Commissioning of the Mu2e Data AcQuisition system and the Vertical Slice Test of the straw tracker

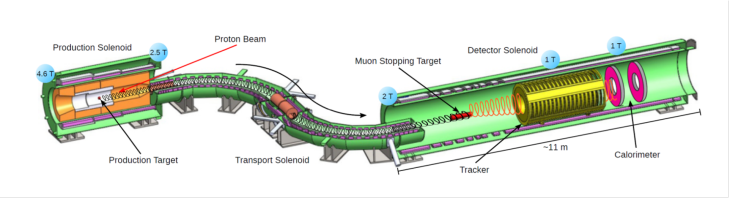
Intern: Sara Gamba
Supervisors: Pavel Murat, Simone Donati

Fermi National Accelerator Laboratories

September 27th 2023

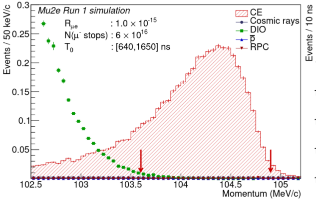
Mu2e experiment at Fermilab

$$\mu^- + \text{Al} \rightarrow e^- + \text{Al}$$



- Looking for Charged Lepton Flavour Violation;
- Mu2e will improve SINDRUM II limit ($7.0 \cdot 10^{-13}$) by 4 orders of magnitude;
- Momentum resolution: 2 MeV/c FWHM (SINDRUM II) to 1 MeV/c (Mu2e);
- Three years of running:
  - $3.6 \cdot 10^{20}$ protons;
  - Expected background level below 1 event.

Signals and backgrounds

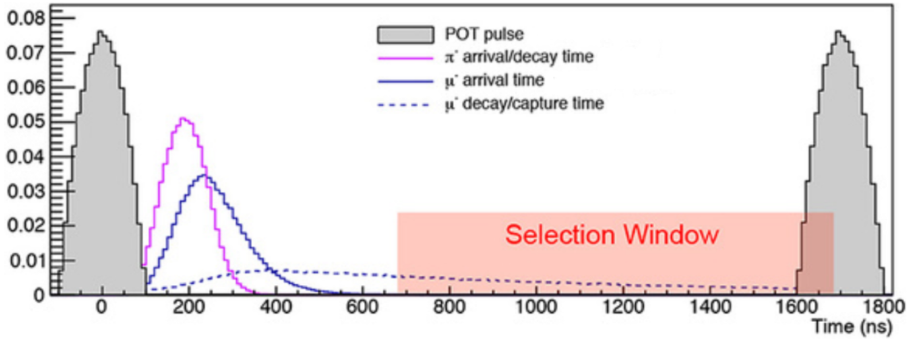


$$E_{CE} = m_\mu - E_{rec} - E_{bind}$$

Sources of background e^- (around 105 MeV/c):

- Cosmic particles, CRV;
- DIO of μ^- entering the DS;
- $\bar{p}$ by the proton beam and annihilation (absorption elements in the TS);
- RPC: rapidly falls in time. Requirement: delayed live-time window with respect to the proton pulse arrival at the production target.
- e^- entering the DS and scattering in the Al (delayed live-time window and an excellent proton beam extinction);
- RMC, similar to RPC, but with a lower maximal energy.

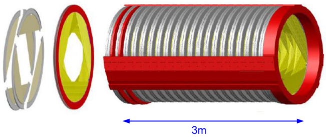
RPC and timing

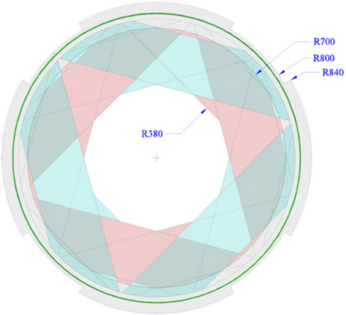


- Proton pulses, separated by a time window of 1695 ns;
- RPC rapidly falls in time;
- Selection window after 640 ns.

