

Analysis of the milliQan demonstrator data at the LHC

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August 15, 2019

1 Introduction

The collection, calibration and analysis of the milliquan demonstrator data is described below. The major remaining tasks are:

- Rerun excluding bad runs 1350-1380
- Make time dependent dark rate estimate (ideally using physics runs)
- Add cosmic shower section
- Add after pulse section
- Add radiation section
- Refine signal selection based on simulation for background and signal
- N_{PE} dependent signal selection to target higher and lower charges

2 The milliQan demonstrator

The milliQan demonstrator is positioned in the PX56 drainage gallery in the site envisioned for the full milliQan detector. PX56 has a diameter of ~ 2.7 m. With the aid of a 3D model constructed from a laser scan of the tunnel, an optimized location has been determined to place milliQan that intercepts maximal mCP flux given the constraint that, at the chosen angle

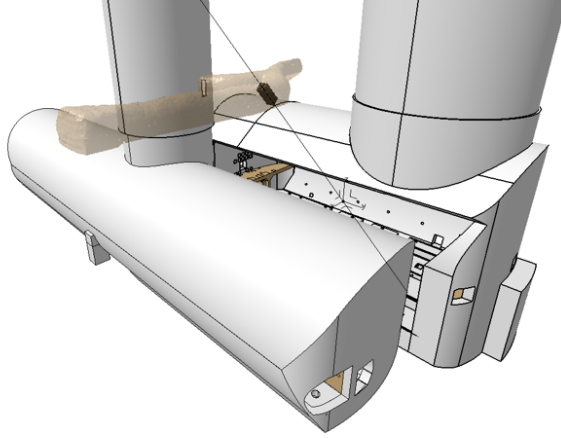


Figure 1: 3D model showing optimal position of milliQan within the PX56 Drainage and Observation gallery located above CMS UXC.

to the IP, it must be able accommodate the length of the detector. The chosen location is almost directly above CMS with a distance to the IP of 33m (17m of which is through rock), and at an azimuthal angle of 43.1 degrees from the horizontal plane. The 3D model showing the location of the demonstrator is shown in Fig. 1.

The milliQan demonstrator is shown in Figure 2. It consists of eighteen $5 \times 5 \times 80$ cm scintillator bars arranged in three layers of 2×3 scintillator+PMT units. In addition to the bars, “slabs” of $2.5 \times 20 \times 30$ cm scintillator and thin panels of $1 \times 18 \times 100$ cm scintillator are inserted to tag charged particles such as muons from the CMS IP, study backgrounds from radiation, and to simulate the active veto of the full detector. There are also several hodoscope packs composed of small arrays of 0.75×18 inch rectangular pieces of plastic scintillator readout via SiPMs attached at one end. These provide finer grained position information that allows crude tracking through the device.

The demonstrator is held in place using a support structure that is able to rotate the demonstrator components into a position aligned towards the CMS IP. The structure is constructed from a steel frame that sits on the floor of the tunnel and hosts a large bearing allowing the upper part of the structure to rotate into alignment.

The alignment of the demonstrator was performed with the help of the CERN alignment team, who installed a set of laser corner cubes that were

surveyed into alignment with the CMS coordinate system. Laser cubes positioned on the detector are aligned by the CERN team with this external coordinate system. The estimated accuracy of the procedure is to point the detector to within 10 cm of the CMS IP, or about 0.1 degrees, which is more than sufficient for this experiment. The alignment is cross-checked using muons from the LHC collisions at the IP using the slabs (see Section 6).

3 Data taking

The data considered in this analysis was collected by the milliQan demonstrator between June 26th 2018 and October 21st 2018. For all physics quality data, the PMT high voltage is set to 1300 V for the R7725s, 1450 V for the R878s and 1550 V for the Electron Tubes (ETs). Events are triggered if there is a signal above the trigger threshold in three trigger groups within a window of 100 ns. Each trigger group contains two channels and the trigger group for each channel is given by $\text{floor}(\text{channel}/2)$. The channel mapping ensures adjacent bars are in the same trigger group.

The trigger thresholds varied during data taking to satisfy rate requirements. The typical threshold for the bars ranges from 2.4 – 7 mV, the typical value for the slabs ranges from 150 – 400 mV and for the panels ranges from 2.5 – 40 mV.

