HPS Trigger Readiness
May 30, 2019

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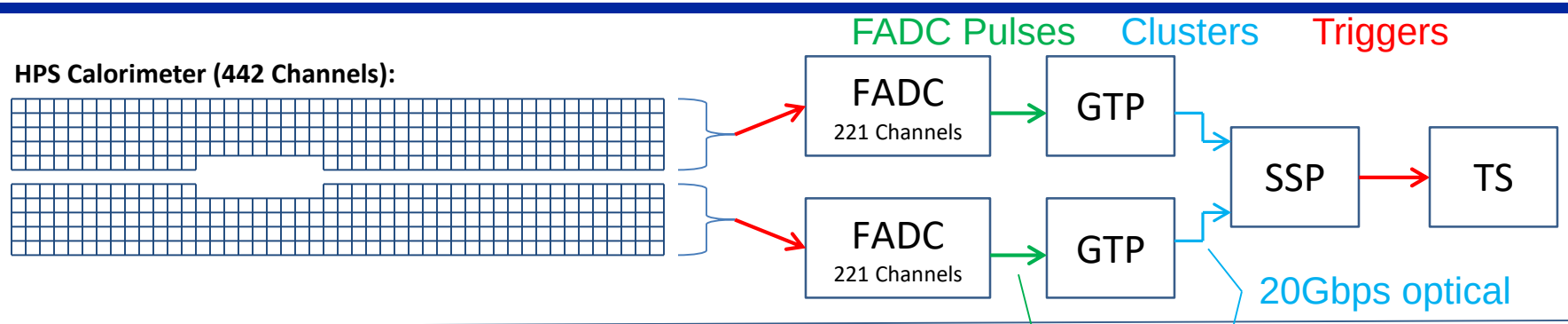
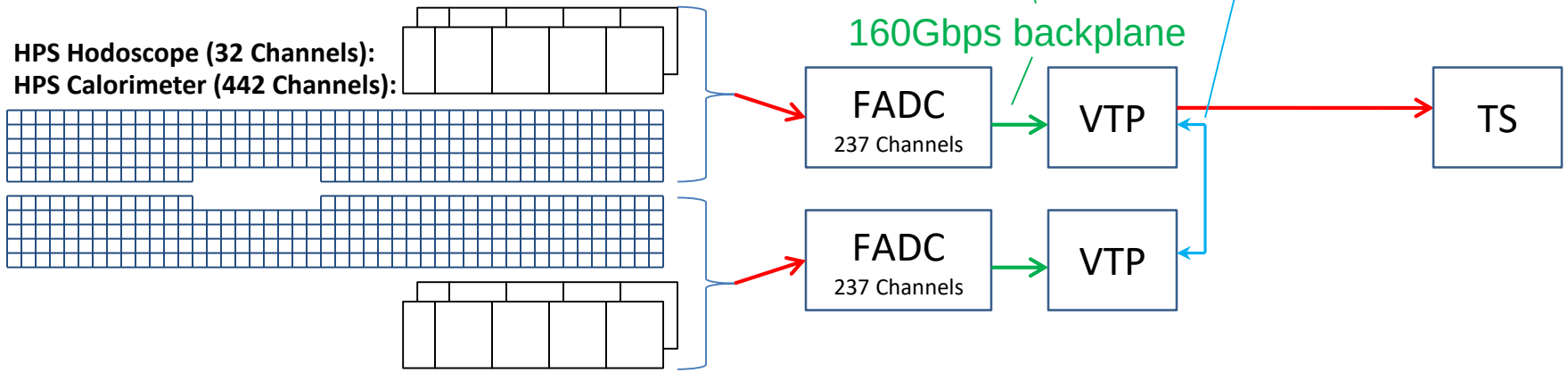
HPS Trigger Hardware Upgrade

HPS 2016 Setup:



HPS 2019 Setup:



GTP+SSP was replaced with VTP:

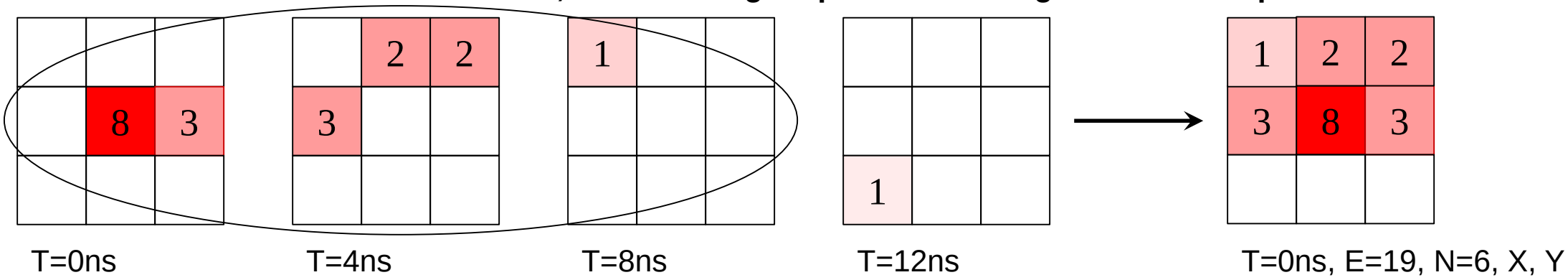
- VTP supports up to 32 trigger bits (currently 17 defined for HPS)
- Single firmware image to compile for entire HPS trigger
- Existing libraries & CODA integration: configure, monitoring, readout already done and used in CLAS12

Cluster Finding

Cluster finding is done by (using 3x3 tower views, all views evaluated in parallel):