The tracker

- 3 m long tracker, 18 stations;
- 3 m downstream of the stopping target in the uniform 1 T region of the DS magnetic field;
- 5 mm diameter and 40-110 cm long straws;
- straw tubes filled with a 80%:20% Ar:CO_2 mixture at a pressure of 1 atm;
- the whole detector will be in vacuum;
- covering radii between 38 cm and 68 cm;
- 96 straws per panel;
- 6 panels per plane;
- 2 planes per station;
- 18 tracking stations: 216 panels.



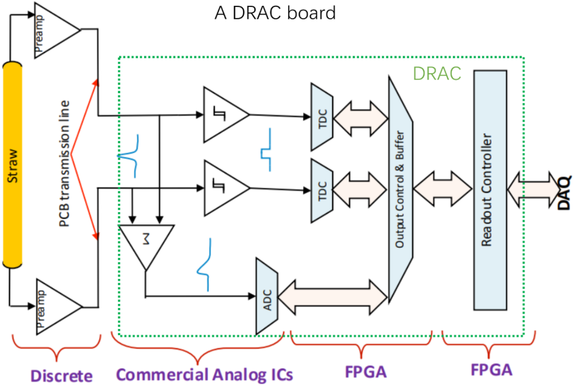


- Mu2e is starting commissioning;
- To commission the tracker we need the DAQ working;
- DAQ needs to be commissioned first;
- The rest of the talk is about DAQ;
- We are learning about things that are working and things that do not work.

Tracker readout

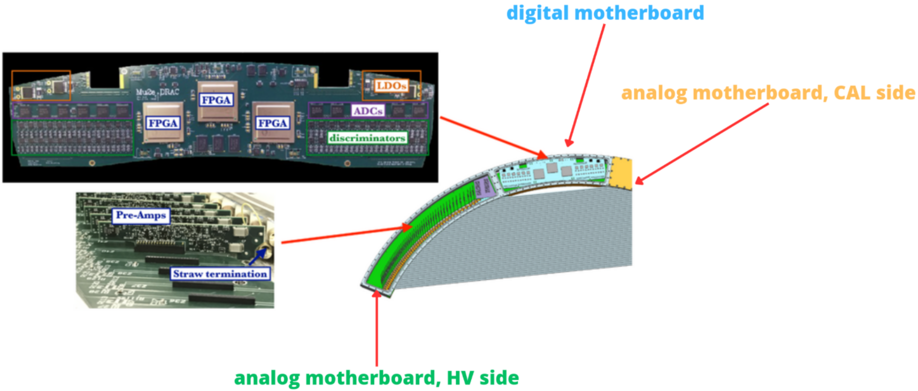
- Signals are readout from the ends of each straw on the panel and amplified;
- Signals sent to digitizer electronics;
- From each straw we get 2 times and a hit waveform (charge);
- DRAC: Digitizer Readout & Assembler Controller.

A DRAC board



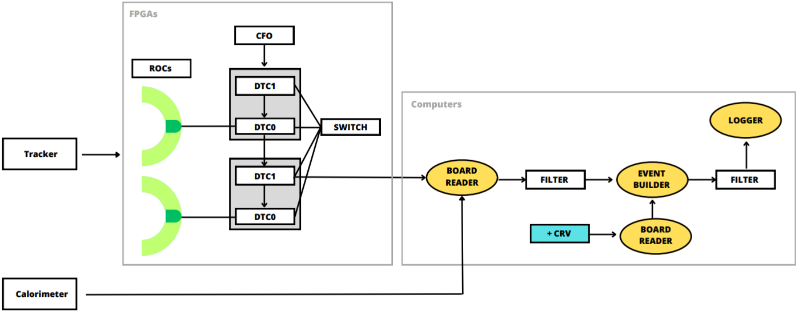
Signal flow chart

Tracker readout-2



- TDCs are implemented in FPGAs.