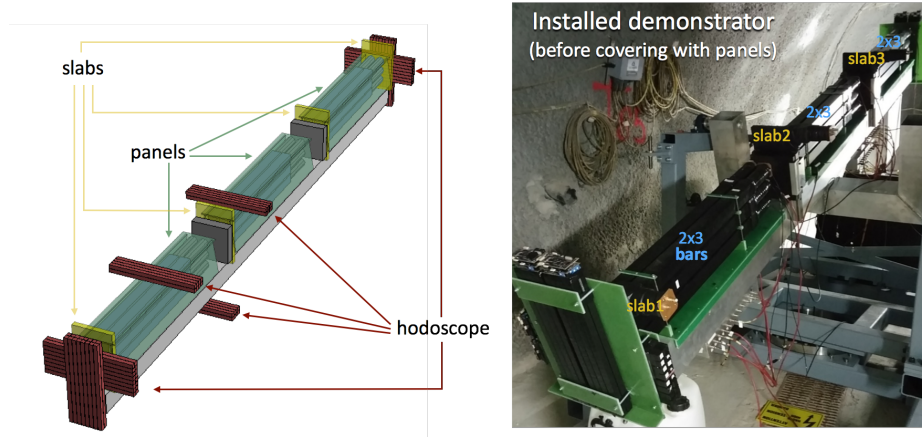


Figure 2: Design of the demonstrator and a photo of the demonstrator before covering it with panels.

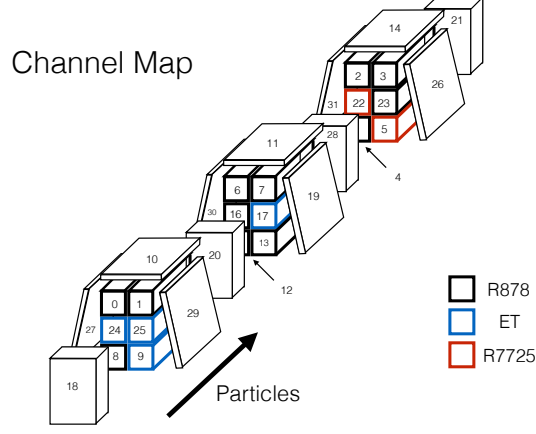


Figure 3: The channel mapping for the milliQan demonstrator. The PMT species are indicated by the colour.

The total data taking time of all physics runs is 2014.6 h. When the data taking rate is high events may not be properly synchronised between the two digitiser boards used for reading channels 0-15 and channels 16-32. To reject unsynchronised events, a requirement is made that both boards record the TDC time. The efficiency of this selection is $\sim 95\%$ giving an effective total time of 1906.4 h, with approximately 876.9 h and 1029.5 h taken during between periods with and without LHC proton-proton collisions respectively. The total proton-proton luminosity collected is 37.2 fb^{-1} , of which 35.1 fb^{-1} satisfies the synchronisation requirement.

4 Reconstruction

The data taken by the demonstrator is comprised of “waveforms” of voltage against time for each channel. In order to reconstruct the deposits of particles in the scintillator, “pulses” are reconstructed from each waveform.

With a sampling rate of 1.6 GHz, the waveforms span 0 to 650 ns (with the pulse that causes the trigger to accept the event placed at $\sim 360 - 390$ ns during triple coincidence running). The waveforms may have a significant pedestal which is measured using the mean value of the amplitude in a side-band region of the waveform from 0 – 50 ns. The mean value of this pedestal measurement for each channel in a physics run is used to define a pedestal

Table 1: Mean and RMS for each channel measured in the sideband region of a physics run

Channel	Sideband mean (mV)	Sideband RMS (mV)
0	-0.2453	0.8637
1	0.009	0.7901
2	-0.007	0.9028
3	-0.07	0.7561
4	-0.661	0.8741
5	-0.252	0.7857
6	0.080	0.8706
7	-0.214	0.7795
8	-1.04	0.8098
9	-0.160	0.7954
10	1.18	0.9941
11	-0.910	0.7833
12	-0.3789	0.9148
13	-1.09	0.7899
14	-0.53	0.9600
15	—	—
16	-0.367	0.8829
17	-0.837	0.8828
18	-0.283	0.8908
19	-0.275	0.8005
20	-0.235	0.8400
21	-0.295	0.8863
22	-0.443	1.061
23	-0.606	0.8085
24	-0.762	0.9275
25	-0.201	0.8194
26	-0.576	0.9087
27	-0.440	0.7757
28	-0.706	0.8507
29	-0.426	0.9169
30	-0.280	0.9577
31	-0.458	0.8018

subtraction with the values shown in Table 1. Significant drifts are seen in the pedestal for channel 30 and so a subtraction is made using the sideband pedestral measurement per event.

Pulses are reconstructed from the waveforms after the pedestral subtraction. Starting from the first sample after the sideband region, the algorithm considers each time sample consecutively and runs as follows until a pulse is started:

- If the sample is above the start threshold in Table 2, increment the pulse starting counter.
- If the sample is below the reset threshold in Table 2, reset the pulse starting counter. This threshold is set as the start threshold minus half

the sideband RMS shown in Table 1.