- **Seed hit (center) must be >= seed threshold**
- **Seed hit must also be a local maximum in both space and time**
- **Cluster is reported with:**
  - **Timestamp of seed hit (large amplitude hit => lowest jitter)**
  - **Number of hits in cluster**
  - **X,Y position of seed hit**
  - **Energy in MeV units**

e.g. for seed threshold of 2 and hit ∆t=+/-8ns, the following hit pattern evolving in time will report 1 cluster:



Hodoscope Logic

Hodoscope Tiles:

T 1	T 2	T 3	T 4	T 5

Hodoscope layers are all identical

- two layers, top & bottom => 4 identical

Pulse processing

- Identical to ECAL hits, FADC reports pulse integral and time (4ns resolution)
- FADC pulse integral threshold
  - can be used to cut noise & dark current
- Hit persistency: 4ns to 32ns
  - Used for coincidence with other hodoscope hits (adjacent tile or layer)
  - Used for coincidence with ECAL clusters

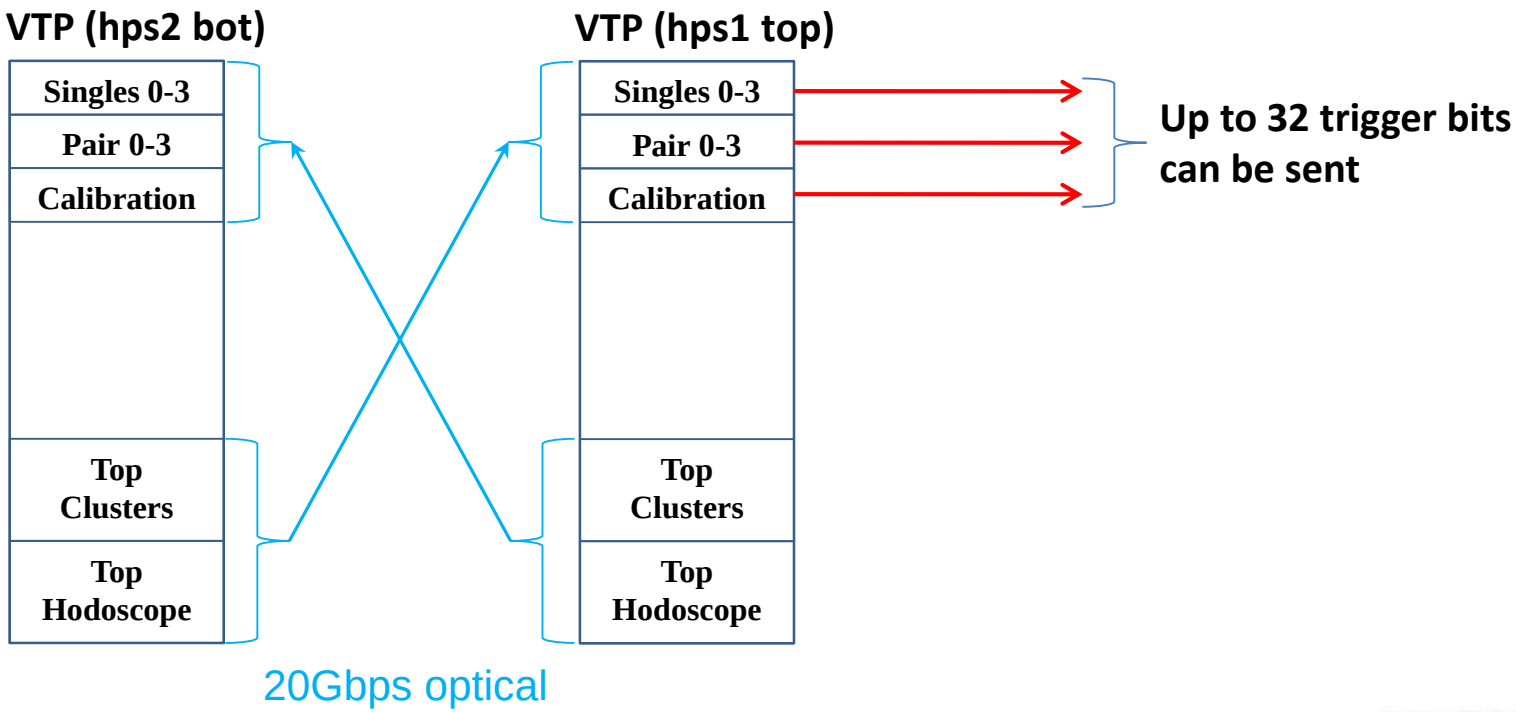
Hodoscope hit processing

- Each tile is evaluated every 4ns, and considered hit if (and $FADC\_Pulse_n > 0$):
  - $(FADC\_Pulse_{n-1} + FADC\_Pulse_n)$ or $FADC\_Pulse_n$ or $(FADC\_Pulse_n + FADC\_Pulse_{n+1})$ >= HodoTileThreshold

Trigger Information Flow

The two VTP exchange trigger information (ECAL clusters, and hodoscope hits)

- **This is required for the pair and cluster multiplicity trigger logic**
- **In the end, both modules have the same information after the data exchange**
- **so both compute the HPS the same triggers, but we only connect 1 to the TS**



HPS Singles Trigger

Trigger equation:

1. $(E_{min} <= Cluster_{Energy} <= E_{max})$ and $(Cluster_{NHits} >= NHits_{min})$
2. $X_{min} <= Cluster_X$ — *Select only positron region*
3. $Cluster_{Energy} >= PDE(Cluster_X)$ — *Position dependent energy cut*
4. $HodoL1_{Hit}$ — *Hodoscope Layer 1 hit*
5. $HodoL2_{Hit}$ — *Hodoscope Layer 2 hit*
6. $HodoL1_{Hit} <-> HodoL2_{Hit}$ — *Hodoscope Layer 1 & 2 matching*
7. $HodoL1_{Hit} <-> Cluster_X <-> HodoL2_{Hit}$ — *Hodoscope Layer 1 & ECAL X & Hodoscope Layer 2 matching*