Mu2e DAQ components diagram

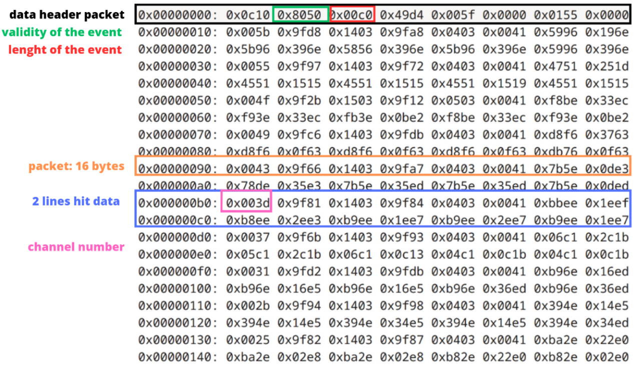


- ROC: ReadOut Controller;
- DTC: Data Transfer Controller (module). One DTC can read 6 ROCs;
- CFO: Command FanOut (module). It synchronizes and checks DTCs;
- CRV: Cosmic Ray Veto.

What are we reading out?

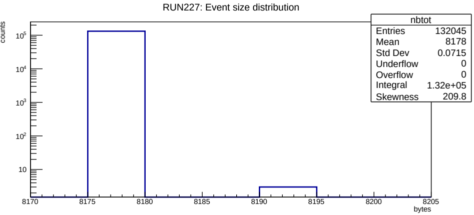
- Reading 1 ROC, which is the equivalent of one panel;
- ROC has 96 channels;
- Generator sends pulses to channels at 250 kHz and 60 kHz;
- We vary the event window which is the equivalent of the difference between proton pulses;
- Event window and generator frequency define the number of *hits per event*;
- ROC buffer has space for 255 hits:
  - $N_{gen} < 255$: $N_{readout} = N_{gen}$;
  - $N_{gen} \geq 255$: $N_{readout} = 255$, because the buffer is already full.

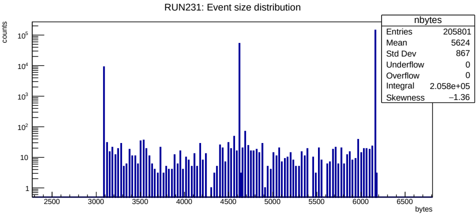
Structure of an event and analysis

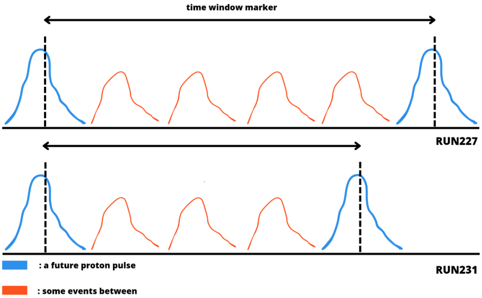


- Analysis of the readout teststands of the motherboard:
  - Sending pulses and trying to understand the output and non-output of the DTC;
  - Validation of event format and failure modes;
  - What rate can we operate and which bandwidth can we reach?

First steps of analysis: event size distribution

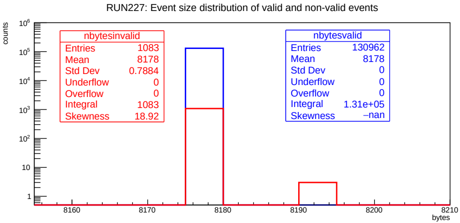


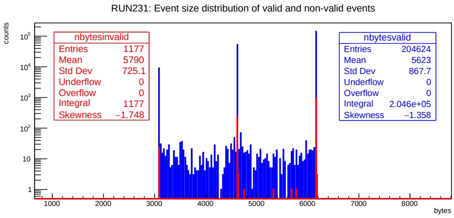




- RUN227 time window: 1000×25 ns;
- RUN231 time window: 300×25 ns;
- Decreasing time window, event size decreases;
- Failure mode: extra 16 bytes event in RUN227;
- Events marked as non-valid;
- RUN231 distribution not yet understood.