- If the pulse starting counter reaches the N samples above start threshold value shown in Table 2, start a pulse.

Once a pulse has been started the pulse end is determined by continuing as follows:

- If the sample is below the start threshold in Table 2, increment the pulse ending counter.
- If the sample is above the reset pulse end threshold in Table 2 reset the pulse ending counter. This threshold is set as the start threshold plus half the sideband RMS shown in Table 1.
- if the pulse ending counter reaches the N samples below start threshold value shown in Table 2, end the pulse.

Each pulse has several attributes defined as follows:

- time: The time of the last sample below the start threshold before the pulse is started.
- calibrated time: The calibrated time of the pulse as defined in Section 5.2.
- duration: The time of the sample after that which triggers the pulse ending minus the time of the last sample below the start threshold.
- height: The maximum amplitude in the pulse.
- area: The sum of the amplitudes across the pulse.
- N_{PE} : The number of photo-electrons (PEs) defined as the pulse area divided by the single PE (SPE) area for each channel (measured as described in Section 5.1).
- delay: Time between start of this pulse and end of previous pulse.

Table 2: Pulse finding thresholds.

N samples above start threshold	N samples below end threshold	Start threshold (mV)	Reset threshold (mV)	End threshold (mV)
7	13	2.0	1.57	2.43
7	13	2.0	1.60	2.40
9	13	2.3	1.85	2.75
7	13	2.0	1.62	2.38
7	13	2.2	1.76	2.64
5	4	2.0	1.61	2.39
7	13	2.0	1.56	2.44
7	13	2.0	1.61	2.39
7	13	2.0	1.60	2.40
4	4	2.0	1.60	2.40
7	13	2.2	1.70	2.70
7	13	2.0	1.61	2.39
7	13	2.0	1.54	2.46
8	13	2.0	1.61	2.39
9	13	2.3	1.82	2.78
7	13	2.5	2.00	3.00
7	13	2.0	1.56	2.44
4	4	2.0	1.56	2.44
8	13	2.0	1.55	2.45
7	13	2.0	1.60	2.40
7	13	2.0	1.58	2.42
8	13	2.0	1.56	2.44
5	4	3.7	3.17	4.23
7	13	2.0	1.60	2.40
4	4	2.0	1.54	2.46
4	4	2.0	1.59	2.41
7	13	2.0	1.55	2.45
7	13	2.0	1.61	2.39
7	13	2.0	1.57	2.43
7	13	2.0	1.54	2.46
7	13	2.0	1.52	2.48
7	13	2.0	1.60	2.40

5 Calibration

5.1 Charge response calibration

The calibration of the N_{PE} per unit charge incident on the detector is crucial for determining the lowest charge to which milliQan can be sensitive. To achieve this, we first compute the number of PEs for cosmic muons incident on the demonstrator. The value for N_{PE} is extracted by dividing the pulse area of cosmic muons by the pulse area of a single PE obtained from delayed scintillation PEs. The method of using delayed scintillation PEs to measure the SPE response was validated using an LED bench measurement as described in App. A. To avoid saturation effects the pulse area of

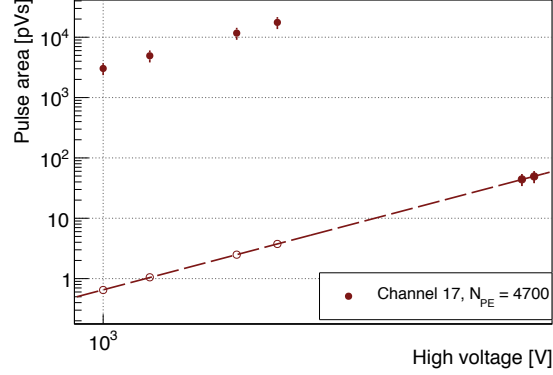


Figure 4: Area versus PMT voltage for a representative PMT for muon and single PEs. A simultaneous fit of the gain curve for the muon and SPE signals, with a floating cosmic photon yield, allows the N_{PE} for $Q = 1$ to be determined.

cosmic muons was measured at lower PMT voltage and extrapolated to the operating voltage.

Figure 4 shows the charge calibration for a representative PMT. The typical value of the measured N_{PE} for down-going cosmic muons with $Q = 1e$ is about 5000. Taking the difference in flight distance of cosmic muons and through-going muons in the scintillator bars (80 cm/5 cm), the N_{PE} for a through-going muon is approximately $5000 \times 80/5 = 80,000$. We then extrapolate N_{PE} to fractional charges by scaling by Q^2 . This gives $N_{\text{PE}} = 1$ for $Q \sim 3 \times 10^{-3}e$, which is consistent with the results obtained from the full GEANT4 simulation.

