PDS trigger rate estimation in ProtoDUNE-HD using the full ProtoDUNE-SP simulation

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NP04 PDS data taking planning

21/03/2024

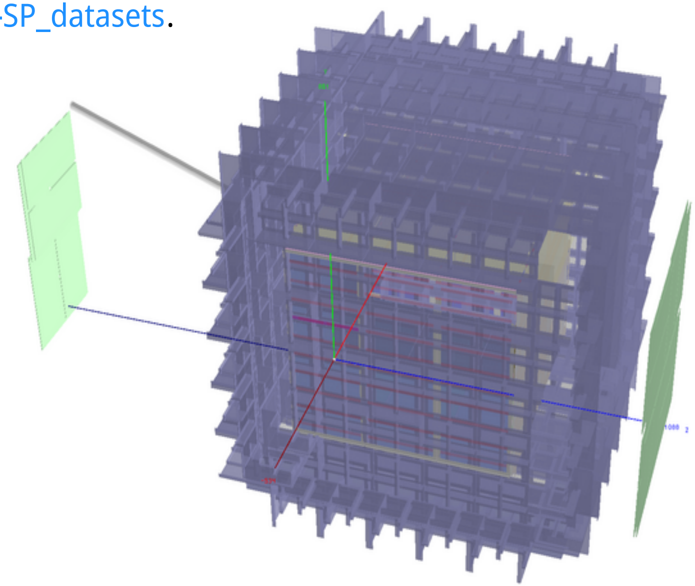
Cosmic-induced light in the ProtoDUNE-SP PDS

- Triggered by the needs of the DAQ group for ProtoDUNE-HD Run II we were asked to provide a more detailed **assessment of cosmic-induced light in the ProtoDUNE PDS**.
- In order to face this task it is possible to use a full-fledged **cosmic ray simulation** based on **Corsika** embedded in the **ProtoDUNE Run I geometry**.
- The MC production used in this work is the one employed for the paper titled "**Identification and reconstruction of low-energy electrons in the ProtoDUNE-SP detector**".
- The PDS modules embedded for Run I are **light guide bars + ARAPUCA** instead of the new X-ARAPUCA ones.

- The dataset definitions can be found at https://wiki.dunescience.org/wiki/ProtoDUNE-SP_datasets.
- The dataset I specifically used is listed with the following names :

PDSPProd2_MC_1GeV_reco_sce_datadriven

which consists of mostly cosmic rays and 1 GeV beam particles on per event basis.



Trigger rate of a PDS module

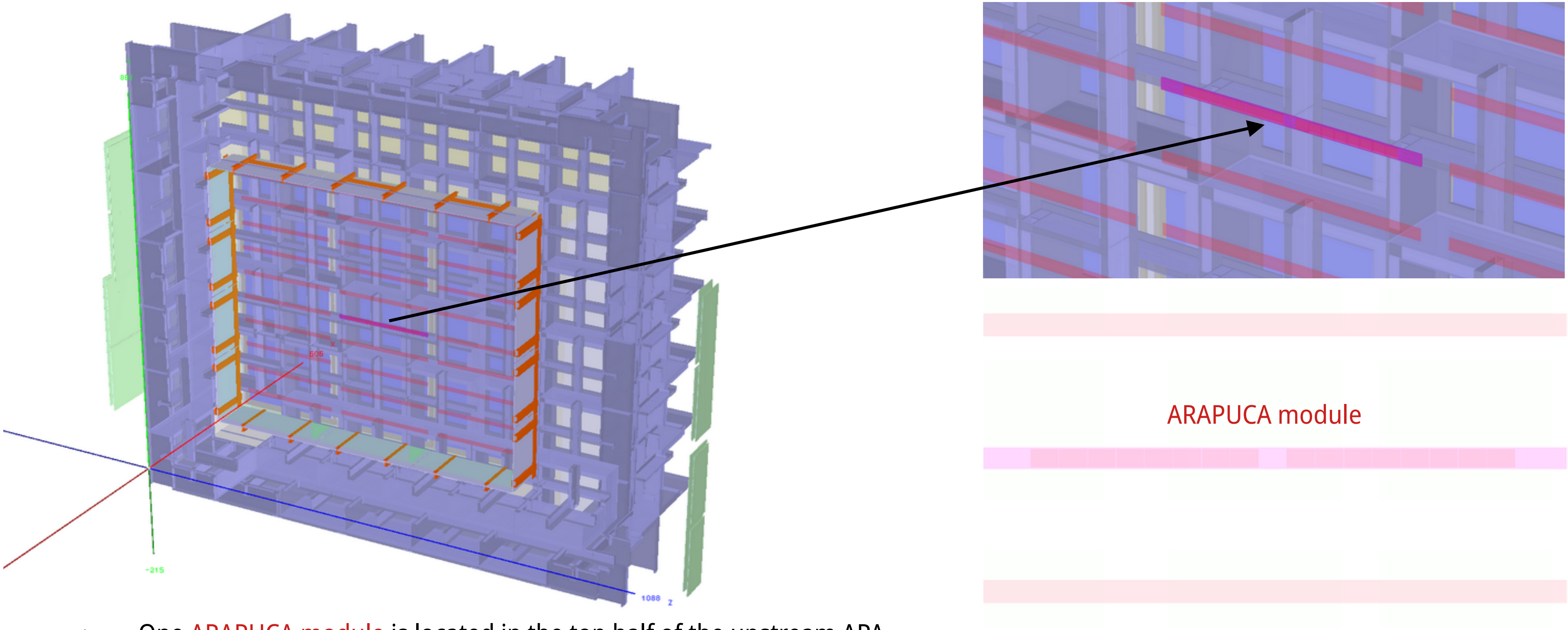
- The aim of this work is to provide an **estimate** of the **trigger rate** of **PDS SuperCells due to cosmic-induced light**.
- The ProtoDUNE-HD PDS for Run II will be based on **X-ARAPUCA light traps** instead of light guide bars + ARAPUCA.
- A **PDS module** is made by **4 SuperCells**.

- Taking into account that the overall photon detection efficiency (PDE) of a SuperCell is 3%, one wonders :
  - how many photons are detected on a SuperCell when a cosmic muon passes by ?
  - what is the expected SuperCell trigger rate due to light produced by the crossing of muons in the active volume ?

- Using a cosmic ray simulation embedded in the ProtoDUNE Run I geometry I could only provide an **estimate of the trigger rate of PDS modules**, and **not** the one for **individual SuperCells** (i.e. PDS channels).
- Anyway, the **trigger rate of a PDS module** can be considered as an **upper limit to SuperCell trigger rate**.

Optical Detectors

- The number of **Optical Detectors** in the simulation is **90**, whereas the total number of PDS modules in ProtoDUNE-SP is **60**.
- Indeed, in the simulation there are 2 PDS modules made by **16 ARAPUCA cells**.

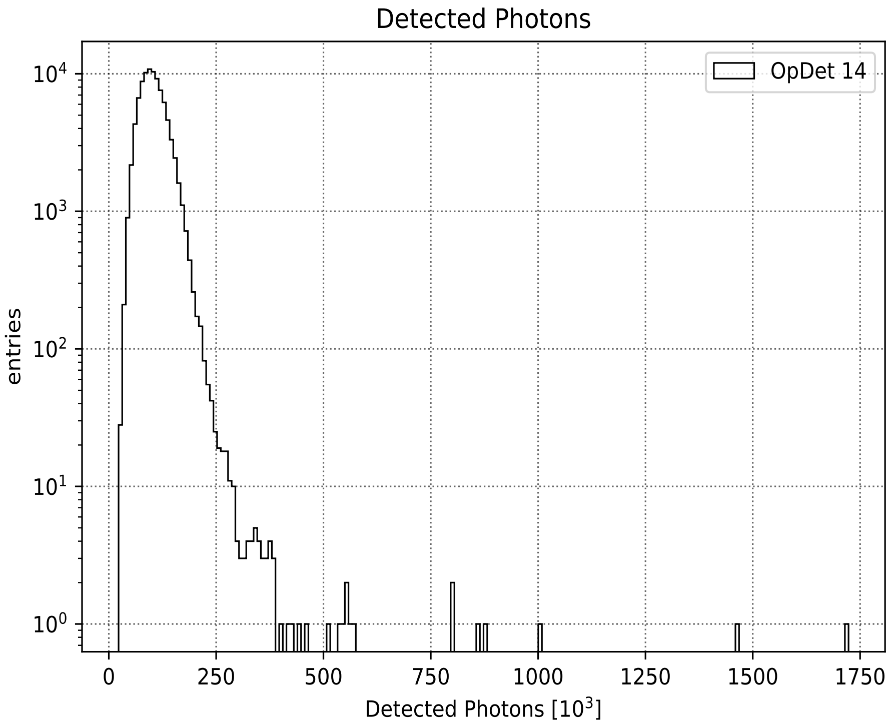


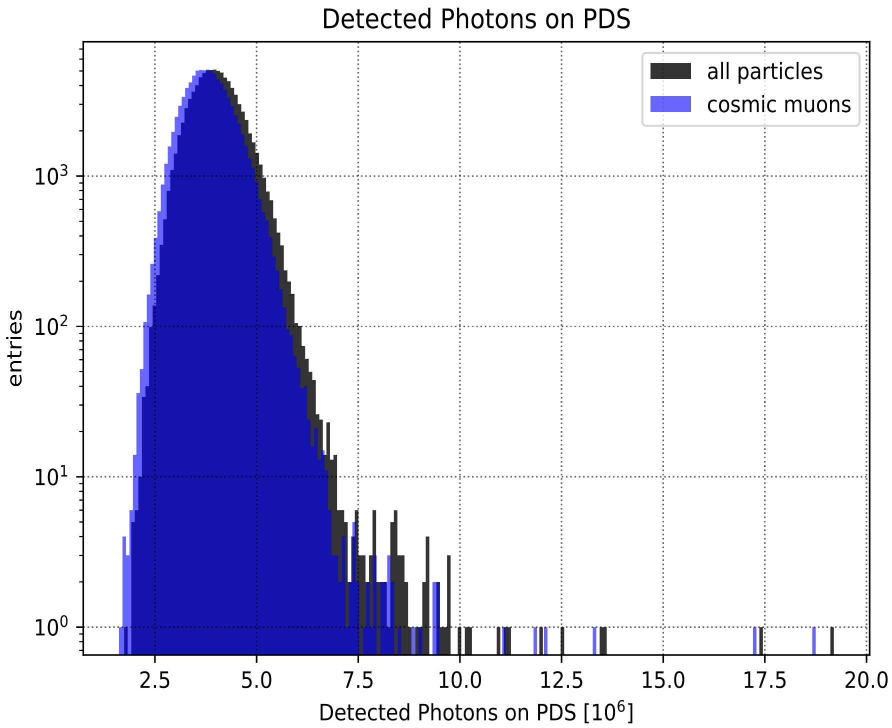
- One ARAPUCA module is located in the top half of the upstream APA in the beam-side drift volume. A second is located in the middle of the APA in the center of the opposite drift volume.

2 virtual PDS modules created merging info from the corresponding 16 ARAPUCA cells.

Detected Photons on PDS due to cosmic muons

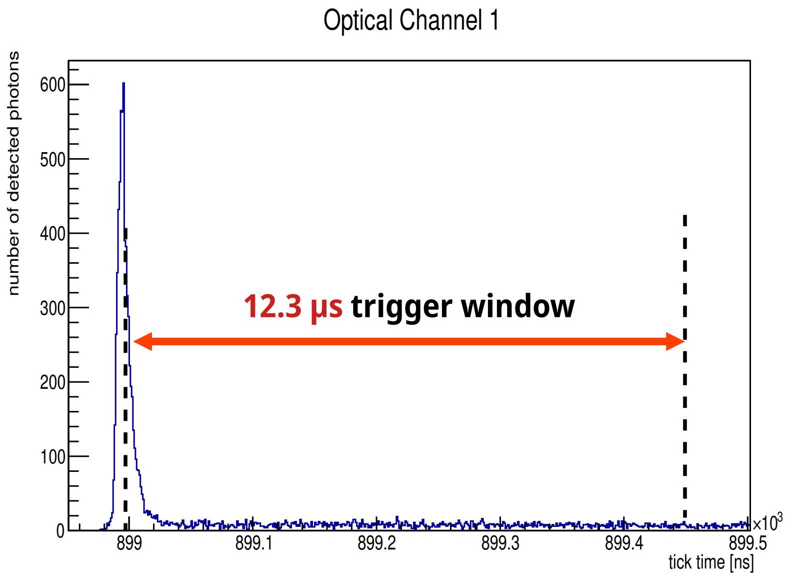
- The **sim::SimPhotonsLite** is a compact representation of photons on a channel.
- This object contains only the **total count of photon arriving at a certain time on the channel**. **The time is discretized in ticks**.
- Detected Photons on Optical Detectors due to cosmic muons.
- Using **OpDetBackTrackerRecord** to match optical photons arriving at Optical detector with its MCTruth cosmic primary.