Failure mode: events marked as non-valid





Valid event:

```
0x00000000: 0x0c10 0x8050 0x00c0 0x1ba6 0x0000 0x0000 0x0155 0x0000
0x00000010: 0x005b 0x0660 0x1409 0x062e 0x0409 0x0041 0x5a56 0x2565
0x00000020: 0x5a56 0x1565 0x5956 0x1565 0x5956 0x1565 0x5a56 0x1565
0x00000030: 0x0055 0x061b 0x1509 0x07fb 0x0409 0x0041 0x4751 0x0d13
0x00000040: 0x4751 0x351d 0x4751 0x351d 0x4751 0x351d 0x44d1 0x351d
0x00000050: 0x004f 0x07b3 0x1409 0x079b 0x0409 0x0041 0xfabe 0x2bea
0x00000060: 0xf9be 0x2bea 0xf9be 0x2bea 0xfabe 0x2bea 0xfabe 0x1be6
0x00000070: 0x0049 0x064f 0x1409 0x0660 0x0409 0x0041 0x380e 0x00e0
0x00000080: 0x3bf6 0x00e8 0x380e 0x00e0 0x380e 0x00e0 0x380e 0x3f60
```

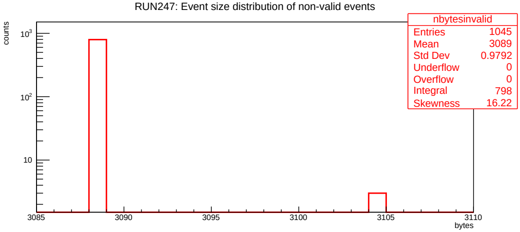
Non-valid event:

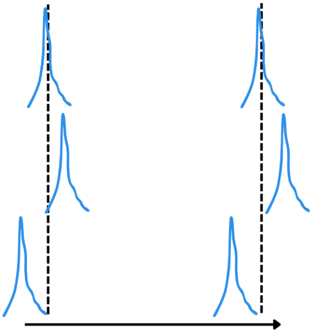
```
0x00000000: 0x0610 0x0050 0x0060 0x1bb7 0x0000 0x0000 0x0155 0x0000
0x00000010: 0x00de 0x5466 0x1408 0x5454 0x0408 0x0041 0x4431 0x231f
0x00000020: 0xc531 0x131c 0xc531 0x2318 0xc631 0x0318 0xc631 0x2310
0x00000030: 0x00d8 0x5475 0x1408 0x5474 0x0408 0x0041 0x87a1 0x1a16
0x00000040: 0x8461 0x2619 0x8561 0x2611 0x8661 0x0611 0x8461 0x0611
0x00000050: 0x00d2 0x5439 0x1408 0x5482 0x0408 0x0041 0xfbbe 0x1be2
0x00000060: 0xf87e 0x07e1 0xfbbe 0x07ee 0xf87e 0x3bee 0xf87e 0x3be1
0x00000070: 0x00cc 0x54cb 0x1408 0x549a 0x0408 0x0041 0xc6f1 0x1f13
0x00000080: 0x2409 0x3f10 0xc7f1 0x3f17 0xc409 0x009f 0xc7f1 0x1f17
```

RUN	nevents	TW [× 25ns]	R/O rate [MB/s]	nvalid [%]
227	132045	1000	0.94	0.82
231	205801	300	0.75	0.57
247	596522	500	2.5	0.19

- Work in progress.

Failure mode: events with extra 16 bytes





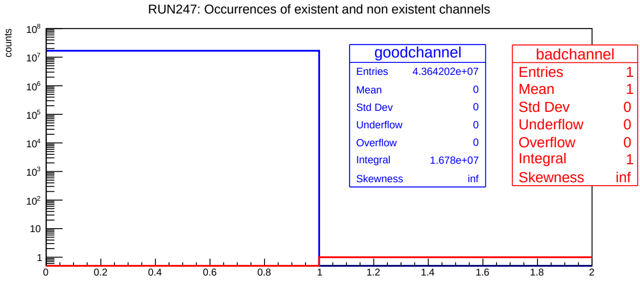
```
0x00000000: 0x0630 0x0056 0x0062 0x49e5 0x005f 0x0000 0x0155 0x0000
0x00000010: 0x005b 0x2058 0x1402 0x2028 0x0402 0x0041 0x5996 0x1966
0x00000020: 0x5996 0x2966 0x5a96 0x1966 0x5b96 0x196e 0x5a96 0x196a
0x00000030: 0x0055 0x2018 0x1502 0x21f4 0x0402 0x0041 0x4591 0x1916
0x00000040: 0x4591 0x191a 0x4791 0x391e 0x4791 0x3916 0x4591 0x1916

...

0x000005e0: 0x67d9 0x3d97 0x67d9 0x3d9f 0xe439 0x0390 0x67d9 0x039f
0x000005f0: 0x0003 0x21eb 0x1402 0x203c 0x0502 0x0041 0xa4a9 0x0a92
0x00000600: 0xa4a9 0x1294 0xa5a9 0x229c 0xa6a9 0x0a9c 0xa729 0x0a9c
0x00000610: 0x008a 0x00e7 0x1400 0x00de 0x0400 0x0041 0x5a96 0x2962
0x00000620: 0x5a96 0x296a 0x5a96 0x0962 0x5896 0x296a 0x5a96 0x296a
```