Newly added singles cuts

Position Dependent Energy threshold: $PDE(x) = C_0+C_1x+C_2x^2+C_3x^3$

Notes:

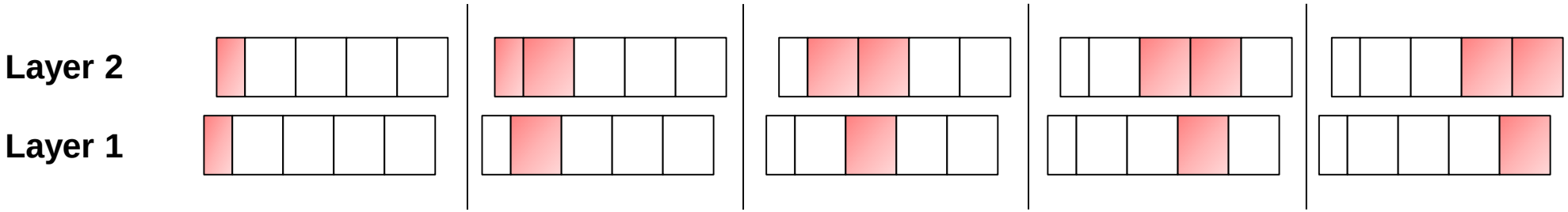
- 2-7 are optionally enabled, 1 is always enabled
- 4-7 options are progressively tighter hodoscope cuts
- $C_0..C_3$ are VME programmable. These are 32bit signed fixed point numbers that cover range from: -6.5E4 to +6.5E4 in 1.52E-5 steps
- This singles trigger is equivalent to the HPS 2016 singles trigger when cuts 2-7 are disabled

Color legend:

- Trigger data from detector
- VME programmable parameter
- Hardcoded parameter/logic

Singles Hodoscope Mapping

Hodoscope Layer 1 -> Layer 2 Geometry Matching:



Hodoscope Layer -> ECAL Cluster X Geometry Matching:

- Currently hardcoded in firmware, can switch to programmable values if there's a strong need or if I have nothing better to do

Layer 1	ECAL Min X	ECAL Max X
Tile 1	5	9
Tile 2	7	10
Tile 3	10	15
Tile 4	15	20
Tile 5	20	23

Layer 2	ECAL Min X	ECAL Max X
Tile 1	5	8
Tile 2	7	12
Tile 3	12	17
Tile 4	17	22
Tile 5	21	23

HPS Pair Trigger

Trigger equation:

$$(|T_{Top} - T_{Bot}| <= \Delta t_{max}) \text{ and}$$
$$(|E_{Top} - E_{Bot}| <= \Delta E_{max}) \text{ and}$$
$$(E_{min} <= E_{Top} + E_{Bot} <= E_{max}) \text{ and}$$
$$(E_{min} <= E_{Bot} <= E_{max}) \text{ and}$$
$$(E_{min} <= E_{Top} <= E_{max}) \text{ and}$$
$$(Nhits <= HitThreshold) \text{ and}$$
$$(\text{Min}(E_{Top}, E_{Bot}) + R \times F <= Threshold_{Slope}) \text{ and}$$
$$(|\tan^{-1}(X_{top}/Y_{top}) - \tan^{-1}(X_{bot}/Y_{bot})| <= Coplanarity_{Angle})$$

} Same cuts as we had for previous runs

Notes:

- Pairs only formed with cluster on opposite sides (top & bottom). All combinations of cluster pairs not implemented (i.e. 2 clusters on same side aren't paired)
- Geometric cuts have coordinates hardcoded in FPGA firmware

Color legend:

- Trigger data from detector
- VME programmable parameter
- Hardcoded parameter/logic

HPS Cluster Multiplicity Trigger

Trigger equation:

1. $(E_{min} <= Cluster_{Energy} <= E_{max})$ and $(Cluster_{NHits} >= NHits_{min})$
2. $\sum_{t}^{t+\Delta t} NClusters_{top} >= NClustersTop_{min}$
3. $\sum_{t}^{t+\Delta t} NClusters_{bot} >= NClustersBot_{min}$
4. $\sum_{t}^{t+\Delta t} (NClusters_{top} + NClusters_{bot}) >= NClustersTot_{min}$

} New trigger

Notes:

- This logic allows triggering on any number of clusters meeting the selected energy range (E_{min},E_{max}) within the programmable time window (Δt)
- For example, to trigger in 3 clusters where one is on the opposite side: $NClustersTot_{min} = 3$, $NClustersBot_{min} = 1$, $NClustersTop_{min} = 1$

Color legend:

- Trigger data from detector
- VME programmable parameter
- Hardcoded parameter/logic

HPS Calibration Triggers

LED

- Nothing special – just passes the LED trigger through (from FADC to VTP to TS)

Cosmic

- Discriminates PMT cosmic scintillators and does top/bottom PMT timing coincidence

Hodoscope

- Requires Hodoscope Layer 1 and Layer 2 timing coincidence
- Just for testing, but could be a good trigger source to validate ECAL only trigger efficiency

Pulser (my favorite trigger)

- Used as “random” trigger source
- Useful for:
  - Acquiring background events
  - Trigger efficiency studies
  - Deadtime measurement
  - Unbiased (for at least most of the readout window) - can be used to measure rates of any physics process (given enough statistics)