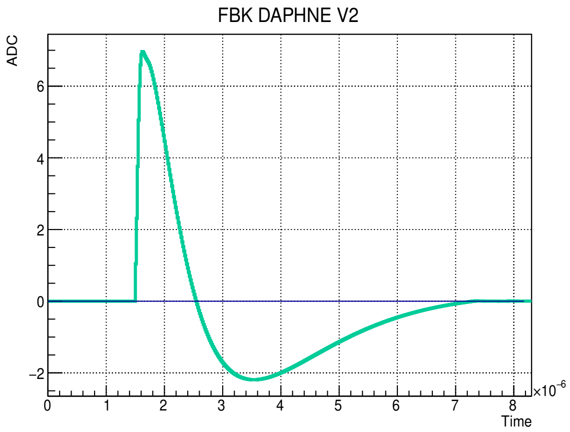




Trigger Counter

- The PDS SuperCells have a **photon detection efficiency** (**PDE**) of **3%**.
  - Given the number of photons arriving at each Optical Detector it is thus possible to estimate on average the fraction of photons detected by a PDS module and the corresponding average number of photo-electrons.
- The **trigger threshold** is set to **1.5 photo-electrons (p.e.)**.
- I have considered a **trigger window** of **12.3 μs** (**DAPHNE**) → to be update w/ the **16.4 μs waveform length**
- The **SiPM time response to s.p.e.** can be taken into account using an **integration window**.
  - it is set to **500 ns**., that is half the SiPM response time to s.p.e.

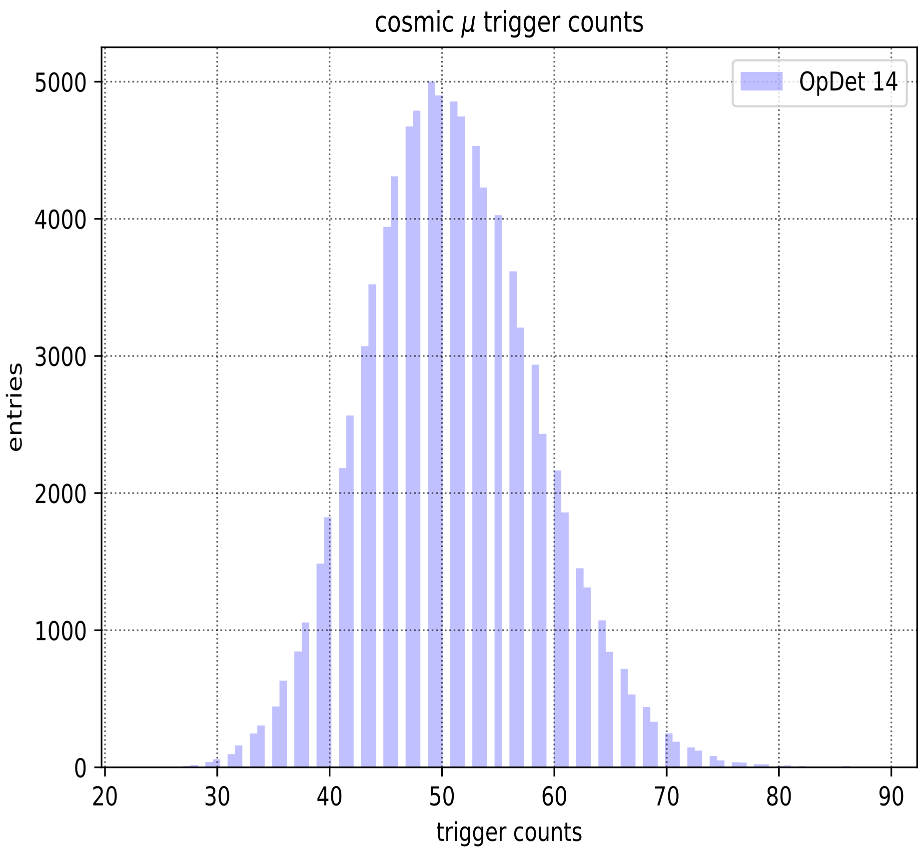


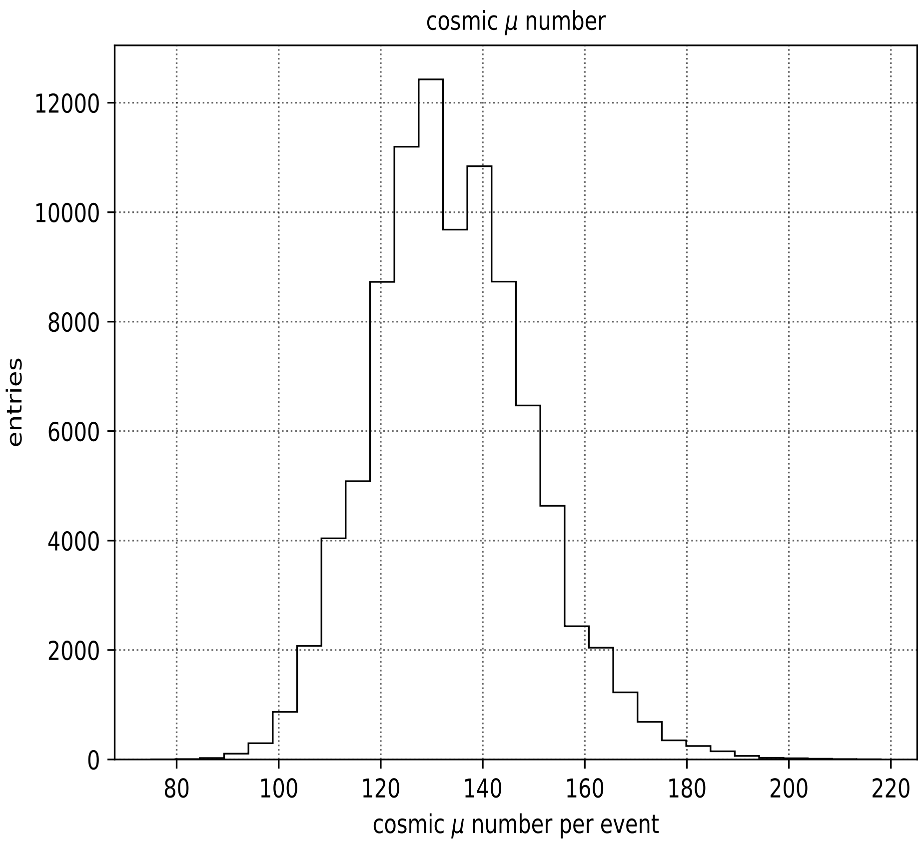


From M. Delgado **PDS Deconvolution & OpHit Finder** talk @ DUNE Collab. Meeting September 2023

Trigger count on Optical Detectors

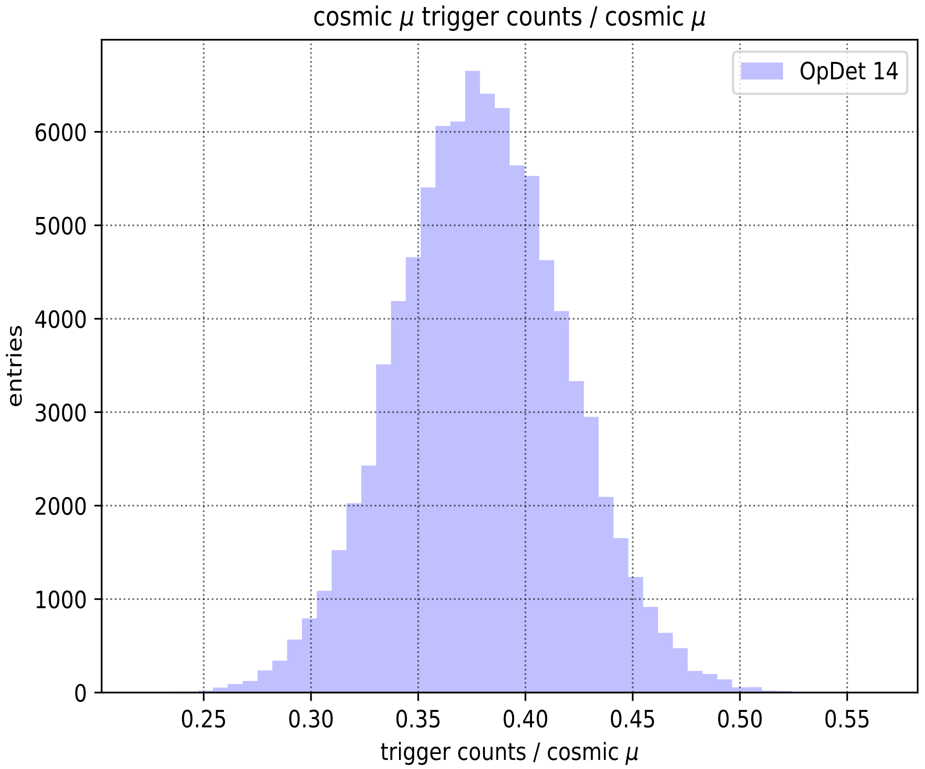
- Trigger count on Optical Detectors due to **cosmic muons**.

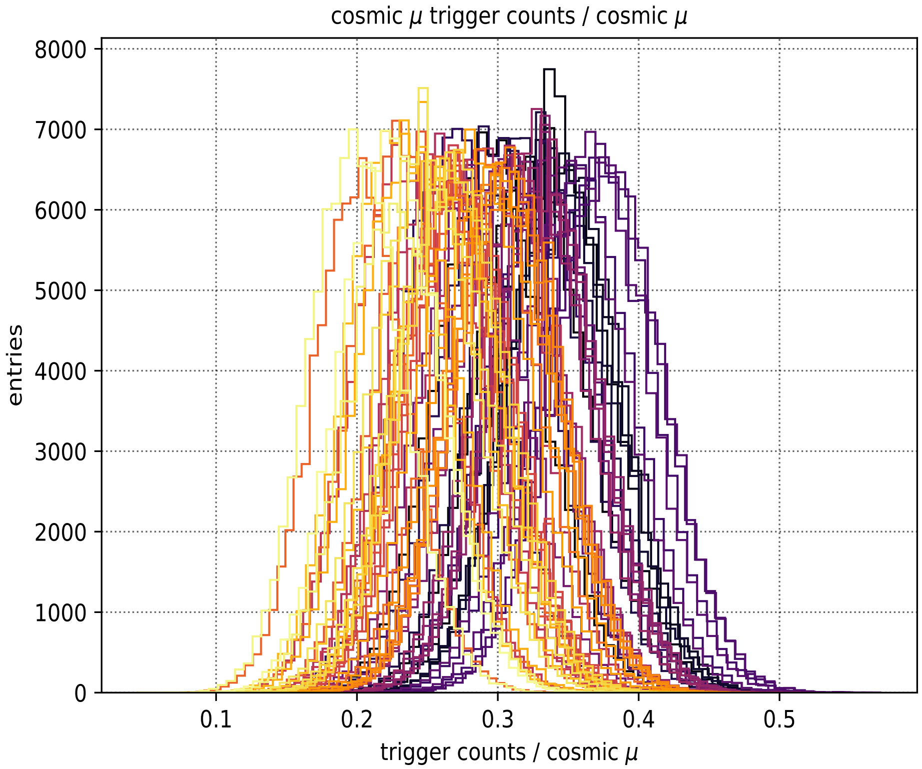




PDS trigger probability

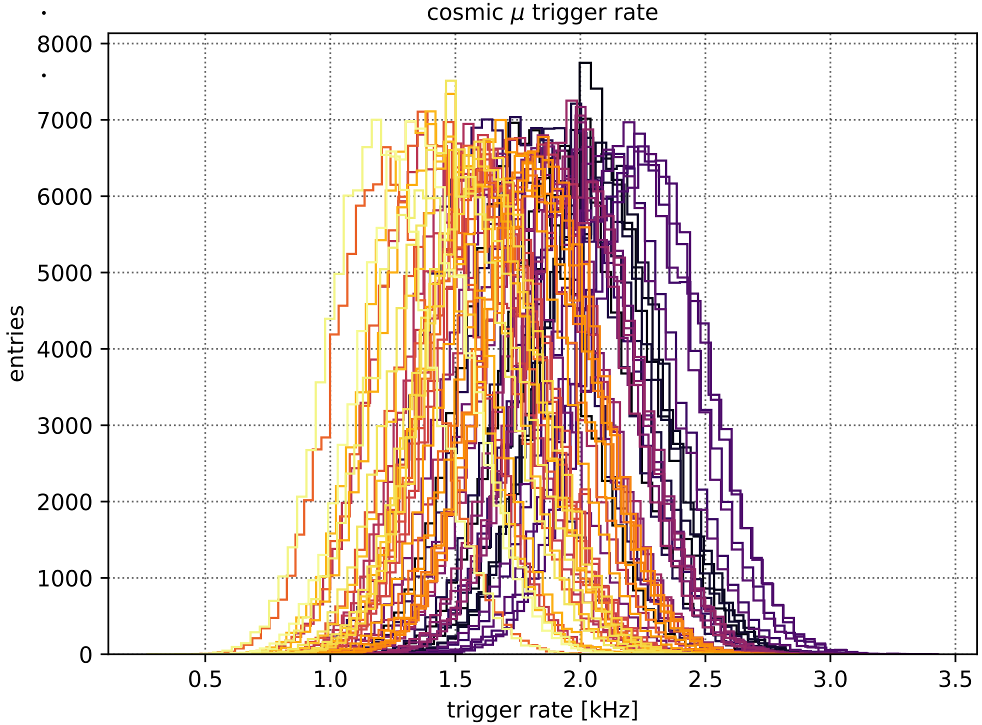
- The **PDS trigger probability** is the probability than a muon crossing ProtoDUNE volume fires an Optical Detector.
- The trigger probability is computed as the ratio of the recorded trigger counts to the number of cosmic muons producing optical photons.