: CAL1 (not the last)

: HV1 (not the first)

- Studying the time of 0x008a, we find a time of 5 ns;
- We think that we had a timing misallignment between channels.

Failure mode: non existent channels




```
0x00000000: 0x0610 0x8050 0x0060 0x3ac7 0x0104 0x0000 0x0155 0x0000
0x00000010: 0x005b 0xa22d 0x1401 0xa234 0x0401 0x0041 0xa955 0x155a
0x00000020: 0x56aa 0x2aa5 0xa955 0x155a 0x56aa 0x2aa5 0xa955 0x155a
0x00000030: 0x0055 0xa24f 0x1401 0xa241 0x0401 0x0041 0xa955 0x155a
0x00000040: 0x56aa 0x2aa5 0xa955 0x155a 0x56aa 0x2aa5 0xa955 0x155a
0x00000050: 0x004f 0xa27a 0x1401 0xa273 0x0401 0x0041 0xa955 0x155a

...

0x000005b0: 0x000f 0xa239 0x1401 0xa258 0x0401 0x0041 0xa955 0x155a
0x000005c0: 0x56aa 0x2aa5 0xa955 0x155a 0x56aa 0x2aa5 0xa955 0x155a
0x000005d0: 0xa955 0x155a 0x56aa 0x2aa5 0xa955 0x155a 0x56aa 0x2aa5
0x000005e0: 0xa955 0x155a 0x56aa 0x2aa5 0xa955 0x155a 0x56aa 0x2aa5
0x000005f0: 0xa955 0x155a 0x56aa 0x2aa5 0xa955 0x155a 0x56aa 0x2aa5
0x00000600: 0xa955 0x155a 0x56aa 0x2aa5 0xa955 0x155a 0x56aa 0x2aa5
```

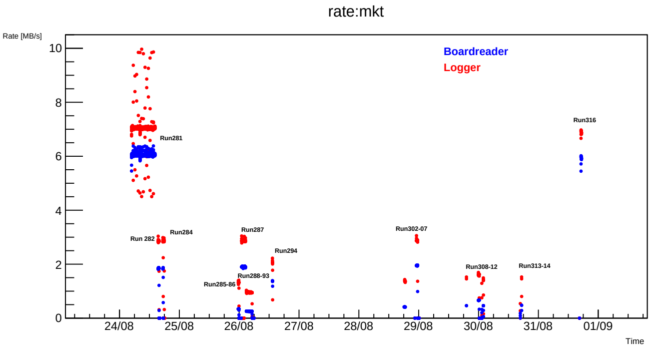
: value greater than 96 channels (green)

: lenght of the event (red)

: repeated pattern (blue)

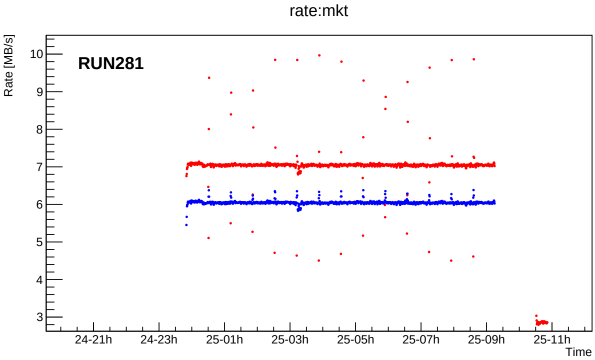
- Something that should be fixed in the firmware, work in progress;
- Few events: at most, in one run, 2 events like this.