Trigger Bit List

TS Trigger Bits

- 0: Single Top 0
- 1: Single Top 1
- 2: Single Top 2
- 3: Single Top 3
- 4: Single Bottom 0
- 5: Single Bottom 1
- 6: Single Bottom 2
- 7: Single Bottom 3
- 8: Pair 0
- 9: Pair 1
- 10: Pair 2
- 11: Pair 3
- 12: LED
- 13: Cosmic
- 14: Hodoscope
- 15: Pulser
- 16: Cluster Multiplicity

- **Trigger list can grow up to 32**
- **Adding more of the same is easy**
  - **Will likely add another “Cluster Multiplicity”**
- **Planning to add back the FEE trigger we had back in 2016**
  - **Probably a dedicated trigger bit and won’t be part of the singles trigger this time**
- **Please discuss with Valery or me about any changes needed with this list – we expect/hope it’s very close, if not already, final**

Trigger Configuration Files - 1

Example/template HPS trigger file:

- $CLON_PARMS/trigger/HPS/Run2019/TEST/hps_ben_test.trg

Singles Setup:

```
# Enable trigger
VTP_HPS_SINGLE_EN    0                              1

# Minimum cluster energy: 1 to 8191, units MeV
VTP_HPS_SINGLE_EMIN  0     100                      1
VTP_HPS_SINGLE_EMAX  0    8191                      1
VTP_HPS_SINGLE_NMIN  0       1                      1

# Minimum cluster x coordinate: -31 to 31
VTP_HPS_SINGLE_XMIN  0     -31                      1

# Cluster position dependent energy threshold coefficients
# Cluster Energy >=     C0  + C1*X + C2*X*X+C3*X*X*X
VTP_HPS_SINGLE_PDE   0  1.0   1.0    1.0    1.0    1

# Hodoscope trigger
#                       require hit on l1
#                       |     require hit on l2
#                       |     |      require hit on l1 and l2 with geometry matching
#                       |     |      |      require hit on l1 and l2 with cluster X geometry matching
#                       |     |      |      |
#                       |     |      |      |
VTP_HPS_SINGLE_HODO  0  0     0      0      0      1
```

Trigger Configuration Files - 2

Pair Setup:

```
###################################
# Pair Trigger 0 Setup
###################################

#                               singles trigger bit number
#                               |     settings
#                               |     |-------|     enable cut
#                               |     |       |     |
#                               |     |       |     |

# Enable Trigger
VTP_HPS_PAIR_EN                 0     1

# Minimum cluster energy
VTP_HPS_PAIR_EMIN               0     100

# Maximum Cluster energy
VTP_HPS_PAIR_EMAX               0     8191

# Minimum Hit in Cluster
VTP_HPS_PAIR_NMIN               0     1

# Pair time coincidence: 0 to 16, units +/-ns
VTP_HPS_PAIR_TIMECOINCIDENCE    0     12

# Pair Cluster Sum Max,Min: 0 to 8191, units MeV
VTP_HPS_PAIR_SUMMAX_MIN         0     8191    1     1

# Pair Cluster Difference Maximum
VTP_HPS_PAIR_DIFFMAX            0     8191          1

# Pair Energy,Distance:          dist*F  >= THR, units: F: MeV/mm, THR: MeV
VTP_HPS_PAIR_ENERGYDIST         0     5.5   400     1

# Pair Coplanarity Tolerance: 0 to 180, units: +/-degrees
VTP_HPS_PAIR_COPLANARITY        0     35            1
```

Trigger Configuration Files - 3

Cluster Multiplicity:

```
###################################
# Cluster Multiplicity Trigger Setup
###################################

# Minimum cluster energy
VTP_HPS_MULT_EMIN  1

# Maximum cluster energy
VTP_HPS_MULT_EMAX  8191

# Minimum hits in cluster
VTP_HPS_MULT_NMIN  1

# Cluster Multiplicity
#                  TOP BOT TOT
VTP_HPS_MULT_MIN  1   1   3

# Cluster Multiplicity Time Window
VTP_HPS_MULT_DT   16
VTP_HPS_MULT_EN   1
```

Prescalers:

```
###################################
# Trigger Ouput Setup
###################################
VTP_HPS_LATENCY                 1900

# Prescale: 0 to 65535 (note: 0 disables the trigger output)

VTP_HPS_PRESCALE                0       0   # Single 0 Top
VTP_HPS_PRESCALE                1       0   # Single 1 Top
VTP_HPS_PRESCALE                2       0   # Single 2 Top
VTP_HPS_PRESCALE                3       0   # Single 3 Top
VTP_HPS_PRESCALE                4       0   # Single 0 Bot
VTP_HPS_PRESCALE                5       0   # Single 1 Bot
VTP_HPS_PRESCALE                6       0   # Single 2 Bot
VTP_HPS_PRESCALE                7       0   # Single 3 Bot
VTP_HPS_PRESCALE                8       0   # Pair 0
VTP_HPS_PRESCALE                9       0   # Pair 1
VTP_HPS_PRESCALE                10      0   # Pair 2
VTP_HPS_PRESCALE                11      0   # Pair 3
VTP_HPS_PRESCALE                12      0   # LED
VTP_HPS_PRESCALE                13      1   # Cosmic
VTP_HPS_PRESCALE                14      1   # Hodoscope
VTP_HPS_PRESCALE                15      0   # Pulser
VTP_HPS_PRESCALE                16      0   # Multiplicity
```

Calibration:

```
###################################
# Calibration Trigger Setup
###################################

# Hodoscope trigger: require hits on top, bottom, or both
VTP_HPS_CALIB_HODOSCOPE_TOP_EN  1
VTP_HPS_CALIB_HODOSCOPE_BOT_EN  0

# Cosmic trigger: time coincidence: 0 to 1024, units: ns
VTP_HPS_CALIB_COSMIC_DT         40
# Require hits on top, bottom, or both
VTP_HPS_CALIB_COSMIC_TOP_EN     1
VTP_HPS_CALIB_COSMIC_BOT_EN     1

# Pulser trigger: frequency: 0 to 125MHz, units: Hz
VTP_HPS_CALIB_PULSER_EN         0
VTP_HPS_CALIB_PULSER_FREQ       10.0
```