PDS trigger rate due to cosmic muons

- The **muon rate** at sea level is about **1 cm^{-2} min^{-1}** for a thin horizontal detector.
  - **cosmic μ rate** = 166.7 Hz / m^2
  - the upper surface of the ProtoDUNE LAr active volume is **6 x 6 m^2** .
  - the expected mean trigger probability due to cosmic muons for a single PDS module is ~ 30%



The **PDS trigger rate** due to cosmic muons is expected to be about :

0.3 trigger / μ x 167 μ s^{-1} m^{-2} x 36 m^2 = **1.8 kHz**

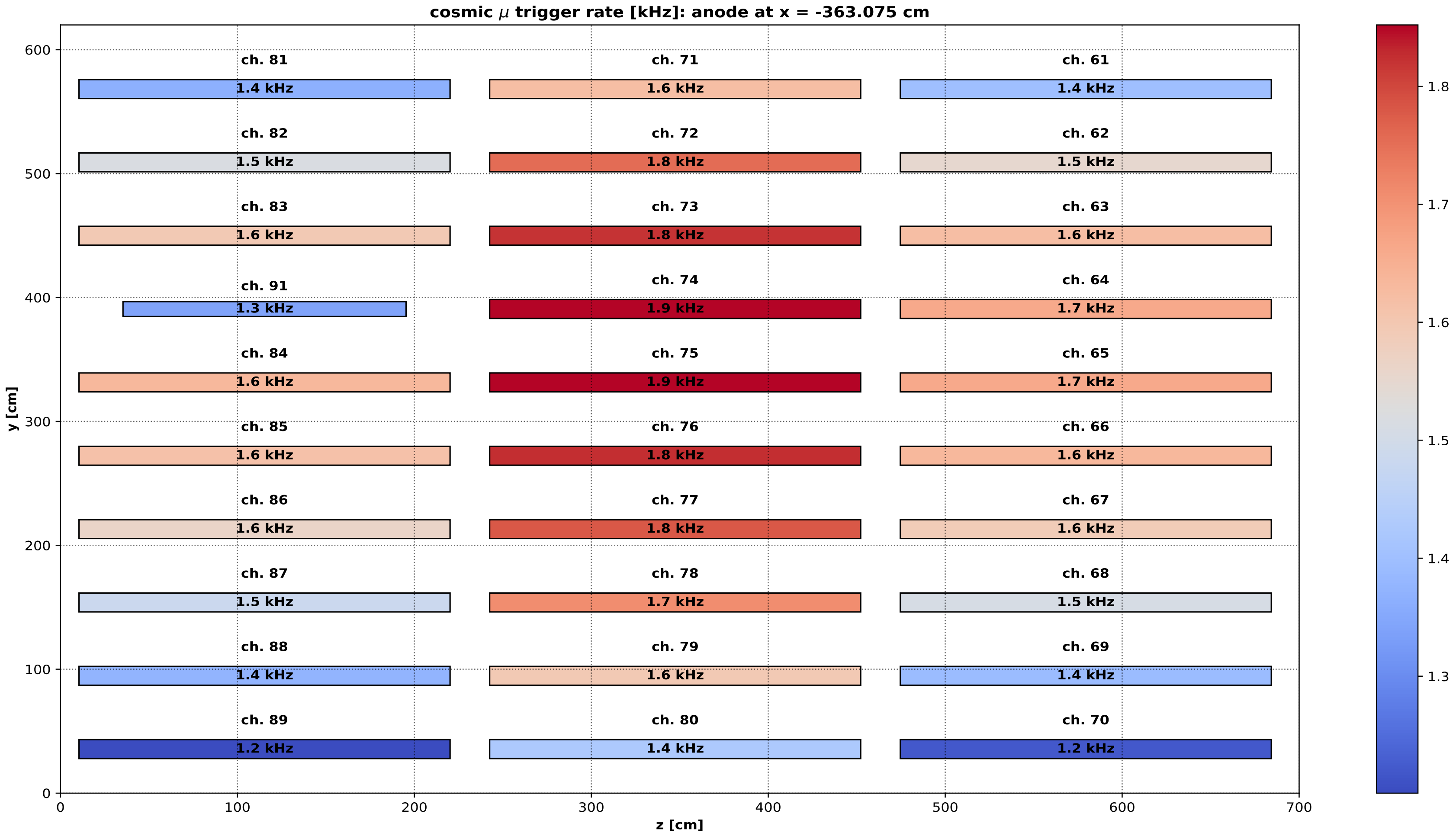
Since the trigger probability due to cosmic muons ranges from 0.1 to 0.5, one could expect a trigger rate due to cosmic muons spanning from **0.6** to **3 kHz**.

The expected data flux can be computed according to :

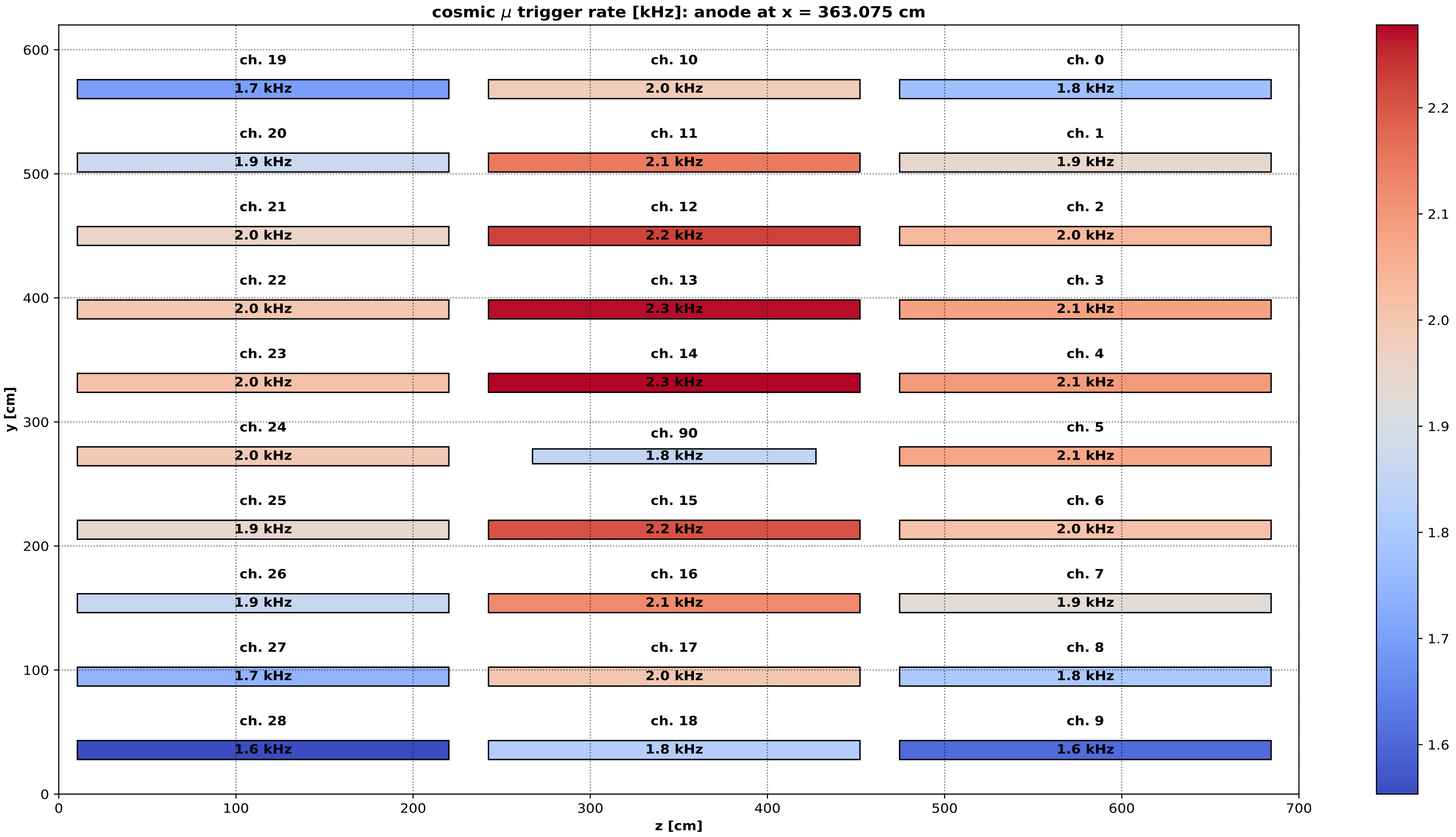
32 bit x 454 rows x 40 channels x trigger rate