Analysis of logger and boardreader rate



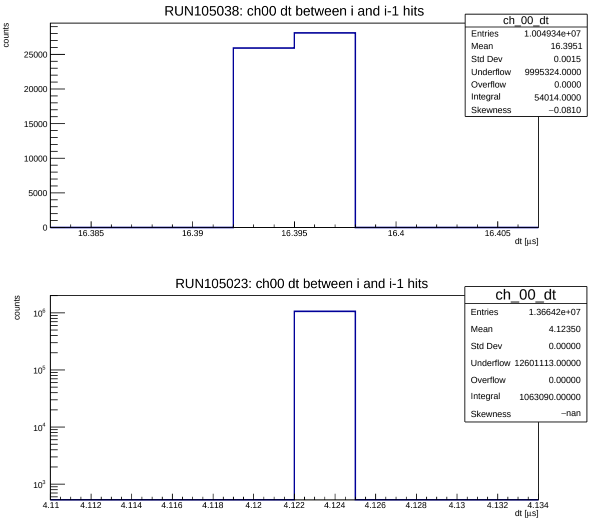
- Rates reported by boardreader (DAQ input) and logger (DAQ output);
- multiple runs, varying:
  - number of ROCs : one or two;
  - number of channels per ROC: 4-96;
  - length of the time window 12.5 - 50 μs.
- $R_{br} < R_l$: work on understanding in progress;

Zooming on each RUN



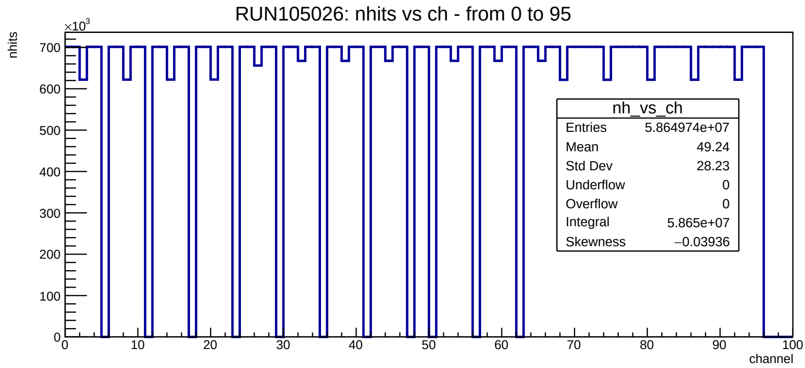
- rate spikes in RUN281 (longest one - 1 ROC): closing output files.
- RUN294: read 2 ROCs with 96 channels each:
  - the rate dropped down by a factor of 3: work in progress.
- 500MB in 13 min → 0.7MB/s but ARTDAQ reports 7MB/s: need to understand why!

Validation of generator frequency



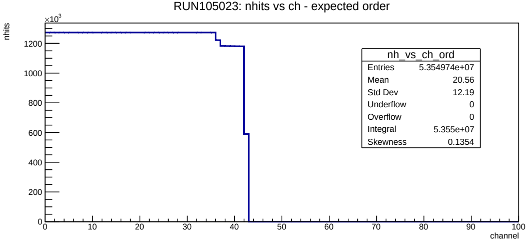
- Generating *hits* in each channel at 31.29 MHz$/(2^7+1)$ and 31.29 MHz$/(2^9+1)$;
- Generator frequency validated with accuracy better than 20 ps.

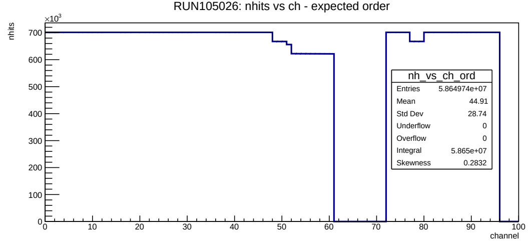
Occupancy: number of hits vs channel number



- Mode of overflowing hit buffer;
- Not a uniform distribution of number of hits vs channels;
- Not the same occupancy for all channels.