5.2 Time calibration

The timing calibration is crucial to achieve the targeted $\sim 15\text{ ns}$ window between pulses arriving in each layer in order to effectively reject backgrounds from uncorrelated sources. The calibration procedure is designed such that a muon travelling upwards through the detector from the IP should have the same time value in every channel.

First, channels in the same "slice" (left or right side of each layer) are calibrated using down-going cosmic muons, tagged as a muon pulse hitting the top panel and each channel in a particular slice. The mean value of the

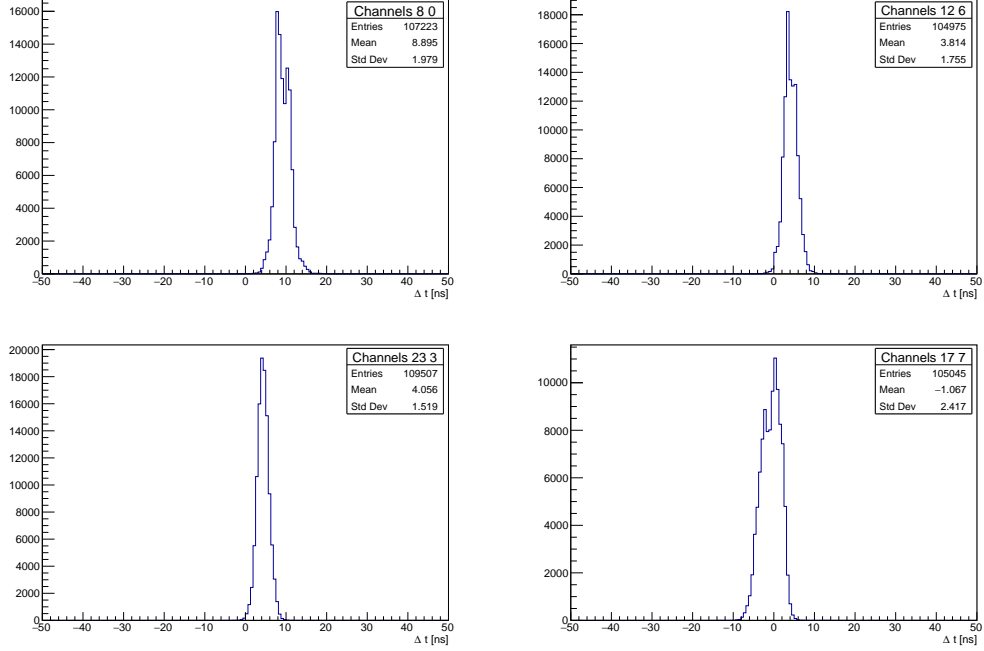


Figure 5: Example time differences between channels in the same slices. The mean values are used to calibrate the intra-slice timing.

time difference of each channel relative to the top channel of each slice is taken as the calibration. Figure 5 shows the time difference between the channels for several example calibrations. The standard deviation ranges from 1.7 to 2.8 ns.

After applying the intra-slice calibration, the slices are then calibrated using down-going cosmic muons, tagged as muon pulse hitting the top panel and both slices in a particular layer. The mean value of the time difference relative to the left slice of each layer is taken as the calibration. Figure 6 shows the time difference between the slices for each layer. The standard deviation ranges from 2.3 to 2.8 ns.

The slab timing is then calibrated using beam muons, tagged as a muon pulse hitting all four slabs. In order to avoid bias from cosmic muons, the modal value of the time difference relative to the slab closest to the CMS IP (channel 18) is taken as the calibration. Figure 7 shows the time difference between the slabs and channel 18.