w/ mean **1.05 Gb/s**, spanning from **0.35 Gb/s** to **1.74 Gb/s**

PDS trigger rate due to cosmic muons : anode display

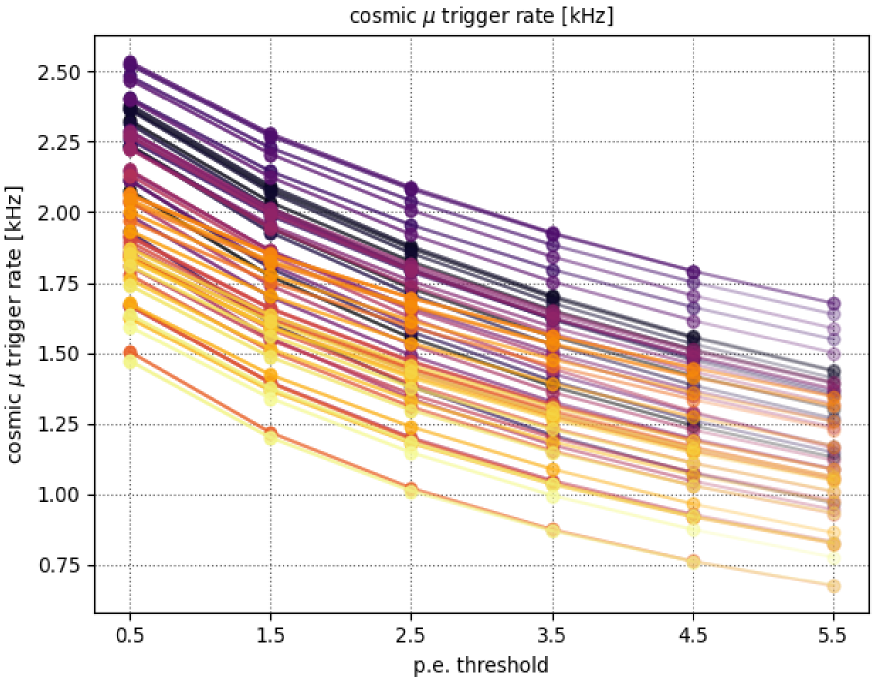


PDS trigger rate due to cosmic muons : anode display

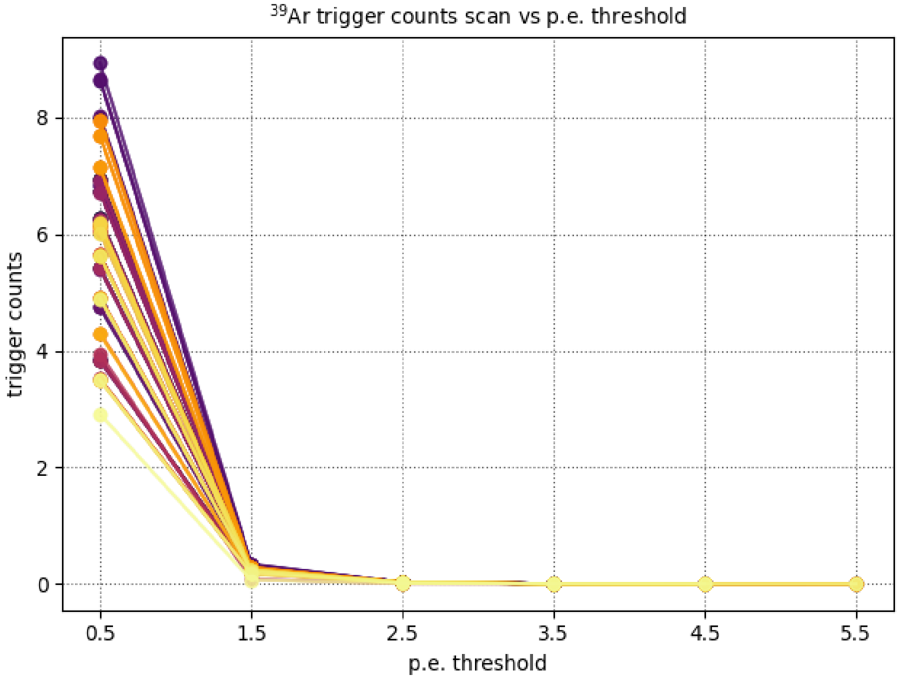


Trigger rate with increasing photo-electron threshold

trigger rate as function of p.e. threshold



cosmic μ



^{39}Ar

Conclusion and next step

- A first preliminary estimate of the **PDS trigger rate** due to cosmic muons was provided using Corsika in ProtoDUNE-SP Run I geometry :
  - The trigger rate due to cosmic muons is expected to be **~1.8 kHz**, spanning from **0.6** to **3 kHz**.
  - The expected data flux is **1.05 Gb/s**, spanning from **0.35 Gb/s** to **1.74 Gb/s**
  - Since computed for a **PDS module**, this is can be considered an **upper limit** **for the trigger rate of a SuperCell channel**.
- Scan of trigger rate vs increasing p.e. threshold.
- Next step :
  - run a small **Corsika** simulation using the **ProtoDUNE-HD geometry**.

Backup

DAPHNE streaming capabilities

- The DAPHNE bandwidth is 4.8 Gb/s.
- The trigger rate due to cosmic muons spans from 0.6 kHz to 3 kHz.
- The expected data flux can be computed according to :
  - 32 bit x 454 rows x 40 channels x trigger rate
- The estimated data flux is expected to have a mean value of **1.05 Gb/s**, spanning from **0.35 Gb/s** to **1.74 Gb/s**.

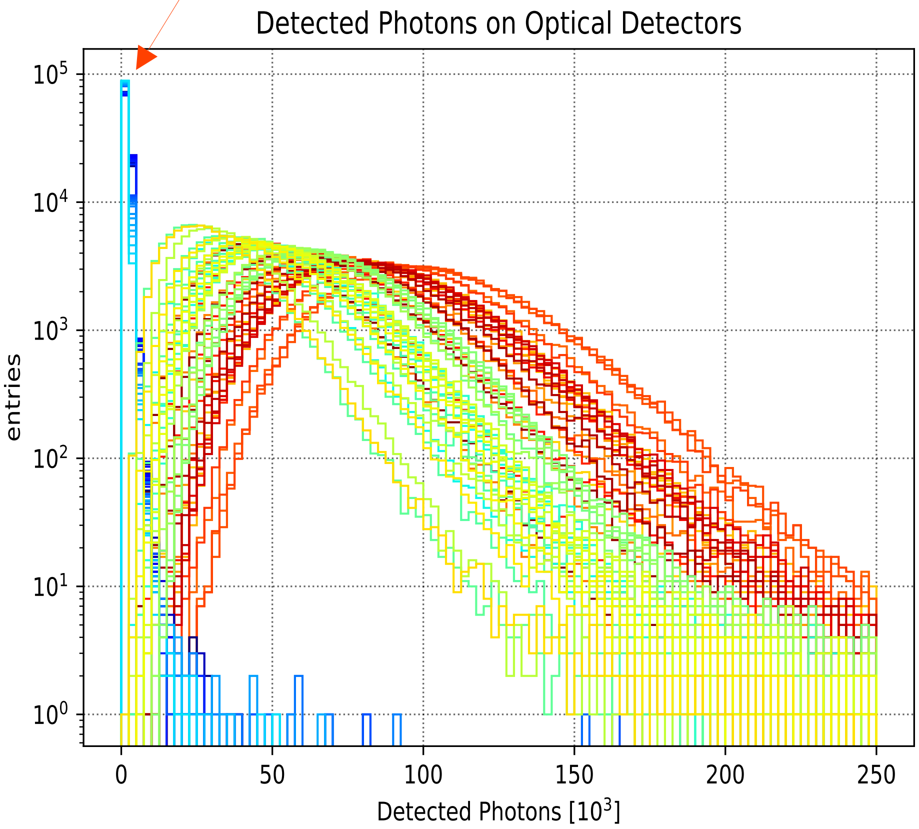
	K/D	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	Link						Slot				CrateID										DetID						Version					
1	0000	Timing master Time stamp [31:0]																															
2	0000	Timing master Time stamp [63:32]																															
3	0000	Time_Pulse_UB (10 bits, so 6 high order bits are 0)																Time_Peak (8 bits, so 2 high order bits are 0)										Channel					
4	0000	Max_Peak																Time_Pulse_0B (11 bits, so 5 high order bits are 0)															
5	0000	ADC([3:0],2)				ADC([13:0],1)														ADC([13:0],0)													
6	0000	ADC([7:0],4)								ADC([13:0],3)														ADC([13:4],2)									
7	0000	ADC([11:0],6)												ADC([13:0],5)														ADC([13:8],4)					
8	0000	ADC([1:0],9)		ADC([13:0],8)														ADC([13:0],7)														ADC([13:12],6)	
9	0000	ADC([5:0],11)						ADC([13:0],10)														ADC([13:2],9)											
10	0000	ADC([9:0],13)										ADC([13:0],12)														ADC([13:6],11)							
11	0000	ADC([13:0],15)														ADC([13:0],14)														ADC([13:10],13)			
...	0000	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
446	0000	ADC([3:0],1010)				ADC([13:0],1009)														ADC([13:0],1008)													
447	0000	ADC([7:0],1012)								ADC([13:0],1011)														ADC([13:4],1010)									
448	0000	ADC([11:0],1014)												ADC([13:0],1013)														ADC([13:8],1012)					
449	0000	ADC([1:0],1017)		ADC([13:0],1016)														ADC([13:0],1015)														ADC([13:12],1014)	
450	0000	ADC([5:0],1019)						ADC([13:0],1018)														ADC([13:2],1017)											
451	0000	ADC([9:0],1021)										ADC([13:0],1020)														ADC([13:6],1019)							
452	0000	ADC([13:0],1023)														ADC([13:0],1022)														ADC([13:10],1021)			
453	0	TBD				Number_Peaks_0B				Number_Peaks_UB				Charge[19:0]																			

From Manuel Arroyave's talk @ ProtoDUNE PDS Sim/Reco meeting 18/03/2024

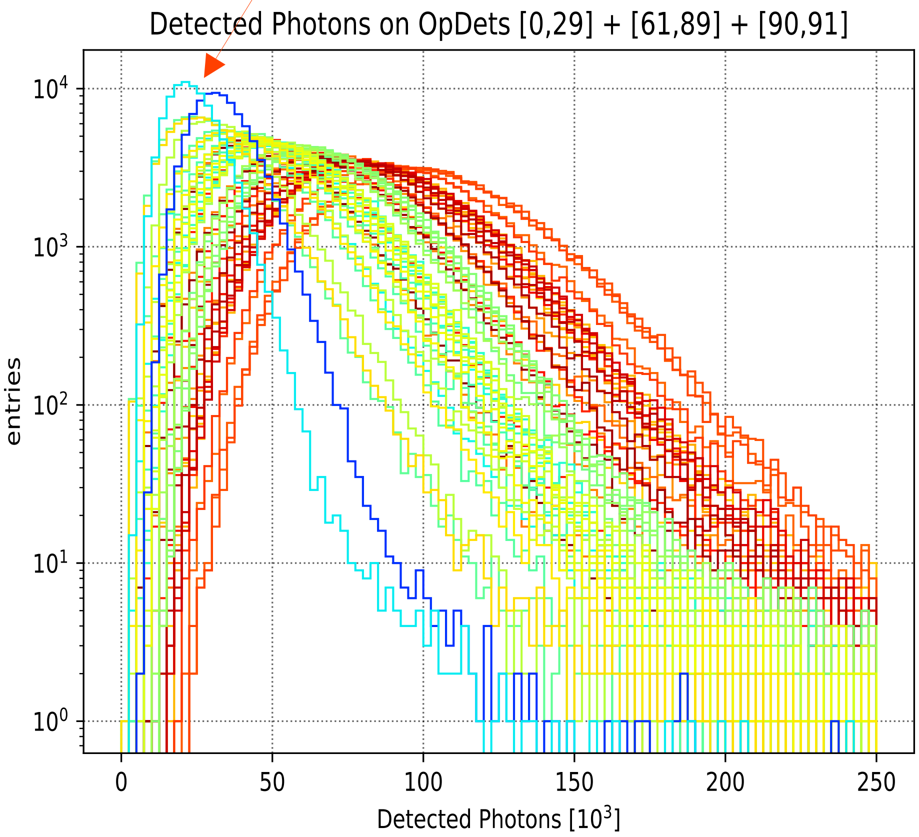
Detected photons on PDS

- Detected photons on Optical detectors.

