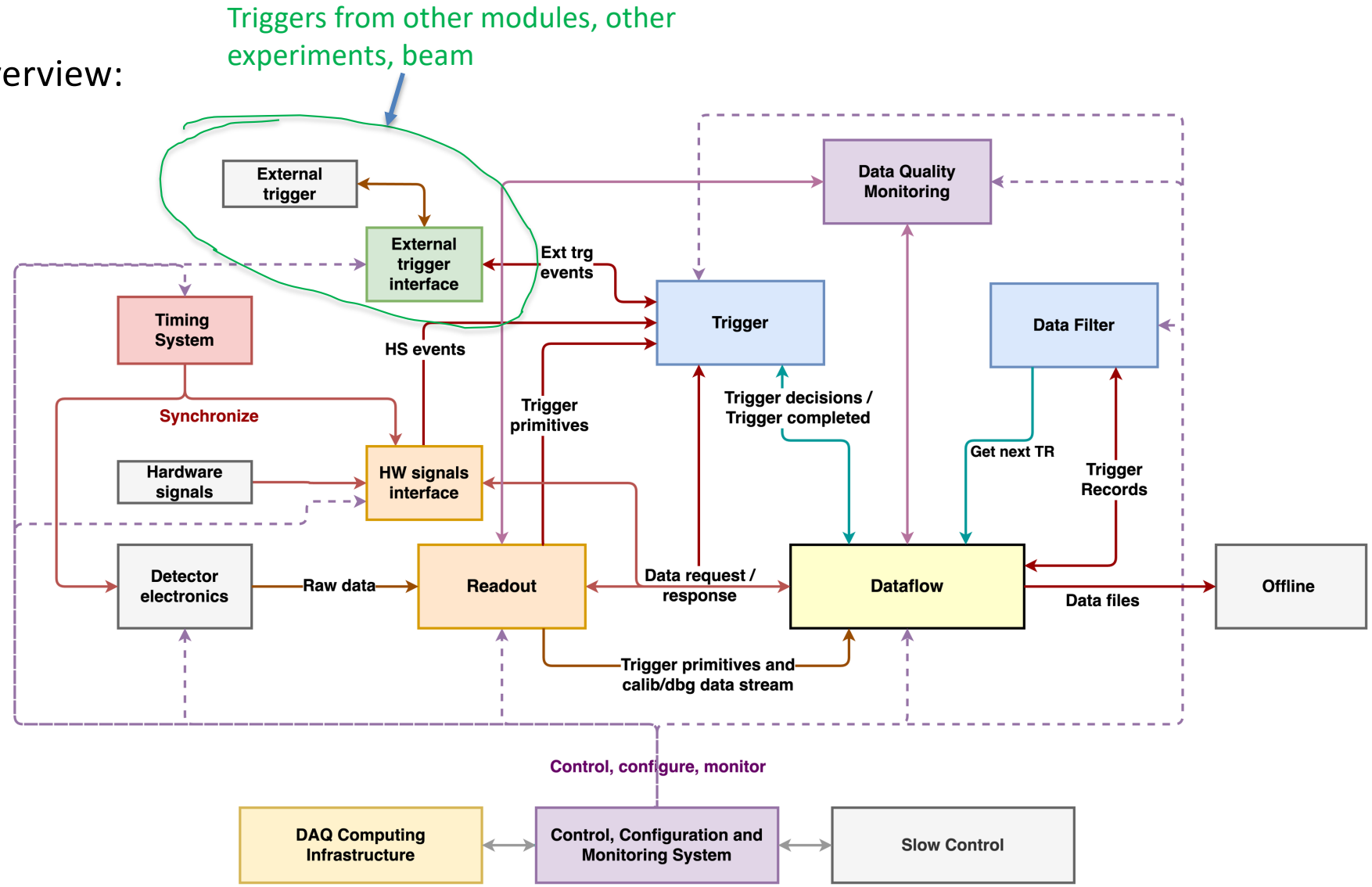
DUNE Trigger Basics

DAQ Overview:



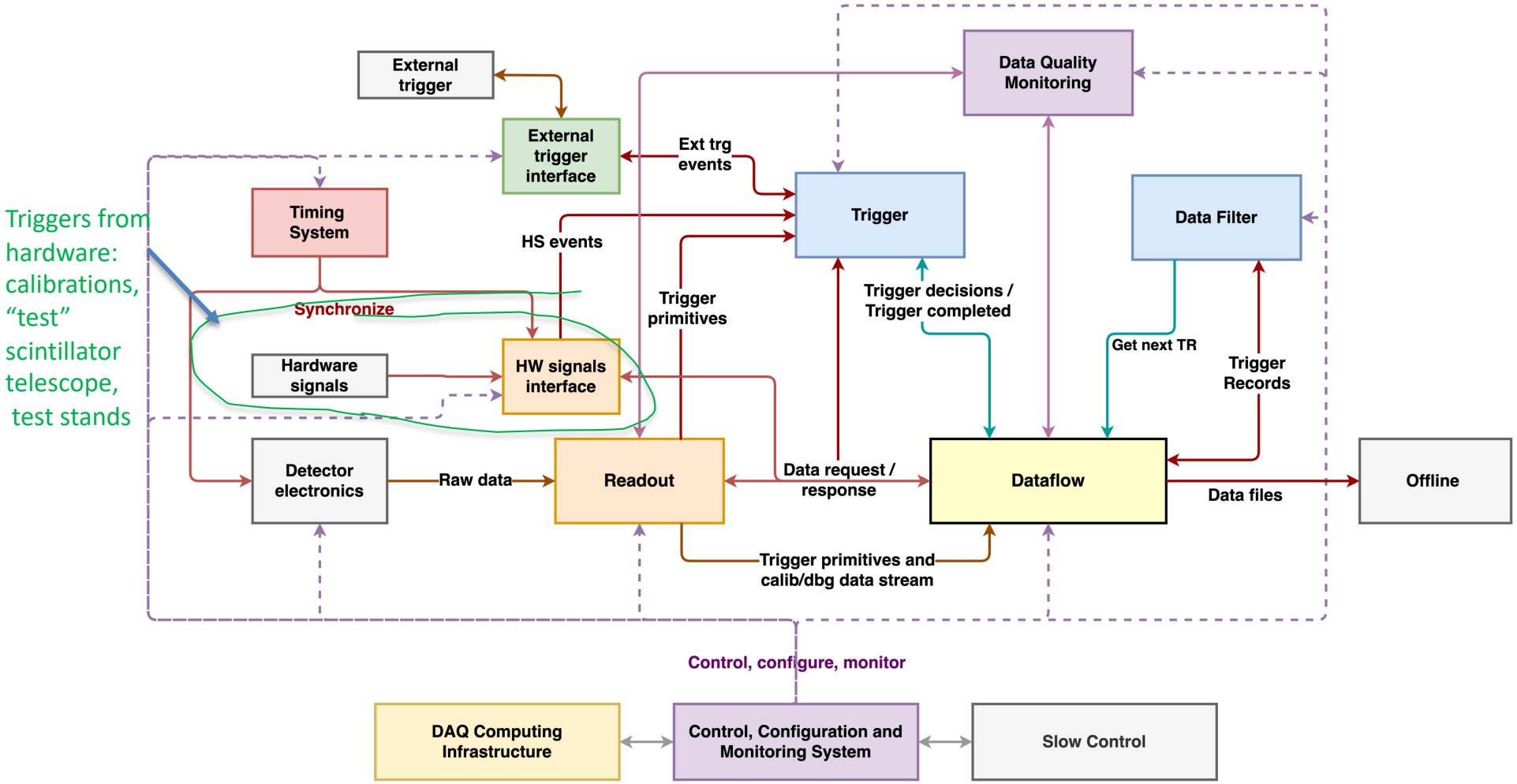
DUNE Trigger Basics

DAQ Overview:



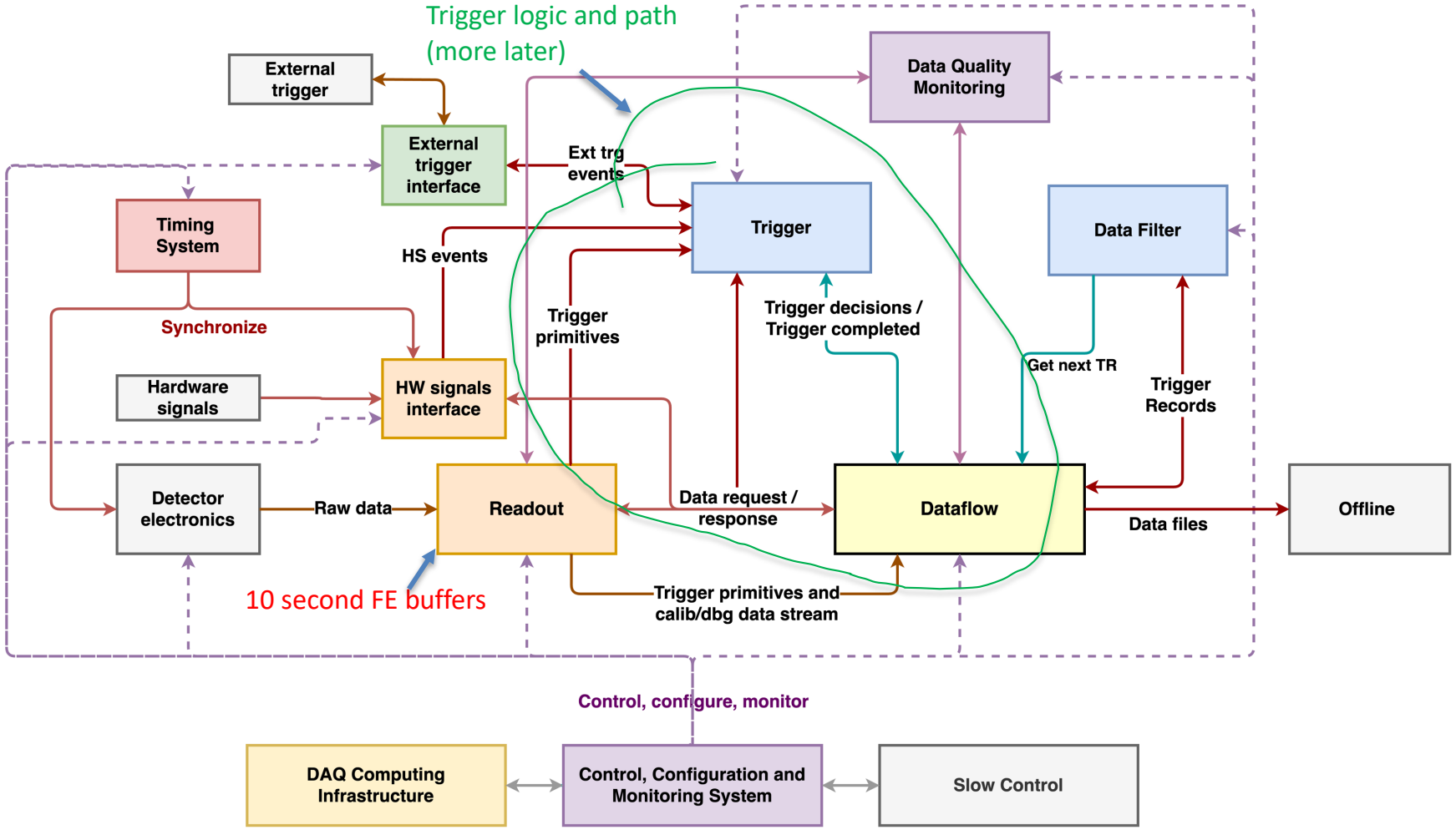
DUNE Trigger Basics

DAQ Overview:



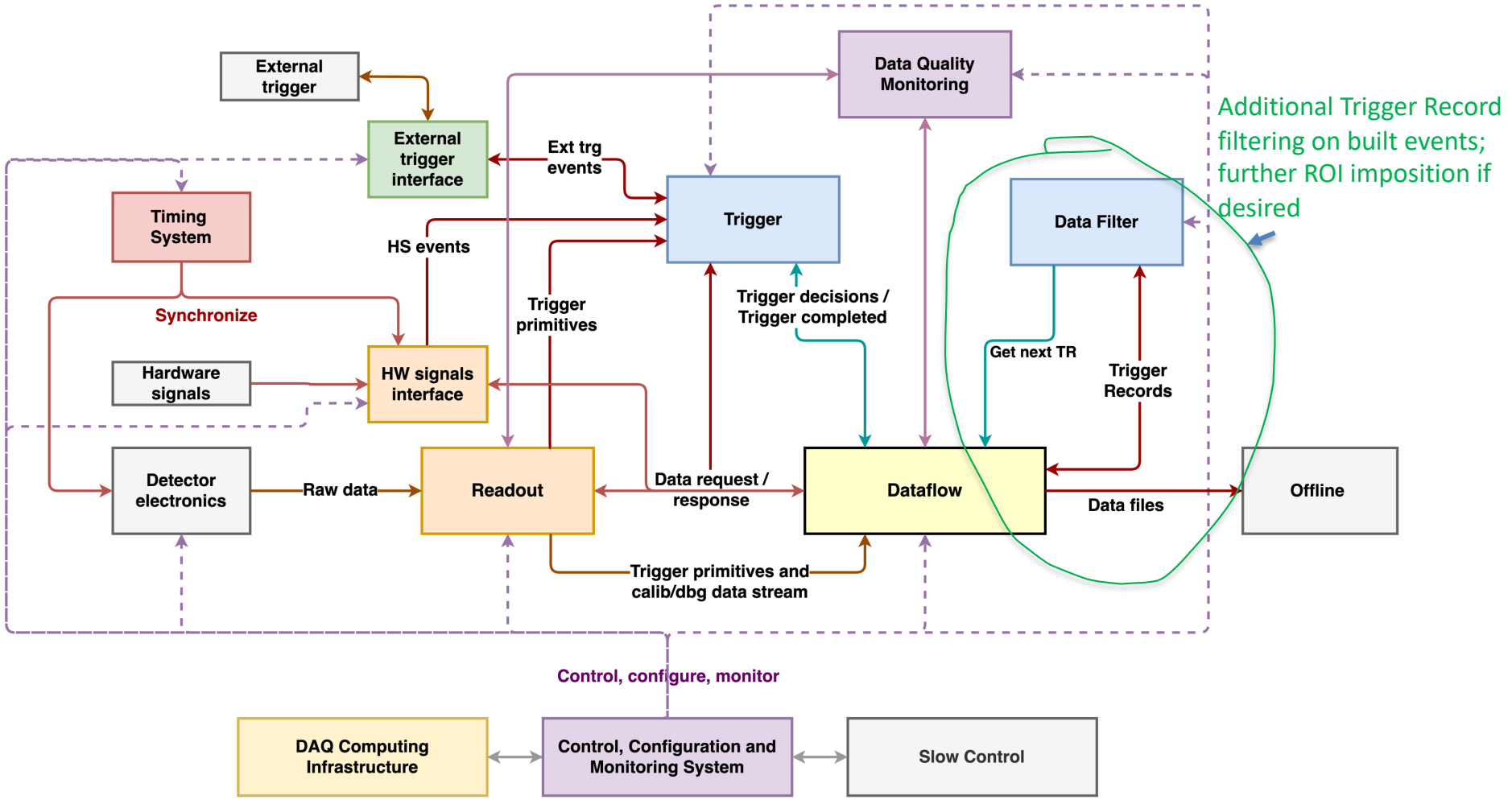
DUNE Trigger Basics

DAQ Overview:



DUNE Trigger Basics

DAQ Overview:



TPC Triggering

Basics

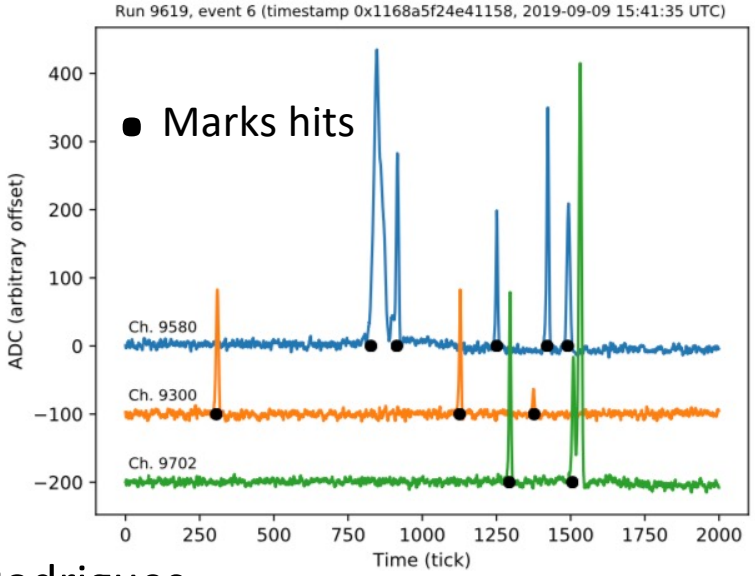
A quick note about the word “threshold”….

- Trigger Primitives have a “hit” threshold
- Trigger Decision based on various “event” thresholds
- Supernova Bursts have a “burst threshold”
  - Once a burst is triggered, the data is acquired with zero threshold for 100 s

Trigger Primitives (TPs)

Hit finding

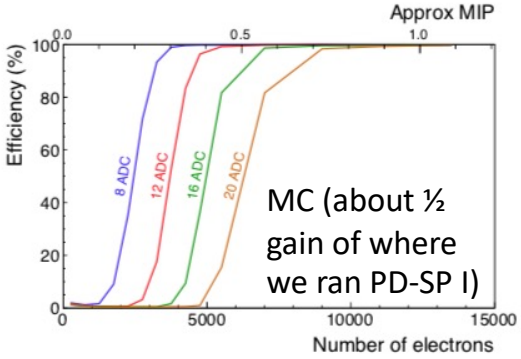
Example from ProtoDUNE-SP

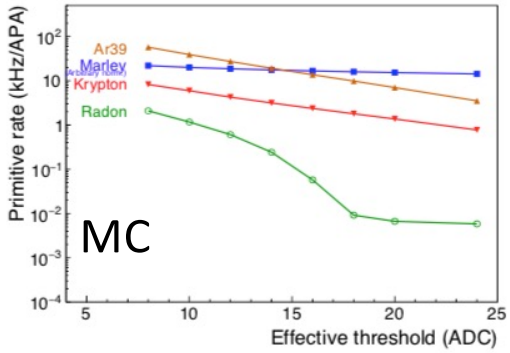


P. Rodrigues

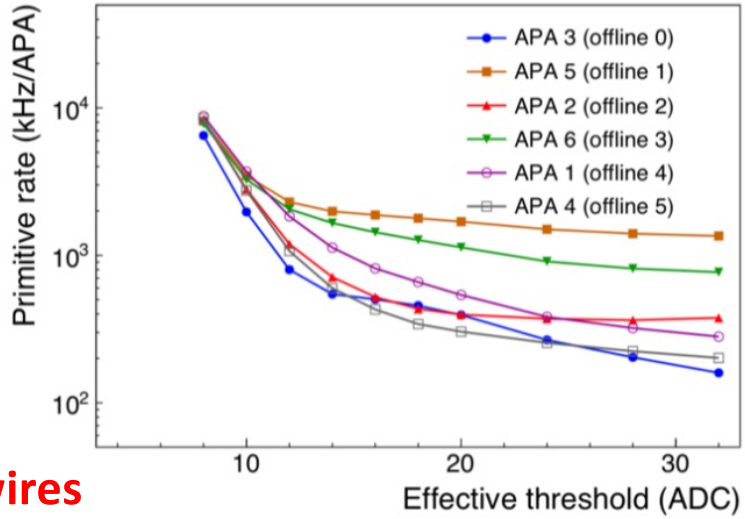
TP threshold was around 1/4 MIP-equivalent, or around 250 keV_{ME} (per wire)

Raw noise in ENC at PD I was ~600 e (collection)