Trigger Configuration Files - 4

ECAL & Hodoscope:

```
# Cluster hit timing coincidence: 0 to 16, units: +/-ns
VTP_HPS_ECAL_CLUSTER_HIT_DT  16

# Cluster seed threshold in: 1 to 8191, units MeV
VTP_HPS_ECAL_CLUSTER_SEED_THR   100

# Hodoscope fadc hit cut: minimum acceptable FADC hit integral: 1 to 8191, units TBD
VTP_HPS_HODOSCOPE_FADCHIT_THR   1

# Hodoscope trigger hit cut: minimum acceptale integral (clustered or single tile): 1 to 8191, units TBD
VTP_HPS_HODOSCOPE_HODO_THR      1

# Hodoscope hit coincidence between L1,L2, and also ECAL clusters (real with is specified value +4ns): 0 to 28, uni
ts: ns
VTP_HPS_HODOSCOPE_HODO_DT       28
```

Trigger Data Banks

Enabled trigger bits and clusters are written to events

- These allow online/offline checking of the trigger decisions
- Some trigger bits (single and pair in particular) have cuts
  - Each cut decision is recorded (so long as the trigger fired)
  - So it is advantageous to defined cuts, but not enable them for triggering – this allows it to operate in tagging mode
  - As an example: a loose singles trigger can be enabled cutting on cluster energy only
    - All hodoscope decisions for the singles trigger will be recorded and a simple analysis can determine the efficiency of each individual cut

From $CLON_PARMS/clonbanks.xml

Important for these banks to be known and ready to be read by online/offline tools that will participate in trigger verification!

```
O(31:23)=0x10+0x0C2 "HPS_CLUSTER"
   0(22:10)         "E"
   0(09:06)         "Y"
   0(05:00)         "X"
   1(13:10)         "N"
   1(09:00)         "T"

O(31:23)=0x10+0x0C3 "HPS_SINGLE_TRIG"
   0(22:20)         "INSTANCE"
   0(19:19)         "TOP_NBOT"
   0(18:18)         "H_L1L2X_GEOM_PASS"
   0(17:17)         "H_L1L2_GEOM_PASS"
   0(16:16)         "H_L2_PASS"
   0(15:15)         "H_L1_PASS"
   0(14:14)         "PDE_PASS"
   0(13:13)         "MINX_PASS"
   0(12:12)         "NMIN_PASS"
   0(11:11)         "EMAX_PASS"
   0(10:10)         "EMIN_PASS"
   0(09:00)         "T"

O(31:23)=0x10+0x0C4 "HPS_PAIR_TRIG"
   0(22:20)         "INSTANCE"
   0(19:14)         "reserved"
   0(13:13)         "COPLANAR_PASS"
   0(12:12)         "EDSLOPE_PASS"
   0(11:11)         "DIFF_PASS"
   0(10:10)         "SUM_PASS"
   0(09:00)         "T"

O(31:23)=0x10+0x0C5 "HPS_CALIB_TRIG"
   0(22:19)         "CALIB_TYPE"
   0(18:10)         "CALIB_FLAGS"
   0(09:00)         "T"

O(31:23)=0x10+0x0C6 "HPS_MULT_TRIG"
   0(22:22)         "reserved"
   0(21:18)         "MULT_TOT"
   0(17:14)         "MULT_BOT"
   0(13:10)         "MULT_TOP"
   0(09:00)         "T"
```

Trigger Verification

- **Firmware simulation**
- **DiagGUI**
- **DAQ Trigger Banks**
- **Random Trigger**
- **Trigger Emulator**

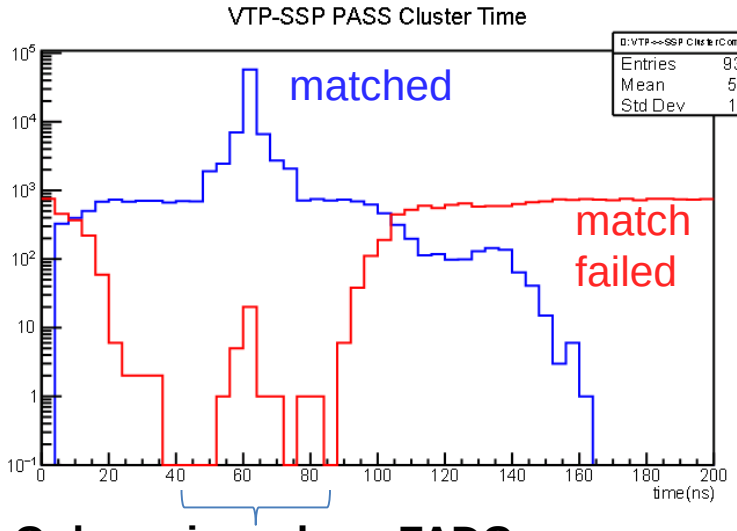
Firmware Simulation

VHDL, Verilog, C/C++ Simulator: Aldec Riviera

- Simulates source files used to compile FPGA projects
- Links to external libraries (e.g. C/C++ EVIO)
  - Can directly read and write DAQ EVIO files
  - Simulate firmware with old HPS runs and record new trigger bank structures
- Cycle accurate simulation of HPS firmware
  - Some models are simplified for speed optimization (e.g. FADC trigger path & SerDes)
- Event simulation rate ~1Hz
  - Not very fast, but plenty can handle ~100k events in a day
- Can verify clusters, singles (old), and pair trigger logic
  - Use HPS run from 2016, run through simulator and record trigger banks
    - Compare new trigger banks to SSP trigger banks
    - Compare new trigger banks to trigger emulator