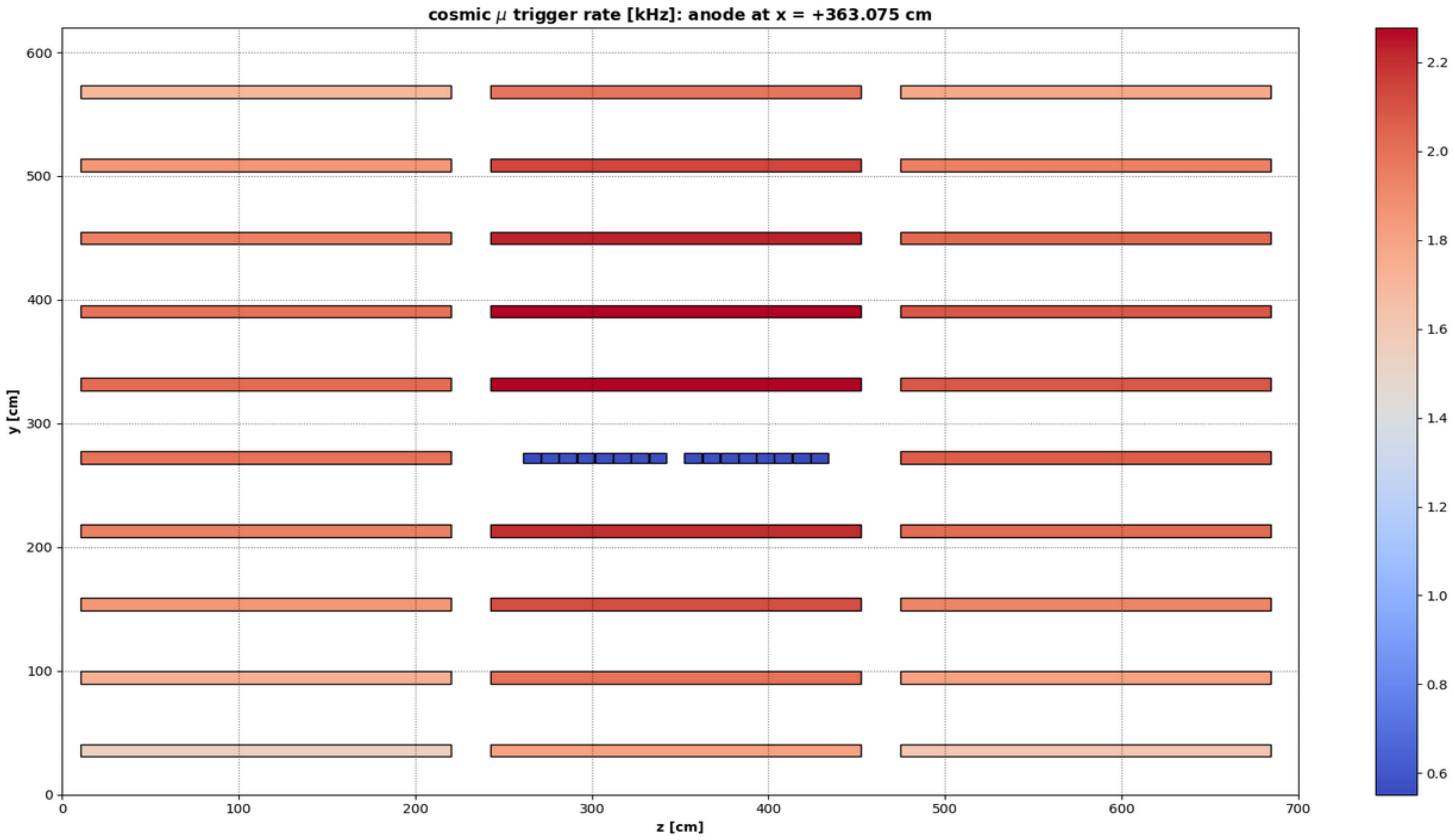
ARAPUCA cells



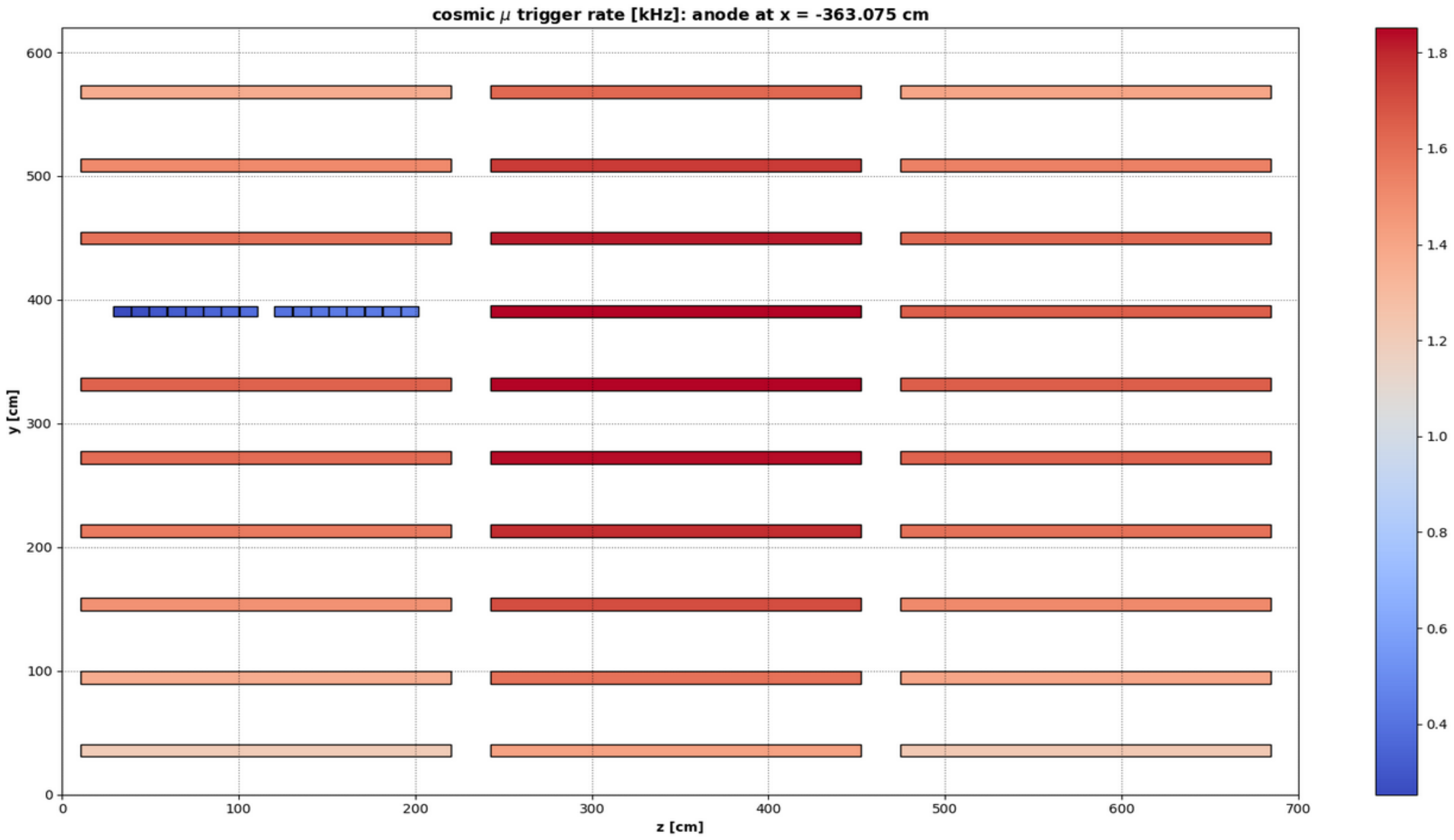
2 virtual PDS modules



PDS trigger rate due to cosmic muons : anode display

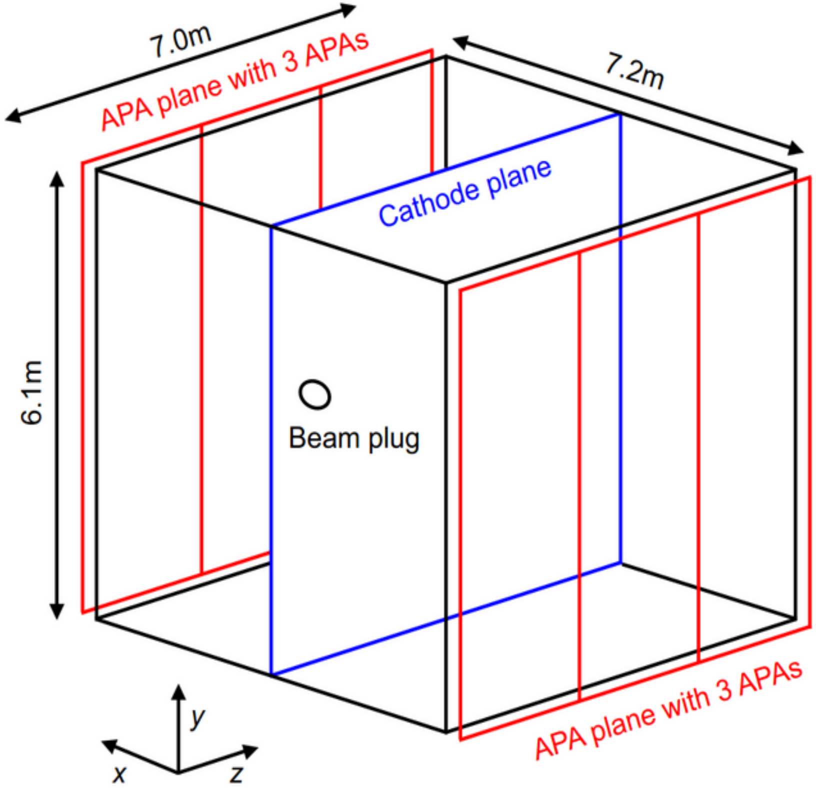


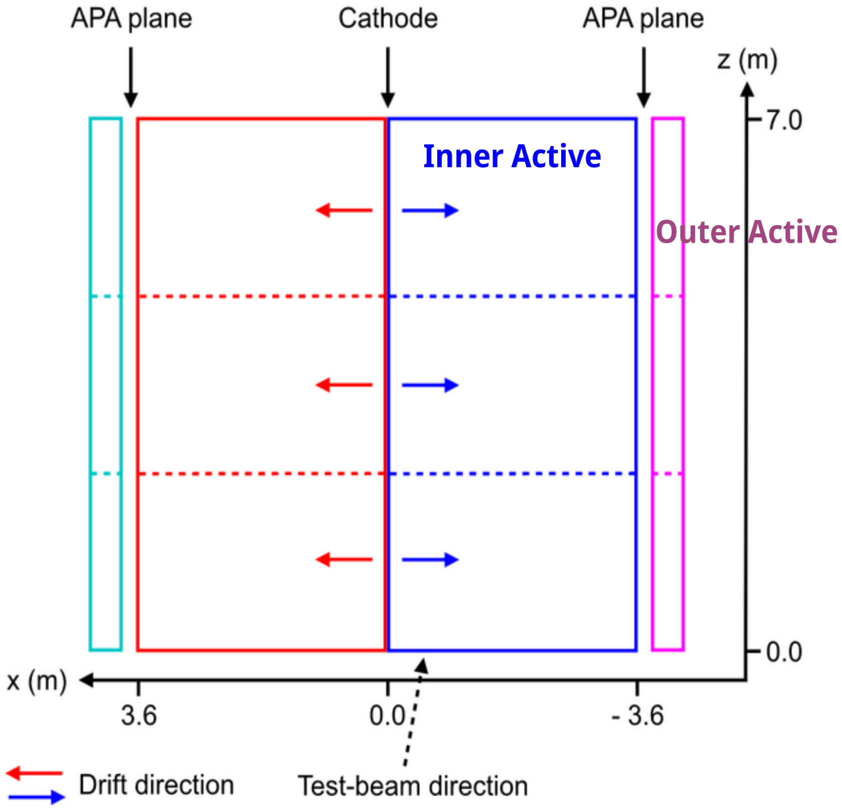
PDS trigger rate due to cosmic muons : anode display



ProtoDUNE-SP geometry [cont'd]

- The origin is located at x=0 at the cathode, y=0 on the bottom of the APA's, and z=0 on the upstream edge of the most upstream APA, so that z coordinates are all positive.
- Geometry schemes are taken from the paper Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora.





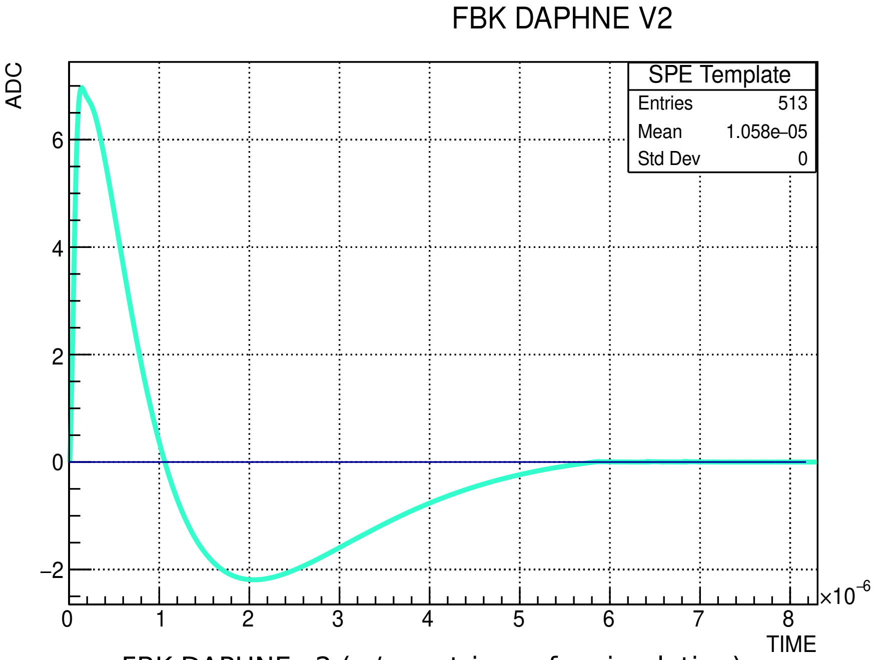
Optical Detectors [cont'd]

- There are **58** Optical Detectors with geometrical dimensions :
  - Length = 209.683 cm
  - Width = 0.476 cm
  - Height = 10.16 cm
- Their IDs are in range [0,28] for those placed at x = 363.075 cm and in range [61,89] for those placed at x = - 363.075 cm.