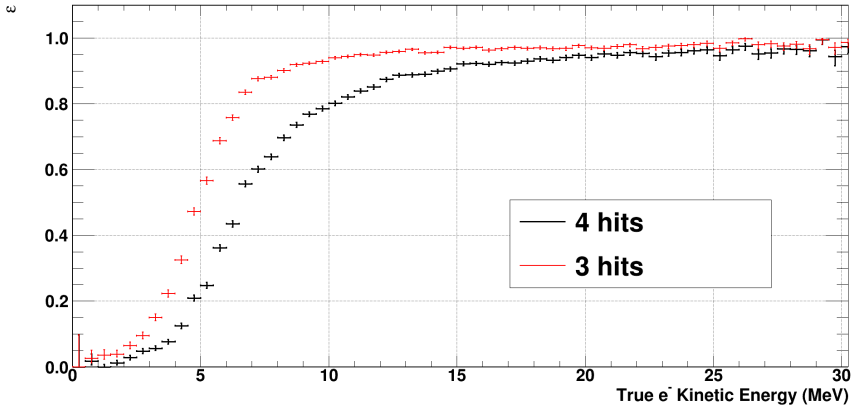
Raw noise RMS in PD I was 3-4 ADC above pedestal



Has been studied also for VD strips instead of HD wires

Supernova Bursts

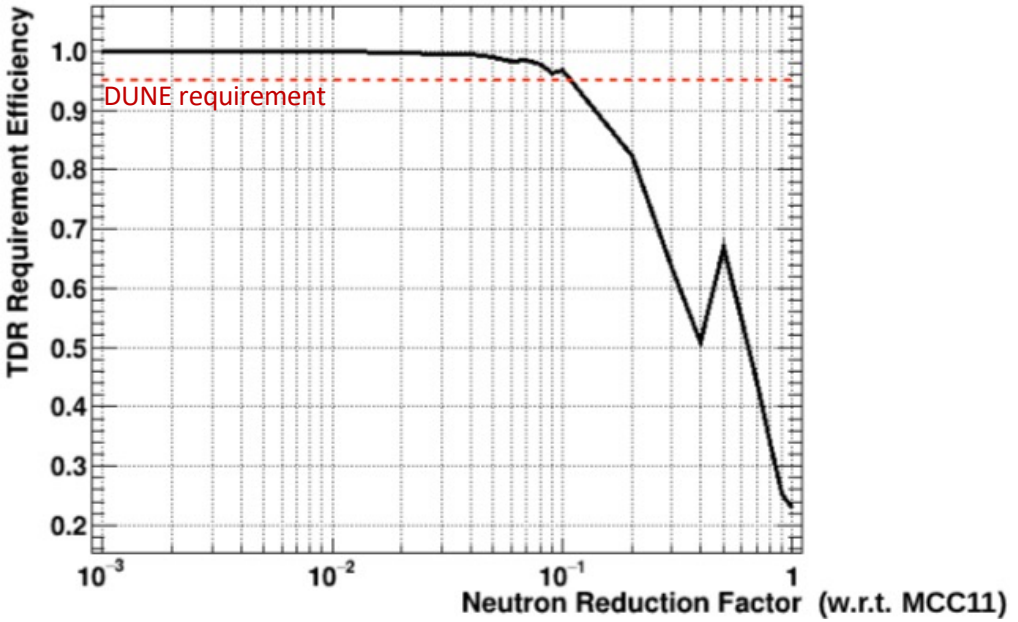
Additional handle: Time and energy profile



Can accommodate more aggressive "trigger activity" threshold but lowering single-interaction threshold hurts without energy-weighting