After applying all previous calibrations the layers are calibrated using

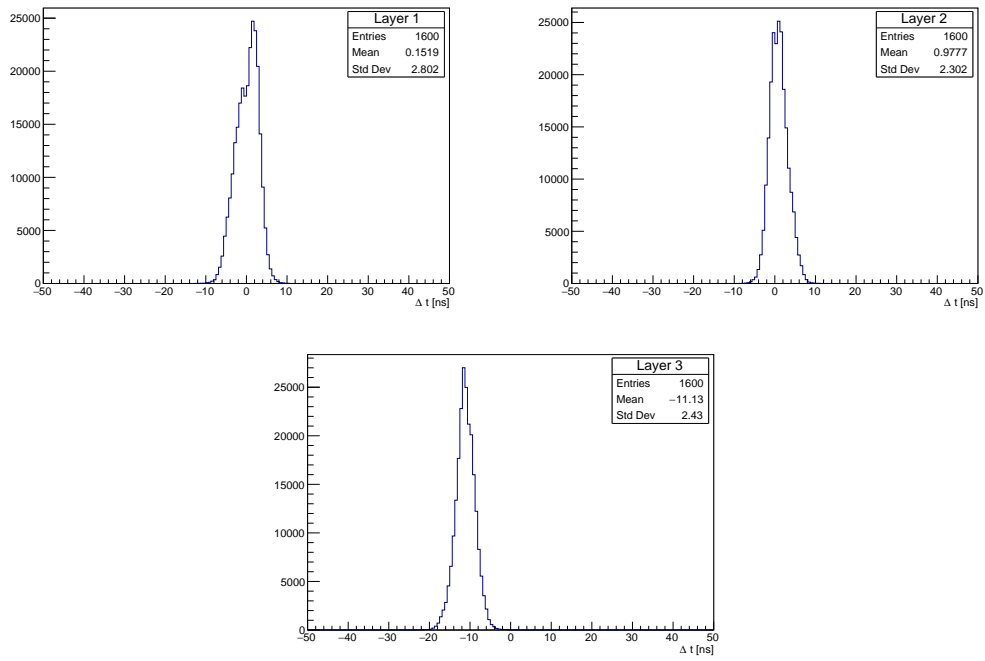


Figure 6: Time differences between slices in the same layer for all layers. The mean values are used to calibrate the intra-layer timing.

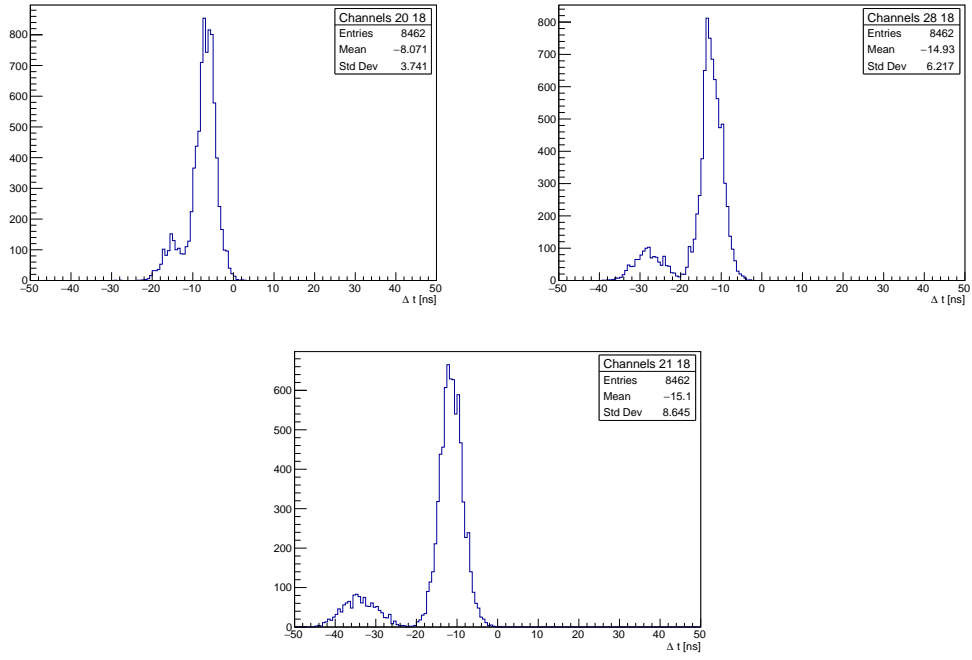


Figure 7: Time differences between each slab and channel 18. The modal values are used to calibrate the inter-slab timing.