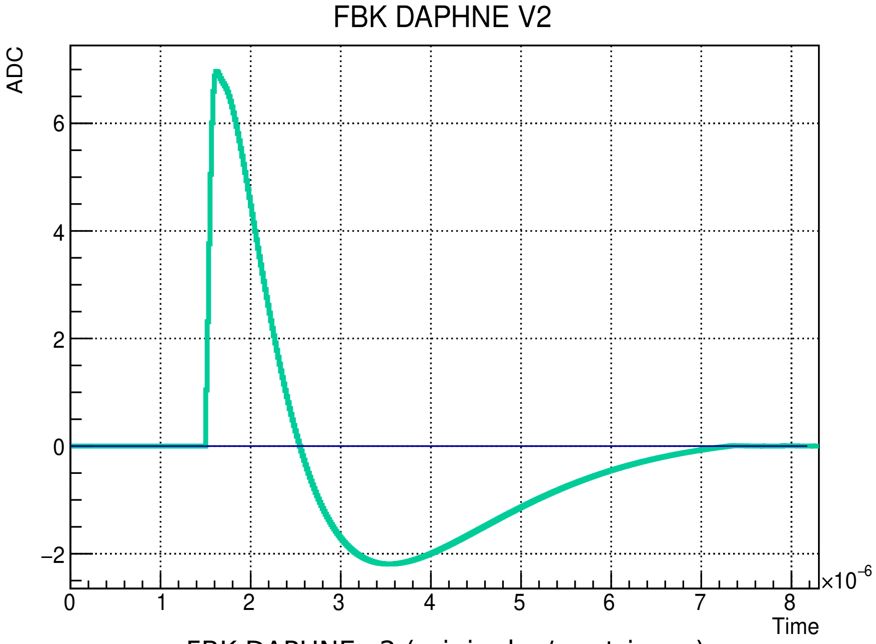
- There are **32** Optical Detectors with geometrical dimensions :
  - Length = 10 cm
  - Width = 0.1 cm
  - Height = 8 cm
- Their IDs are in range [29,44] for a PDS module centered at x = 362.335 cm and y = 272.292 cm and in range [45,60] for a PDS module centered at x = - 362.335 cm and y = 390.692 cm.

Trigger Counter : SiPM time response to single p.e.

- In case only a single p.e. is detected, the PDS would not be triggered since the 1.5 p.e. threshold is not exceeded.
- However, it is important also to take into account the **SiPM time response to single photo-electrons (s.p.e.)**.
- Indeed, if subsequent p.e. were detected within the typical **SiPM time response to single p.e.**, they would be acquired piled-up with the former s.p.e., thus possibly contributing to the trigger if their sum exceed the threshold.



FBK DAPHNE v2 (w/o pretrigger for simulation)

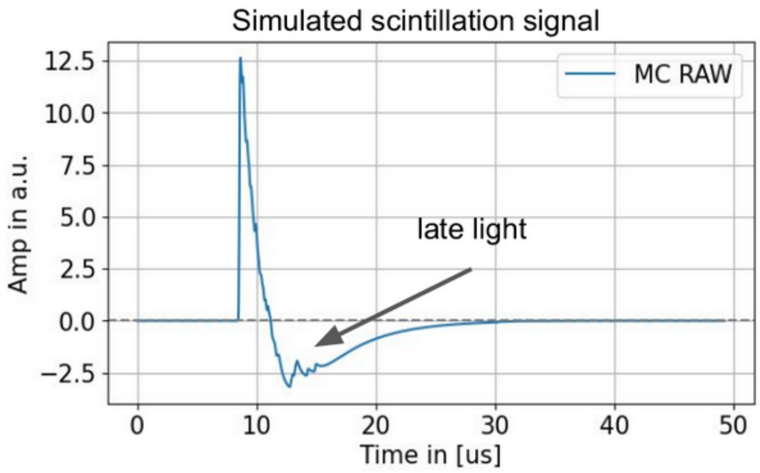


FBK DAPHNE v2 (original w/ pretrigger)

From Maritza Delgado

MOTIVATION

- DUNE X-ARAPUCA signals **will have undershoot** (bipolar signals).
- **Larsoft signals were unrealistic** and the **reconstruction stage** was not optimized for bipolar waveforms.
- To fully **estimate the total charge and time** of each pulse, a deconvolution needs to be implemented.
  - Especially important for **scintillation signals**!
- A deconvolution approach is needed and should provide:
  - Scintillation time profiles.
  - Charge and arrival time reconstruction.

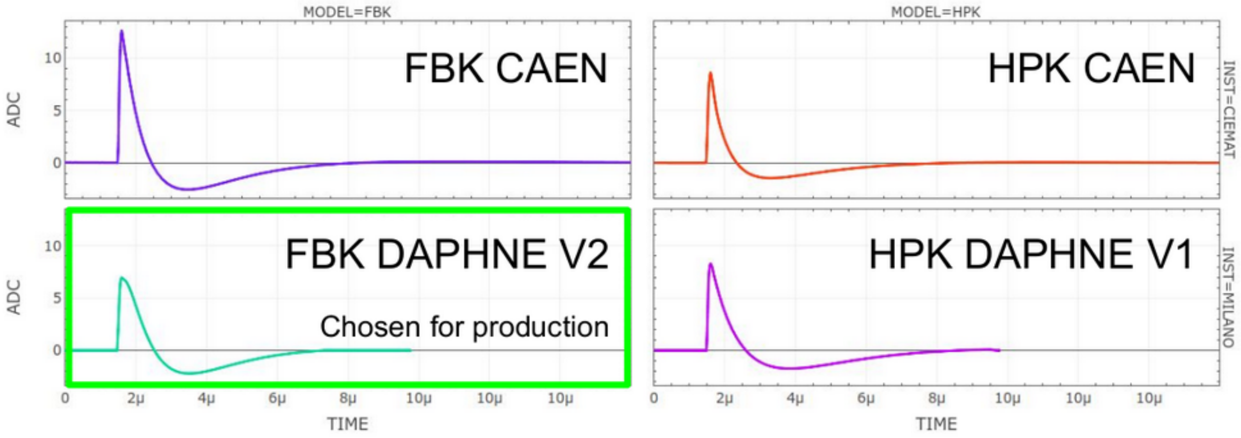


DIGITIZER UPDATES

- **Digitizer module** provides option to include pulse **SPE template from version v09_60_01.**
- Included in the final version of the Digitizer/Deconvolution modules the following templates:
  - 2x CAEN digitizer and the Cold Amplifier (XArapuca with 48 SiPM FBK/HPK)
  - 2x Cold amplifier coupled with DAPHNE (XArapuca with 48 SiPM FBK/HPK)
- **OpHitFinder** has been updated to deal with deconvoluted waveforms.

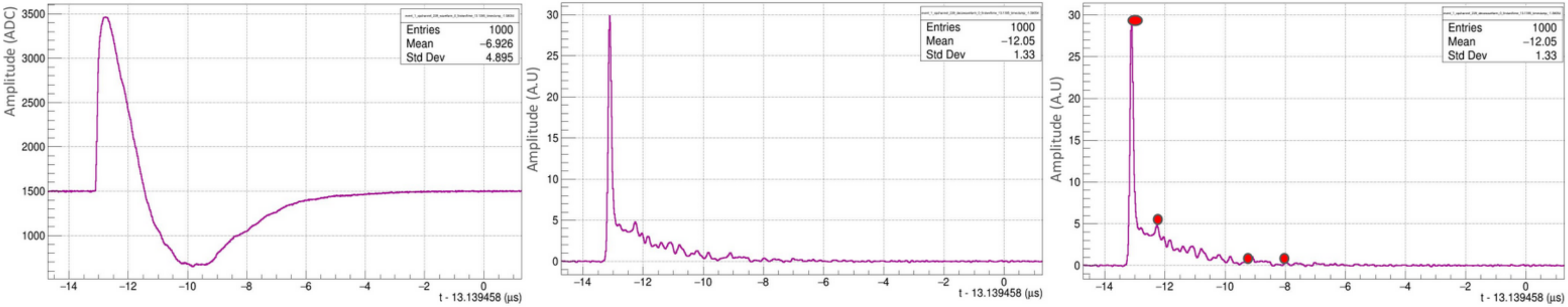
Figures of merit:

- Wvf amp ~8 ADC.
- Pulse width ~1us.
- All wvf evaluated at 45% PDE.



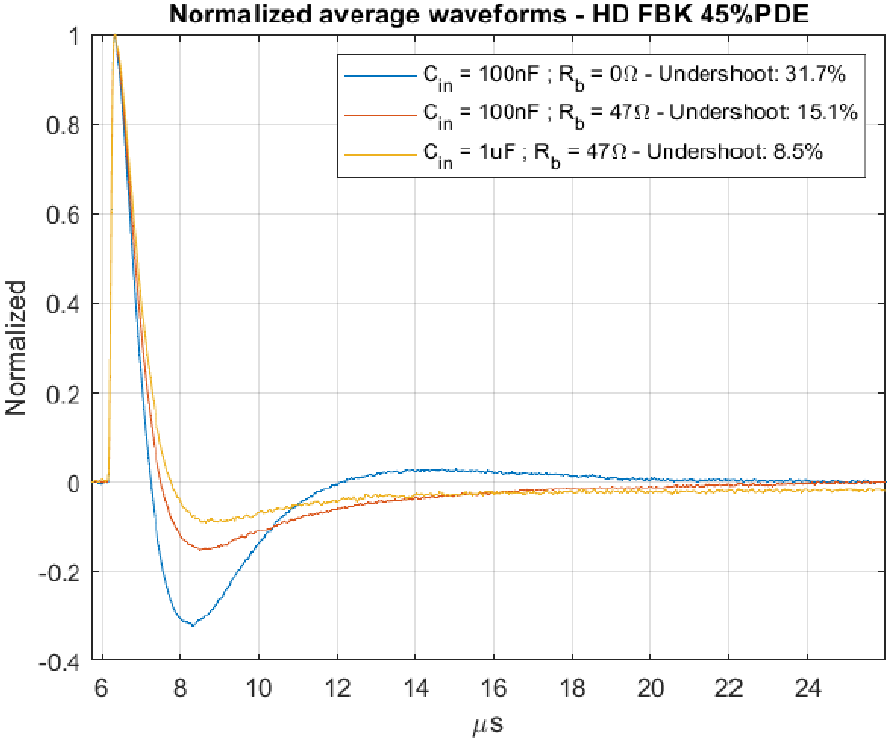
DIGITIZER+DECONVOLUTION+OPHITFINDER

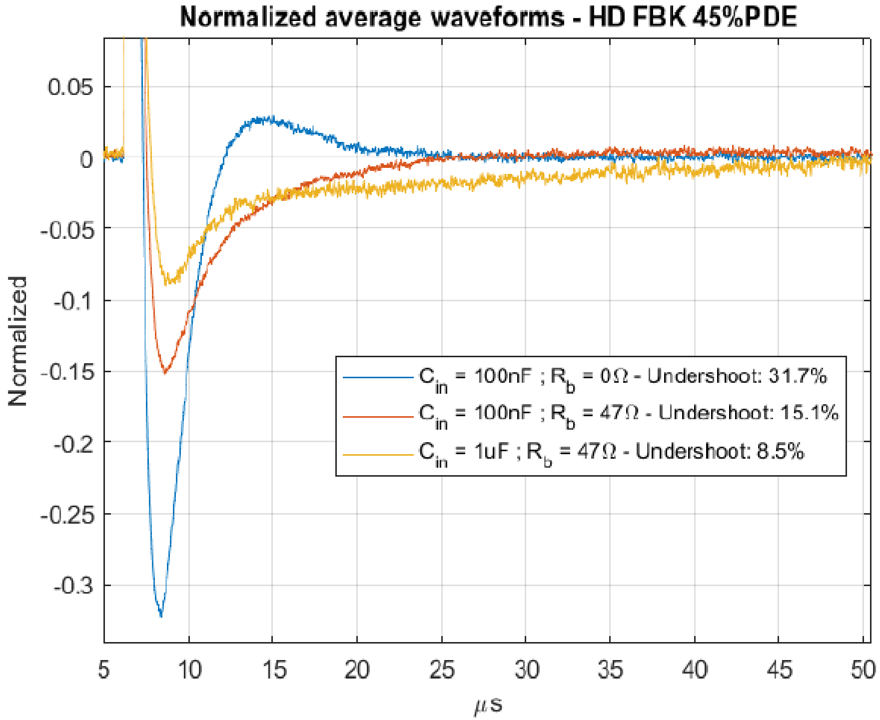
- Analysis combines data from 3 analyzers: **Digitizer, Deconvolution & OpHit Finder.**