T. Bezerra

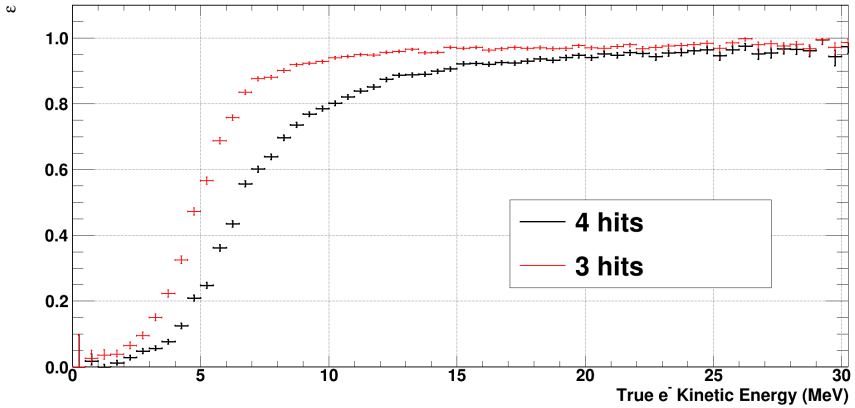
Not including energy profile



Note: we read out ***everything*** for 100 s if we detect a burst---event efficiency does not matter (much) except outside of that window

Supernova Bursts

Additional handle: Time and energy profile



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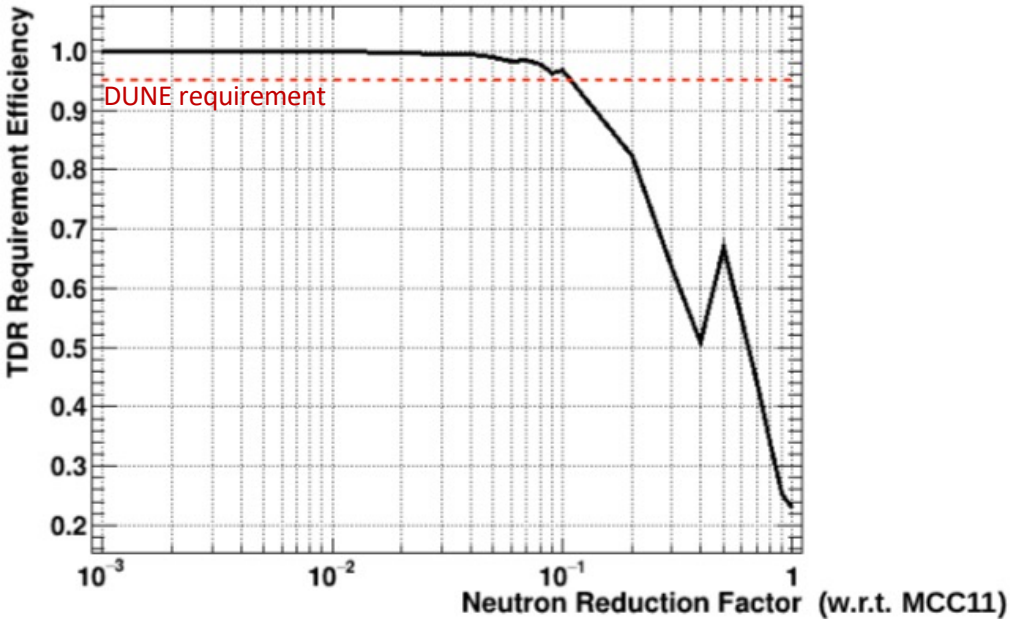
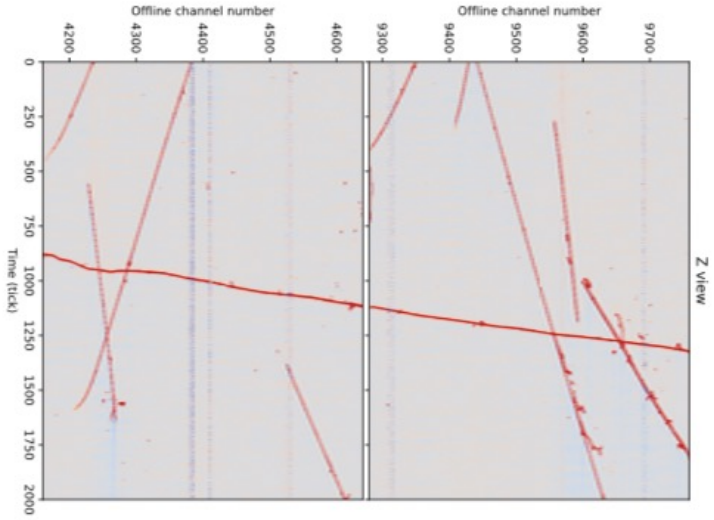
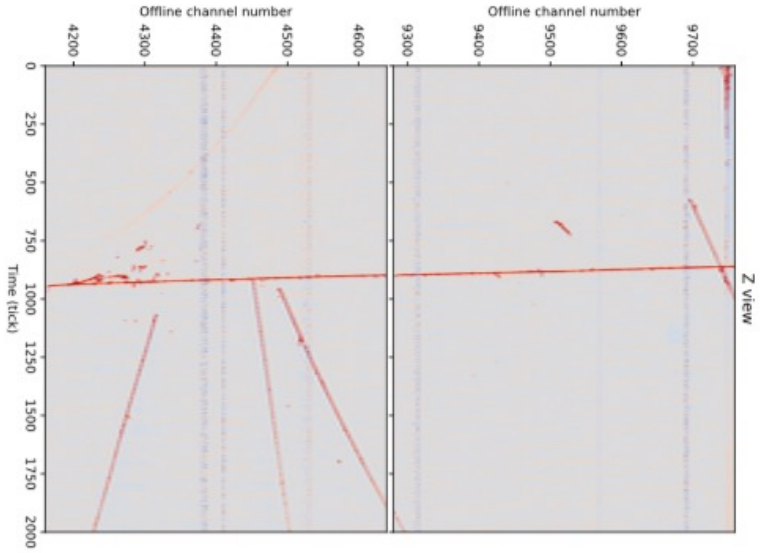