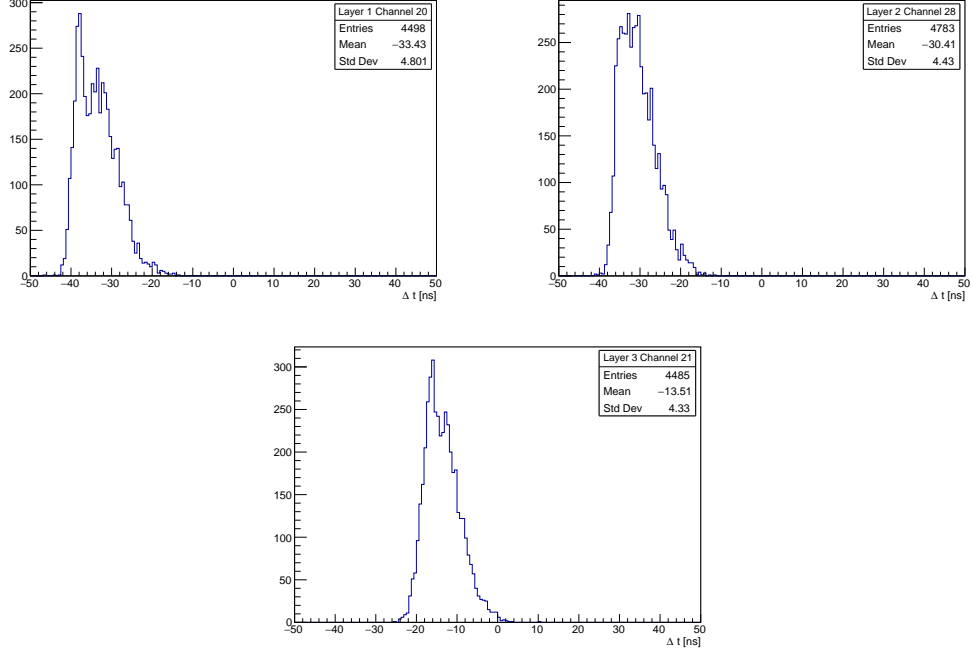


Figure 8: Example time differences between each layer and the closest slab. The mean values are used to calibrate the inter-layer timing.

beam and cosmic muons hitting all four layers, tagged as a muon pulse hitting all four slabs. The mean value of the time difference relative to the slab closest to the layer is taken as the calibration. Figure 8 shows the time difference between the layers and closest slab. The standard deviation ranges from 4.3 to 4.8 ns.

Finally, the panels are calibrated to the layers using cosmic muons tagged as having a muon pulse in the panel and in the layer closest to the panel. The mean value of the time difference relative to the layer is taken as the calibration. Figure 9 shows representative time differences between the panels and the closest layer. The standard deviation ranges from 5.8 to 8.0 ns.

The calibrations for each channel are summarised in table 3. The standard deviation in the time difference between layers is ~ 5 ns, allowing a time window of 15 ns to be defined for signal candidate events, as described in Section 7.

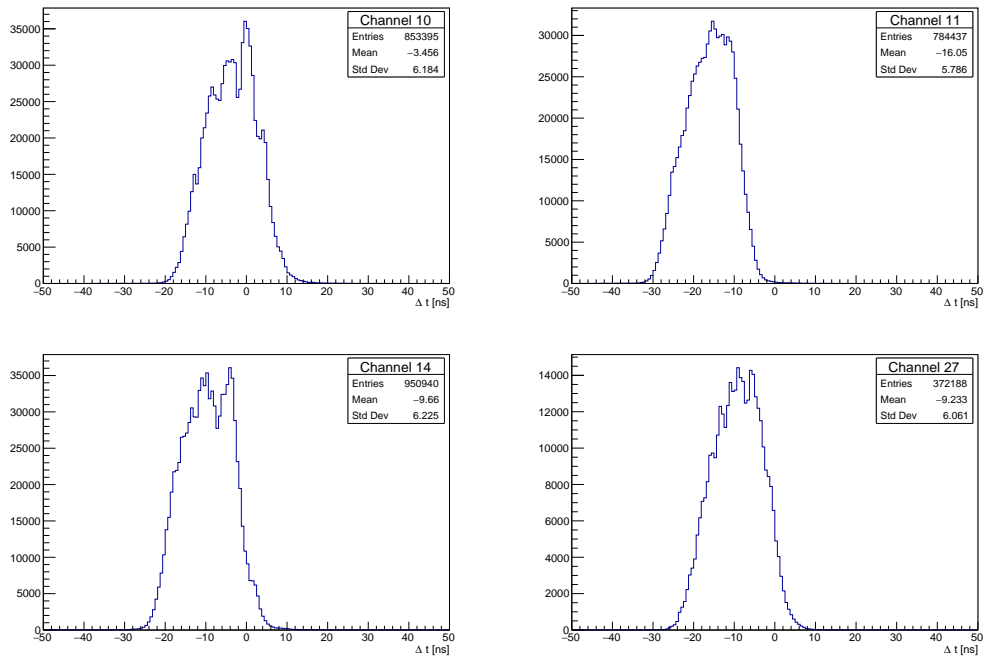


Figure 9: Example time differences between panels and the closest layer. The mean values are used to calibrate the panel timing.

Table 3: Time calibrations for each channel . The values are added to the raw time to define the calibrated time.

Channel	Calibration (ns)
0	33.125
1	33.125
2	13.75
3	24.375
4	23.75
5	35.0
6	30.625
7	29.375
8	24.375
9	33.75
10	3.75
11	16.25
12	26.875
13	34.375
14	9.375
15	—
16	27.5
17	30.625
18	0.0
19	11.25
20	7.5
21	12.5
22	28.125
23	20.625
24	33.75
25	26.875
26	-3.125
27	9.375
28	13.75
29	0.625
30	15.625
31	10.625

6 Alignment

The alignment of the demonstrator is tested using muons originating from the proton-proton collisions at CMS (referred to as “beam muons”. Figure 10 shows the dependence of the total number of particles identified as having a muon pulse in all four slabs on the luminosity of the LHC fill measured by CMS. There is a clear linear dependence with a muon rate of $0.19/\text{pb}^{-1}$ measured in data, which agrees with the expected value from simulation of a muon rate of $0.22/\text{pb}^{-1}$. This provides confidence the demonstrator is correctly aligned with the CMS interaction point.