Digitalization Stage → **Deconvolution "Wiener"/"Gauss"** → **OphitFinder**

Measurements – DAPHNE V2A



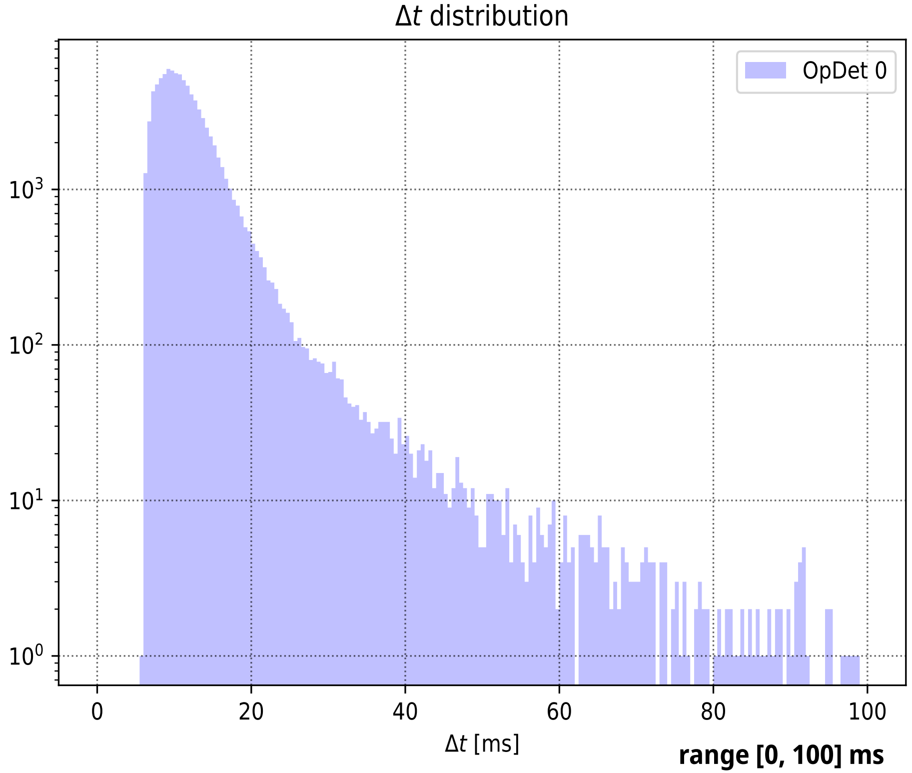


- Inspecting the undershoot behavior, we can see that changing the R_b value from 0Ω to 47Ω does no affect the recovery time of the signal. The shape although changes, eliminating the positive overshoot.
- Changing C_{in} from $100nF$ to $1uF$, reduces the undershoot but affects the recovery time.
- Here, considering a 5% settling condition, the latter configurations yields the best results ($4.4\ \mu s$ – 275 ticks). Considering for example, 1%, the signal takes $12.3\ \mu s$ ($769\ ticks$) to settle with $C_{in} = 100nF$ and 27 μs (1688 ticks) to settle with $C_{in} = 1uF$.

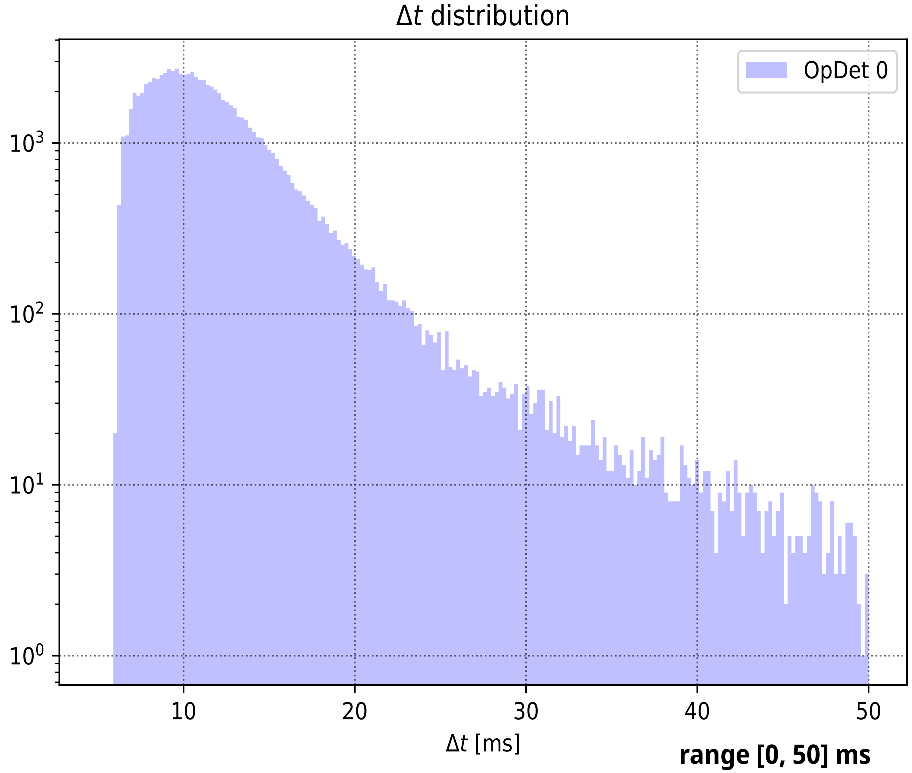
From Esteban Cristaldo Morales

Δt time interval distribution

- For each channel, the **time interval Δt** can be defined as :
  - $\mathbf{\Delta t_{ch} = |\ t_{max,ch} - t_{min,ch}\ |}$
- Therefore the **time interval Δt_{ch}** can be **different for each channel and for each event**.