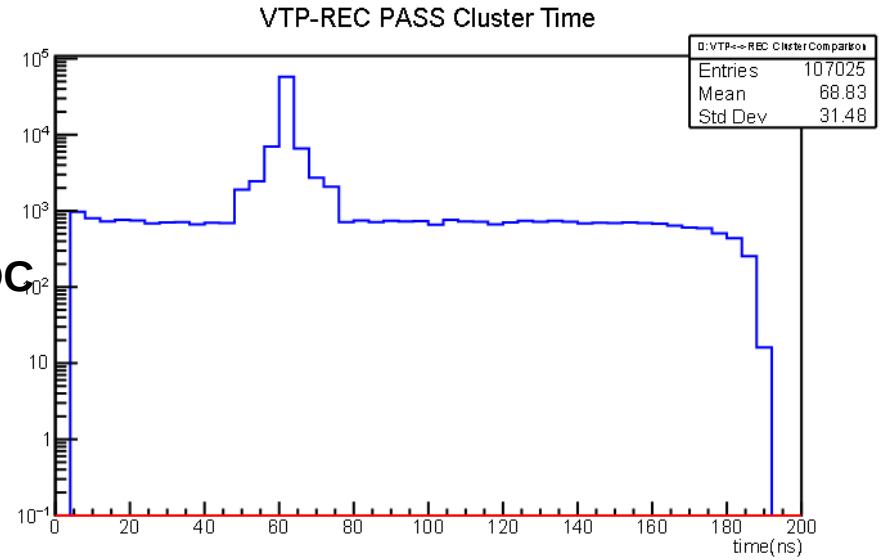
Cluster verification

Examples of comparing ~100k clusters (timestamp, energy, nhits, X, Y) of new firmware against HPS run 8099 trigger banks:



Only region where FADC waveforms are not clipped

- Less than 36ns and above 80ns the FADC waveforms are clipped by the readout window, so energy discrepancies develop causing VTP banks not to match SSP banks
- There are ~20 events that fail to match out of ~100k. These failures are due to pulse pileup creating dead-time on the FADC pulse detection in the trigger. Not easy or impossible to correct for, so this mismatch is not a surprise.
- Comparing VTP cluster banks to trigger emulator a 100% match is seen because both emulator and VTP see the same FADC waveforms (some which are clipped)

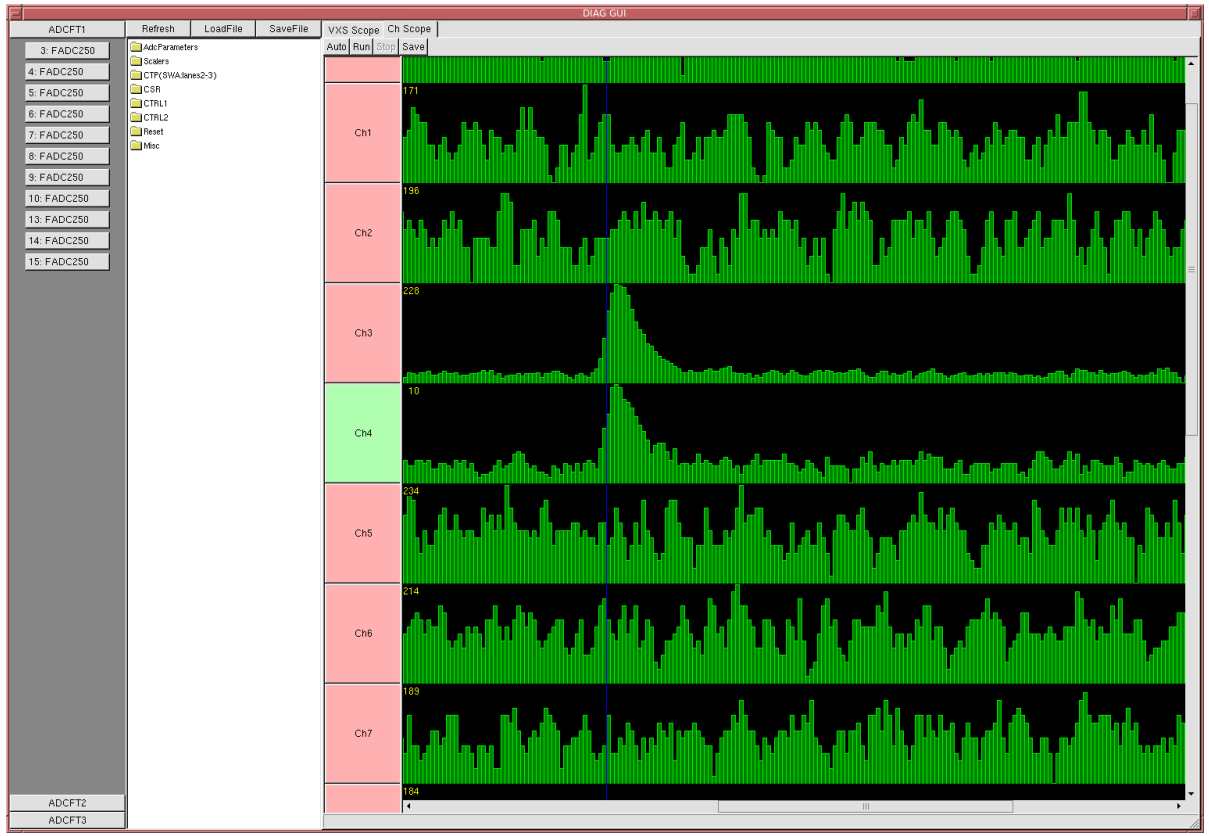


- Singles (old) and Pair trigger logic can be checked the same way (simulation is done, just need to run the analyzer to make the plots – will do soon)