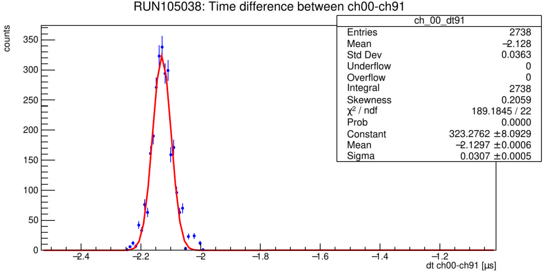
Occupancy: "expected" order

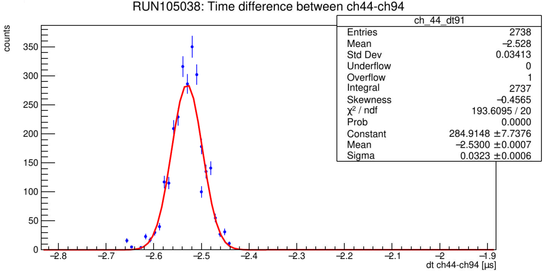




- Tried to change event window and frequency;
- We expected that the buffer gradually fills with channels;
- Probably channels are in a different order.

Calibration of the time difference between channels





- time difference between ch00 and ch91 (first channel of first FPGA);
- time difference between ch44 and ch94 (first channel of second FPGA).

Monte Carlo simulation of the DAQ system

- From 0 μs to $1/f_G$ μs: creation of the first event (t_0) (uniform distribution);

- Hits from the same channel are separated by $1/f_G$ μs: creation of the second event (t_1), adding to t_0 this quantity;

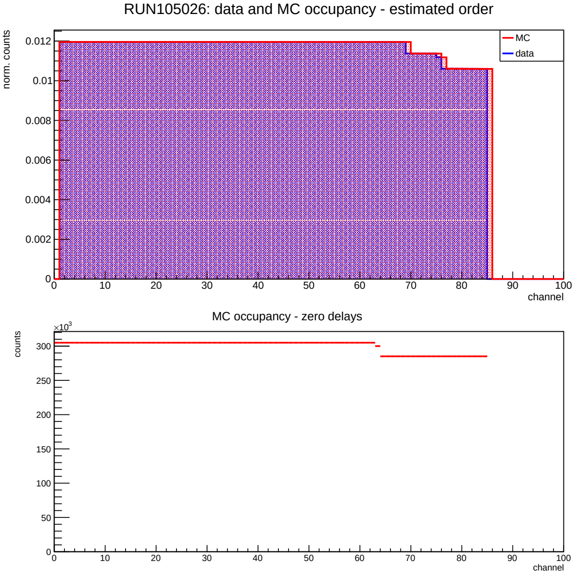
- If the second pulse is cointained in the time window, we add this hit in the event we are building;

- As soon as we reach 255 hits we stop the fill;

- Changing time window and generator frequency, to better compare each RUN with the simulation and adding FPGAs offsets and channel to channel offsets.

Monte Carlo simulation: results

Channels are not ordered as we expected.



Conclusions and goals

- **What did we find and understand?**
  - Structure of a valid event;
  - Different event size distributions;
  - 3 types of failure modes;
  - Analysis of logger and boardreader;
  - Generator frequency has been validated;
  - Analysis of the occupancy and comparison with MC;
  - Delays between channels.
- **Short/Mid-term:**
  - We are now able to read 1MB/s (1 DTC and 1 ROC): our goal is to read 600MB/s with one DTC!
  - Running tests on one station or more;
  - Late fall-early winter: Vertical Slice Test;
- **Long-term:**
  - Integrating the DAQ system in the whole experiment.

Thank you for your attention!

Bibliography

[1] Abdi et al.
Mu2e run i sensitivity projections for the neutrinoless $\mu^- \to e^-$ conversion search in aluminum.
2021.

[2] Gioiosa et al.
Slow control and data acquisition development in the mu2e experiment.
2021.

[3] MyeongJae Lee.
The straw-tube tracker for the mu2e experiment.
2016.