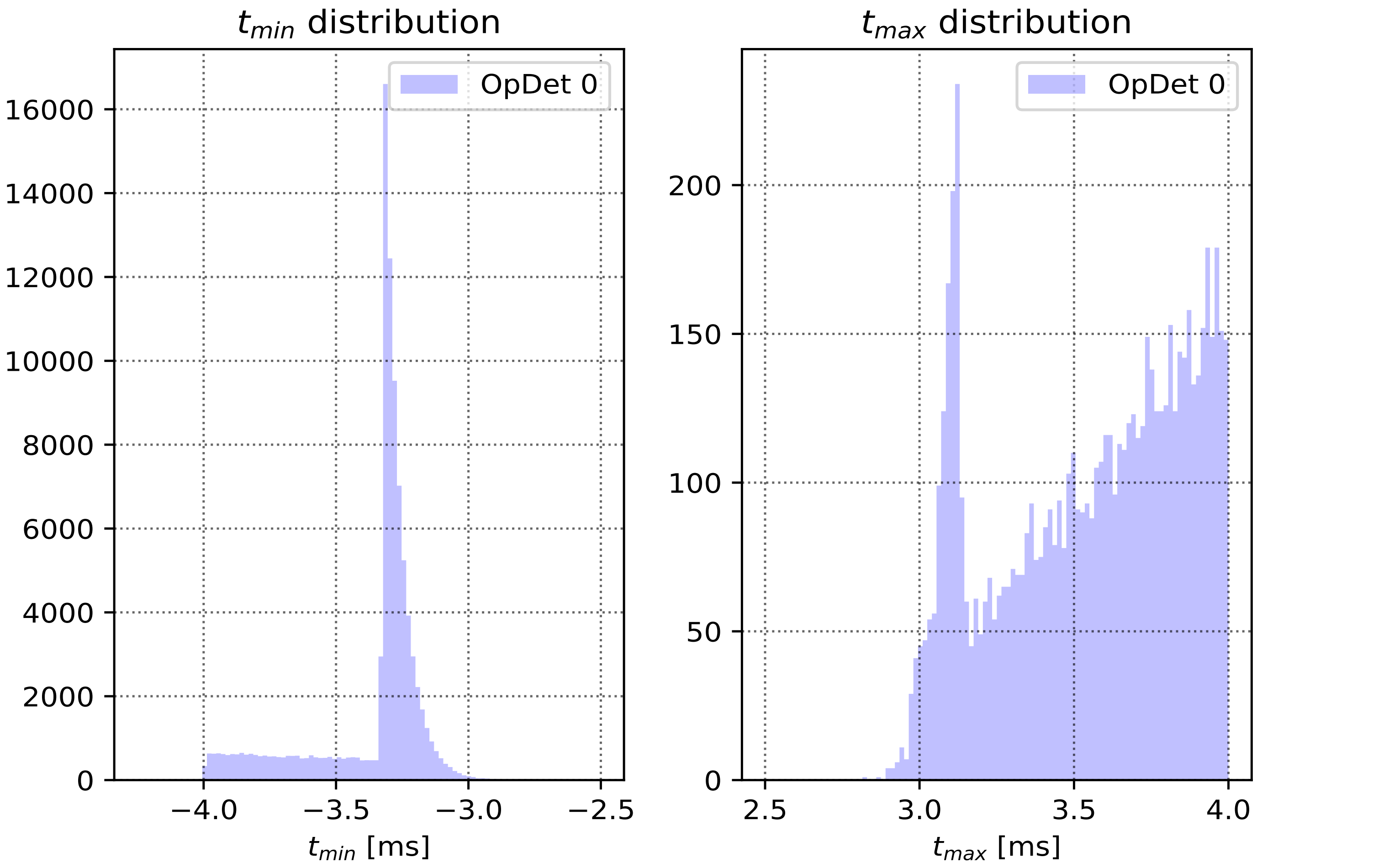


range [0, 100] ms



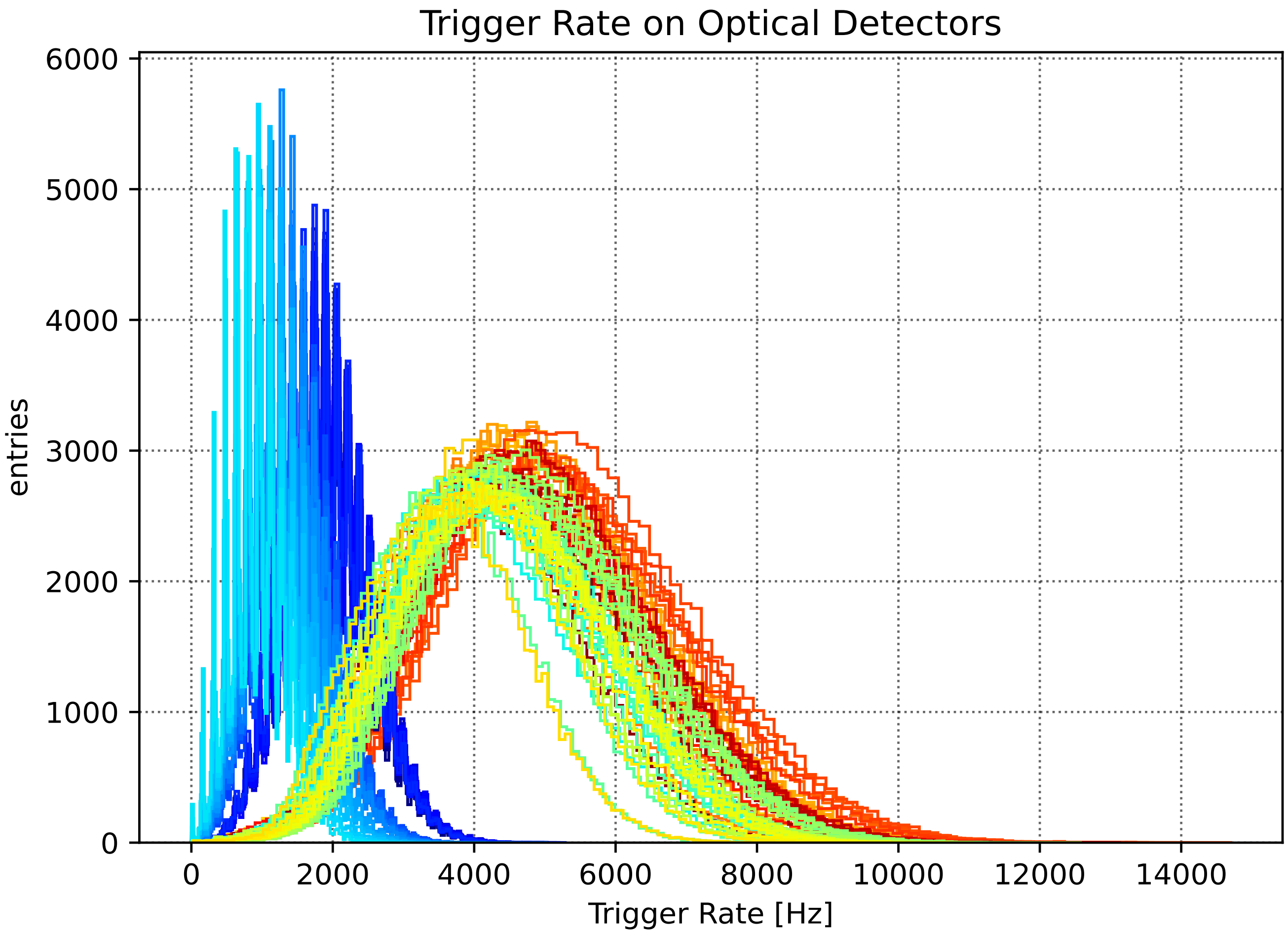
range [0, 50] ms

t_{min} and t_{max} distribution



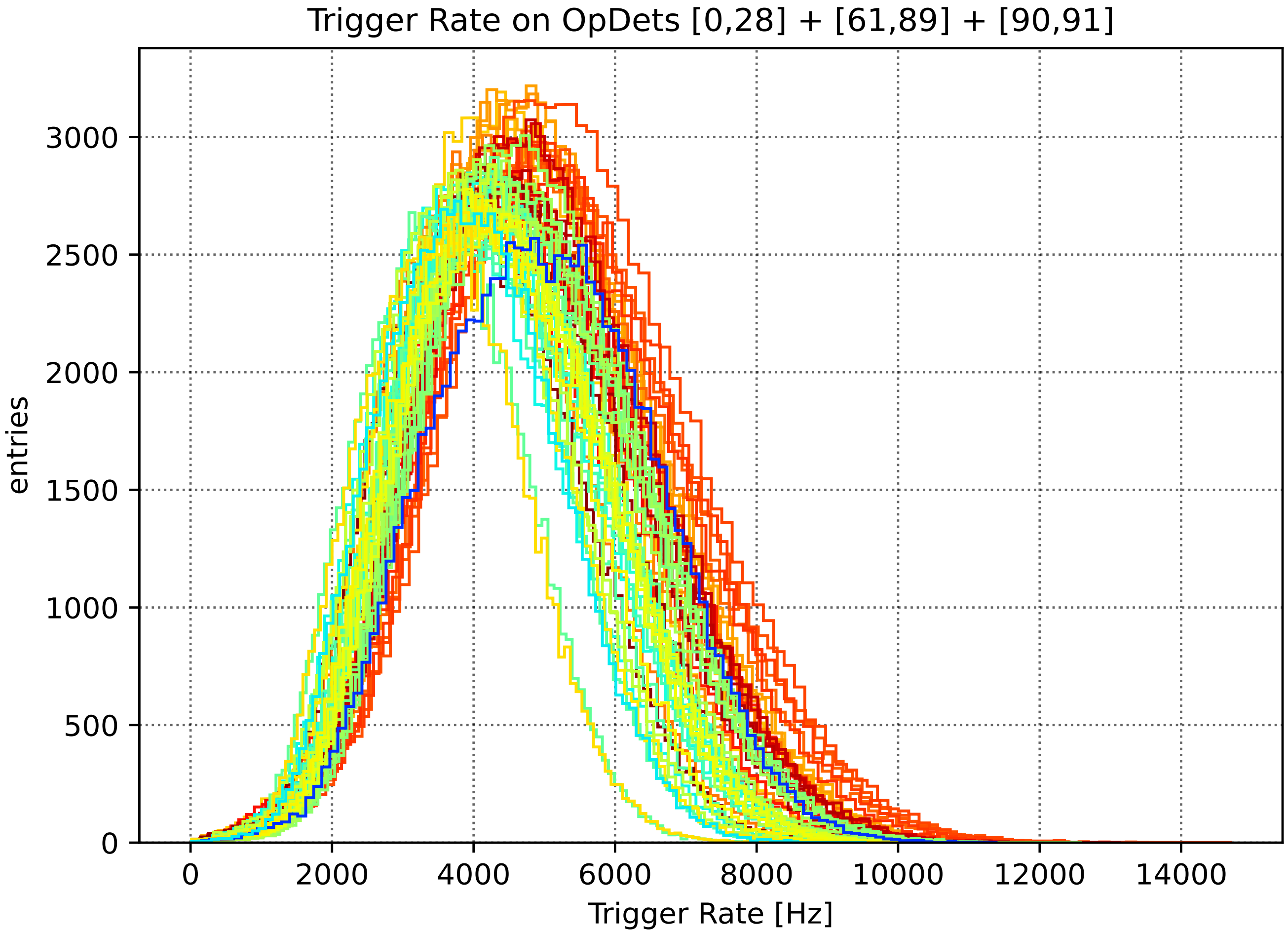
Trigger rate on Optical Detectors

- Trigger rate on 90 Optical Detectors.



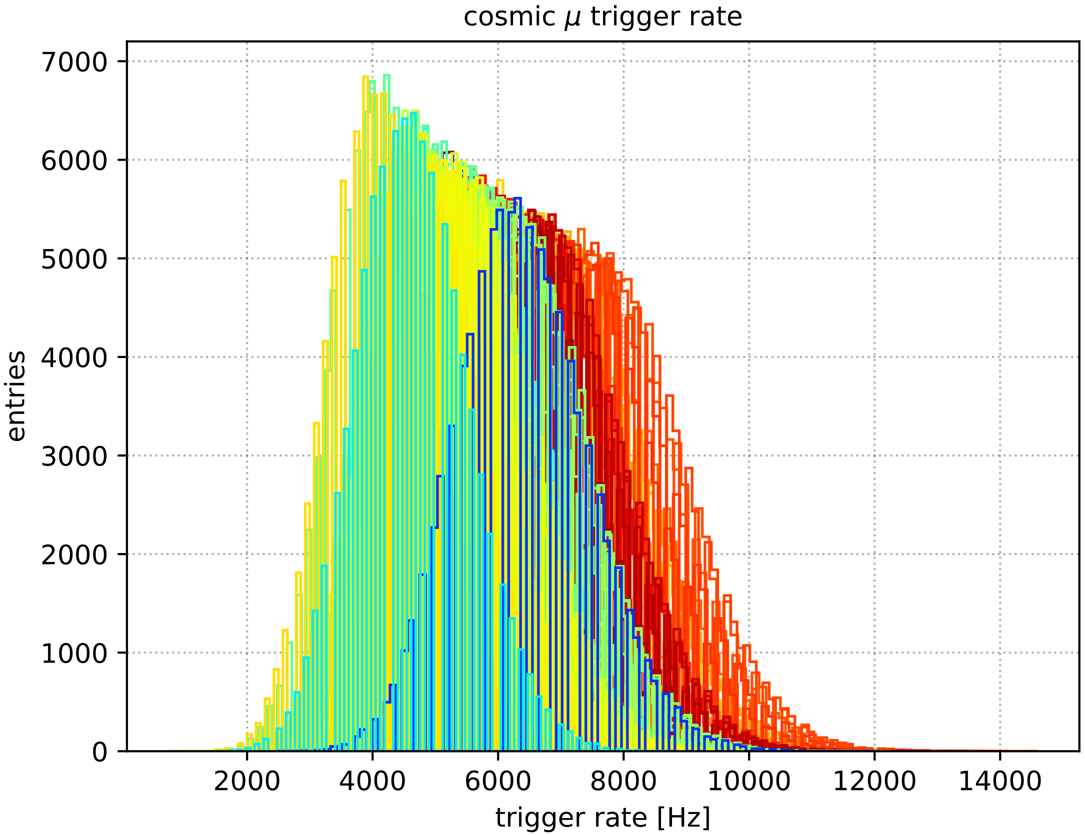
Trigger rate on Optical Detectors

- Trigger rate on 60 Optical Detectors.



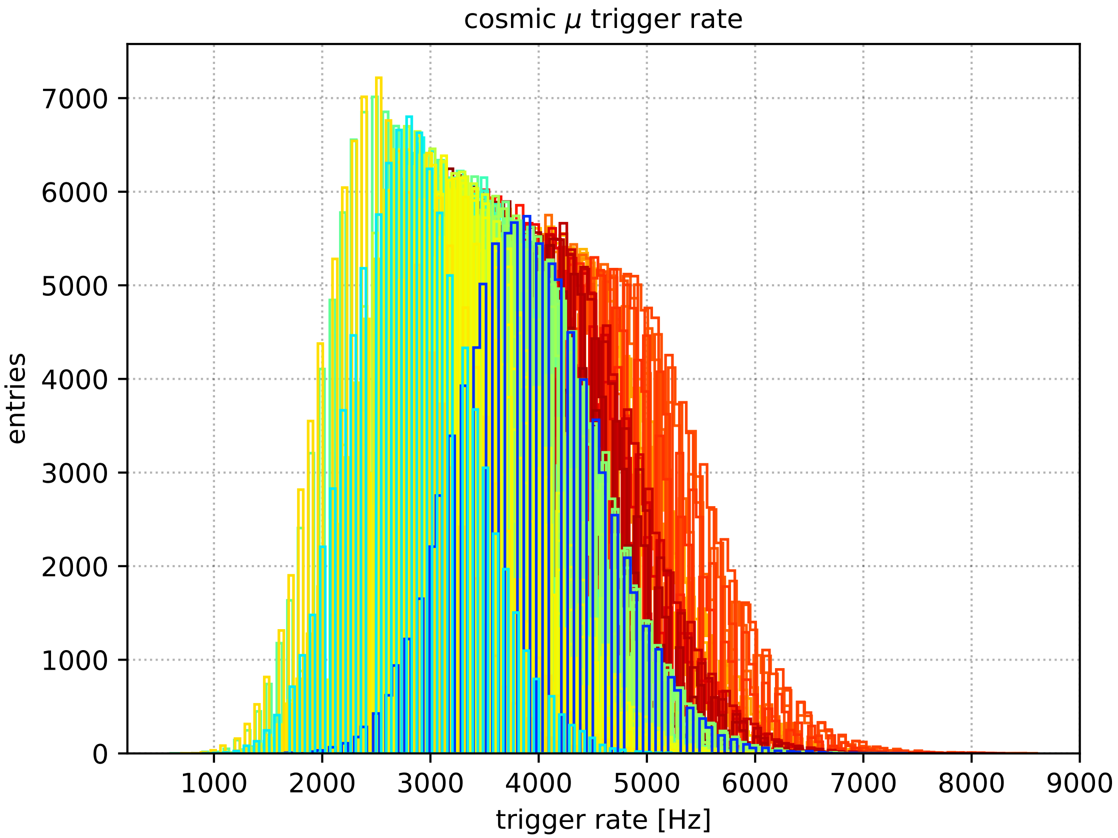
Trigger rate due to cosmic muons: Corsika Sample Time window

- Trigger rate on Optical Detectors due to **cosmic muons** starting from **-3.325 ms** w/ a **6.45 ms time window**.



Trigger rate due to cosmic muons: 10 ms time window

- Trigger rate on Optical Detectors due to **cosmic muons** starting from **-3 ms** w/ a **10 ms time window**.



Cosmic generator time information

- **TimeOffset** : start time of the exposure window [s], relative to the simulation time start.
- **SampleTime** : duration of the simulated exposure to cosmic rays [s].
- The time of the showers is uniformly distributed within the configured time interval, defined by SampleTime starting from TimeOffset.

```
cosmicgenerator: {
   BufferBox: [
      -300,
      300,
      -300,
      300,
      -300,
      300
   ]
   ProjectToHeight: 865
   RandomXZShift: 1000
   SampleTime: 6.45e-3
   ShowerAreaExtension: 2000
   ShowerFluxConstants: [
      17200,
      9200,
      6200,
      9200,
      6200
   ]
   ShowerInputFiles: [
      "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/p_showers_*db",
      "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/He_showers_*db",
      "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/N_showers_*db",
      "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/Mg_showers_*db",
      "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/Fe_showers_*db"
   ]
   TimeOffset: -3.325e-3
   module_type: "CORSIKAGen"
}
```

From **corsika_protodune.fcl**

SampleTime : **6.45e-3**
#0.2 ms (g4 rise time) + 2.25 ms (1 full drift window)
+ 4.0 ms (readout)

TimeOffset : **-3.325e-3**
#4.0 ms readout should start at -0.875 ms to match data