AND: Normal triggering continues in parallel with SN burst trigger---all events above threshold are built, and threshold can be *dynamic*.

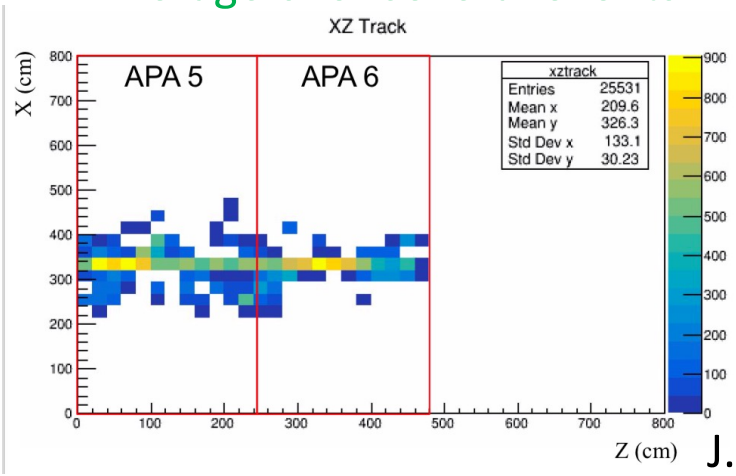
Performance at PD-SP 1

Horizontal Muon Trigger (exclusive)

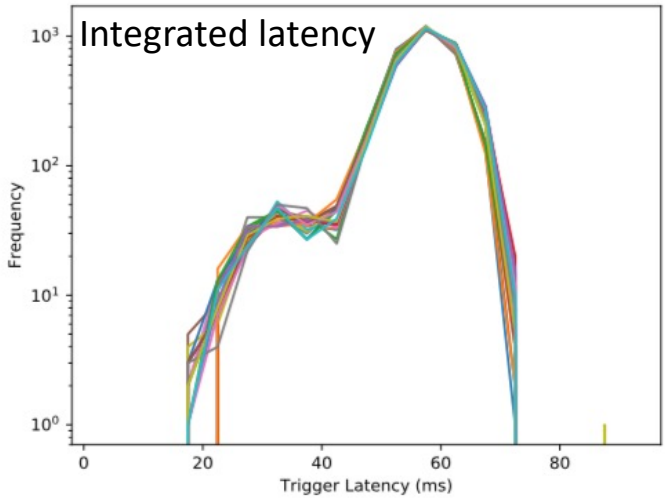




Average over several events



J. Sensenig



Time from data arriving at FELIX to Trigger Decision Buffer depth was 1 second

Triggering is Not the Challenge