The time difference between the slabs closest and furthest from the IP after the calibration described in Section 5.2 also provides confirmation that

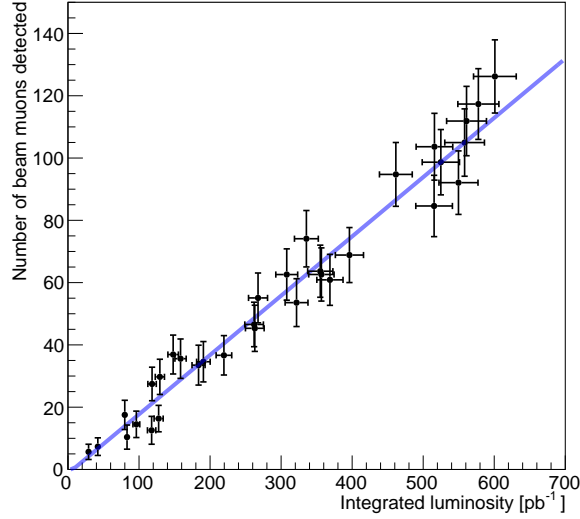


Figure 10: The occupancy of the milliQan demonstrator as a function of luminosity

the pulse timing can be used to discriminate between muons originating from the IP travelling up through the detector and muons from cosmics travelling down through the detector. Figure 11 shows well separated distributions from beam and cosmic muons with a time difference consistent with that expected from the geometrical distance between the slabs ($2 \times 3.6/0.3 = 22$ ns).

7 Search design

In this section a search for fractionally charged particles with the milliQan demonstrator is detailed. The search relies on a triple coincidence of pulses across the three layers of the demonstrator. A range of selections are applied in order to reject contributions from background sources, which are detailed below.

- Dark rate overlap: each PMT has a dark current due to effects such as the thermal emission of electrons from the cathode. The simplest background source comes from random overlap of three such dark rate pulses. In addition, dark rate counts may overlap with a correlated

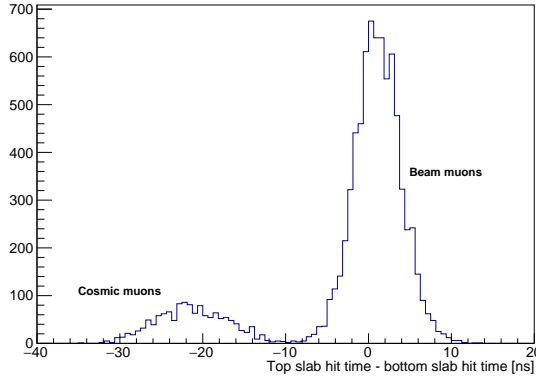


Figure 11: Time difference between the slabs furthest and closest to the CMS IP (channels 21 and 18 respectively). The peak at zero is consistent with originating from beam muons while the peak at ~ -22 ns is consistent with originating from cosmic muons.

double coincidence background from another source.

- Cosmic/beam muon showers: a large number of gammas, neutrons and electrons may be caused by an interaction of a cosmic ray muon with the rock in the demonstrator cavern. This may cause a pulse in each layer of the milliquan demonstrator. Such a background could also be expected from a beam muon which travels close to the demonstrator.
- Radiation: radiation in the cavern, scintillator bars or surrounding material can cause correlated deposits in several bars. The lead blocks placed between layers should reduce the probability of a three layer deposit arising from photons or electrons, however, neutrons will not be shielded.
- Afterpulses: afterpulses arising from correlated deposits may overlap and produce a triple coincidence signature in the demonstrator. The original correlated signature must not be triggered as in this case the afterpulses will fall in the readout deadtime and not be recorded.

Each event is required to have a pulse in a single bar in each layer in order to pass signal selection. If there is activity in any slab or panel the event is vetoed. These requirements reject backgrounds due to cosmic showers,

which are expected to cause deposits across the detector and beam muons passing close to the bars, which will cause significant pulses in the slabs. The bars which contain hits are additionally required to be pointing to the IP such that they have the same position which each layer. This reduces the background from neutrons, cosmic showers and random overlap while being efficient for signal which is expected to have a small angular spread. In each bar a requirement is made of exactly one pulse and low sideband activity to reject backgrounds from overlapping afterpulses. Finally, the maximal calibrated time difference between pulses in different bars is required to be less than 15 ns, which is efficient for signals travelling upwards from the IP and forms a powerful rejection of backgrounds with different paths through the detector or that have deposits in each layer that are uncorrelated in their timing.