DiagGUI – FADC250

DiagGUI is a general purpose tool to gain register access to DAQ modules and display various diagnostics, histograms, scalers, etc…

- **For example, you can look at any FADC250 waveforms and trigger on the channels:**



DiagGUI – HPS Trigger

DiagGUI also has an HPS Trigger GUI that connects directly to the VTP

Direct access to configuration registers

Plots reflect currently selected trigger bit

Trigger Bit & Cut Rates

Hodoscope Hit Rates

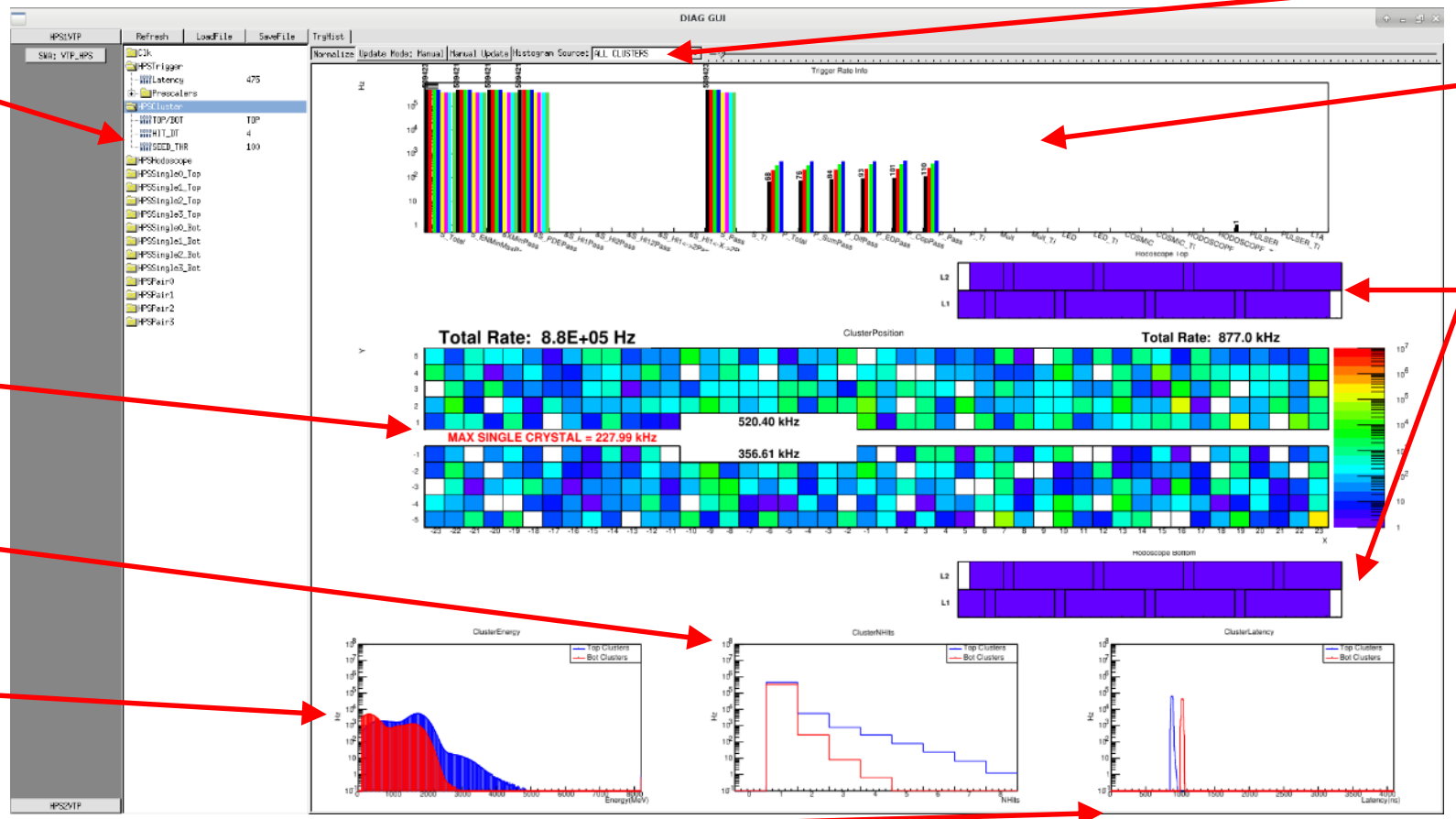
ECAL Cluster Rates

ECAL Cluster Nhits Distribution

ECAL Cluster Energy Distribution

Trigger Latency

Can also select a particular ECAL coordinate to see plots for only it

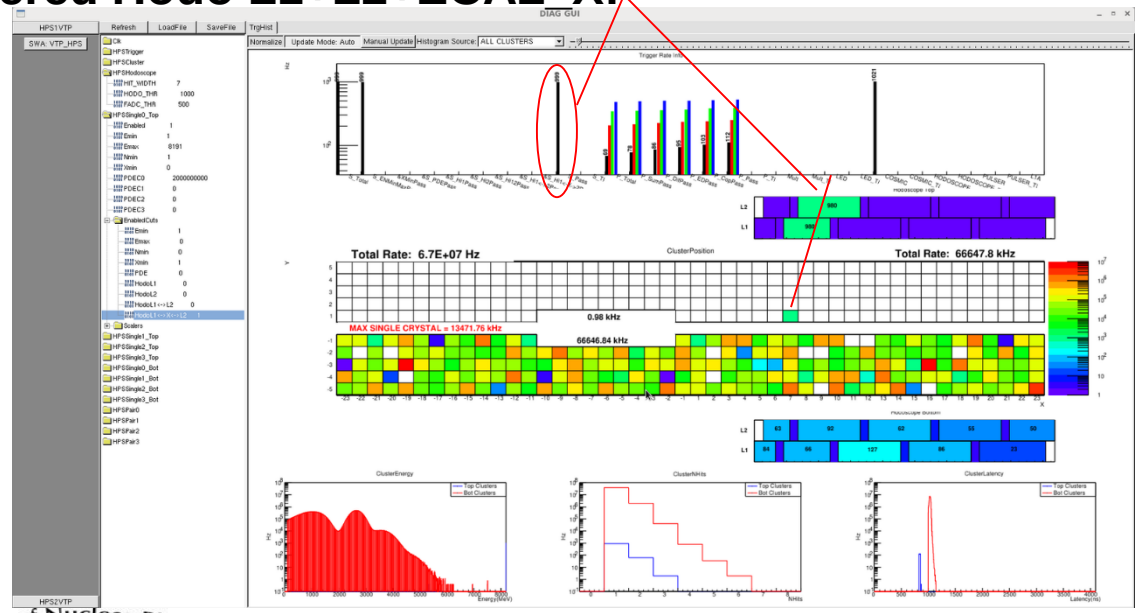


E.g. Hodoscope Testing

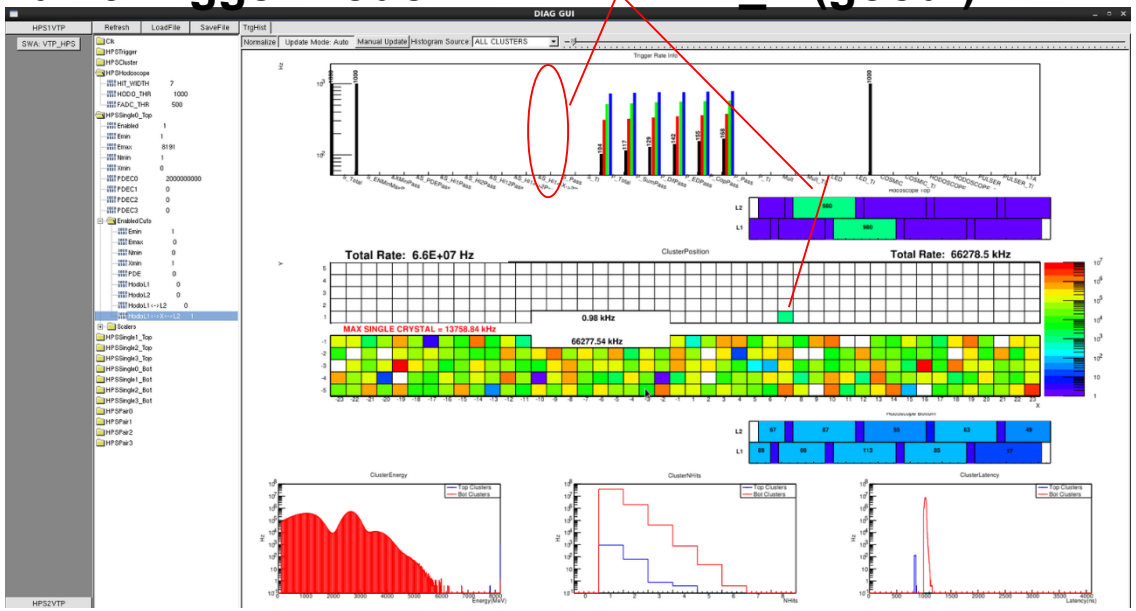
Checked Hodoscope L1, L2, ECAL Cluster timing coincidence

- **"Perfectly" aligned, so a hit on ECAL and Hodoscope are right at the edge of coincidence when Hodoscope width=32ns. The hodoscope stays in coincidence with ECAL up to 32ns before ECAL.**
- **All Hodoscope L1 -> L2 geometry matching checked**
  - **All matches triggered and several non-matches did trigger.**
  - **A few combinations with ECAL Cluster X matching also worked as expected**

Triggered Hodo L1+L2+ECAL_X:



Didn't Trigger Hodo L1+L2+ECAL_X (good!):



Random Trigger

Run random trigger

- Select physics events trigger is expected to be set and check the VTP trigger bank tags
  - Very reliable method, but if the VTP->TS cable was broken or a trigger was prescaled improperly this method would lie about the true efficiency/acceptance!

- Same thing, but check the TS trigger type
  - Much less statistics because the TS trigger type is only recorded over a narrow time window (~20ns?)
  - This does confirm the full trigger chain is working (which includes the cable that goes from the VTP to the TS)

Trigger Emulator

The trigger emulator is a basic ROOT based C++ analyzer

- Reads trigger banks and also reconstruct trigger banks from FADC waveforms
- Compares reconstructed trigger banks to recorded ones reports on discrepancies
- Measures/estimates rates of trigger bits from random trigger
  - A single random trigger run can be taken and fed through the program under various settings to tune parameters
  - These rates should match the running trigger bit rates as well – another good verification step
- It hasn't been updated to handle the latest trigger changes – I'm expecting/hoping other folks and software will be involved in the verification process so I don't resurrect this tool!

Summary

- 1 or 2 calibration trigger bits needed to be added – will do it this week
- A usable production firmware is already installed, but updates will require another release
- Simulation verification is mostly completed (clusters look good, single and pair trigger decisions still needed to be analyzed)
- Hodoscope trigger checkout with pulser so far behaves as expected – probably will take beam to evaluate all combinations to an acceptable level