8 Background determination

The total background as a function of the minimal N_{PE} in the event can be evaluated using data taking periods in which there are no collisions and scaled to the total length of the data taking with collisions. This is shown in Figure 12. The background ranges from 122 events for $0.5 < N_{\text{PE}} < 1.5$ values to 2.6 events for $N_{\text{PE}} > 10$.

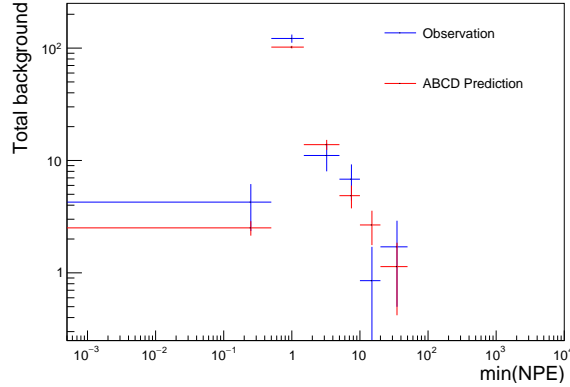


Figure 12: The minimal N_{PE} in the event during data-taking period with no collisions for events passing the signal selection is compared to the prediction from the ABCD method detailed in the text.

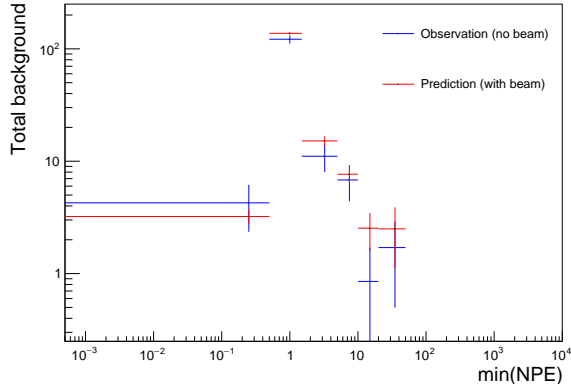


Figure 13: The minimal N_{PE} in the event during data-taking period with collisions for events passing the signal selection is compared to the prediction from the ABCD method detailed in the text.

Table 4: The region definition for the ABCD prediction.

Region	Time selection	Path selection
A (signal)	$\max(\Delta t) < 30 \text{ ns}$	Pointing path
B	$\max(\Delta t) > 30 \text{ ns}$ and $\max(\Delta t) < 100 \text{ ns}$	Pointing path
C	$\max(\Delta t) > 30 \text{ ns}$ and $\max(\Delta t) < 100 \text{ ns}$	Non-pointing path
D	$\max(\Delta t) < 30 \text{ ns}$	Non-pointing path

In order to validate there are no additional backgrounds introduced from collisions, signal depleted control regions are defined by inverting the maximal time difference and pointing path requirements. The background in the signal region is then predicted using the ABCD method for each region in N_{PE} , where the prediction follows $N_A = N_B \times N_D / N_C$ and the regions are defined in Table 4. This prediction is carried out for both the data taking periods with and without collisions and compared to the observation in the data taking period without collisions, as shown in Figures 12 and 13, respectively. Both predictions are seen to agree well with the observation, validating the use of data taken during periods without collisions to measure the background.

In order to determine the sources of the background observed in the signal region various studies have been carried out and are documented in the remainder of this section.

8.1 Dark rate overlap background

The first background source that was considered is the dark rate overlap. The dark rate is measured for each channel using “zero bias” runs in which the data is collected with a random trigger. The average dark rate for the bars is shown in Figure 14. This can be used to estimate the contribution from the random overlap of three dark counts in three bars. The prediction as a function of N_{PE} is shown in Figure 15 and compared to the observation in the signal region during data taking periods without collisions. Random overlap of dark rate can be seen to account for $\sim 25\%$ and $\sim 0.4\%$ of the overall rate for N_{PE} values of ~ 1 and > 5 , respectively. The dark rates are known to vary with time and so this prediction should be repeated with a time dependent measurement.

A dark rate pulse in a particular channel may also overlap with correlated deposits in two other channels. The rate for this can be inclusively determined using runs which are collected with double coincidence triggers and then calculating the triple coincidence rate given the single coincidence rates measured as detailed above. This calculation is approximate as it does not allow for time dependence in the rates and assumes the double coincidence pulses occur at the same time. The result is shown in Fig 16. For $N_{PE} < 5$ the prediction is shown to agree reasonably well with the observation given the limitations in the method discussed above. For $N_{PE} > 5$ the prediction from this method accounts for $\sim 10\%$ of the total rate.

Finally, the background per path is shown in Figure 17. The paths involving the channels with the highest dark rates are seen to have the highest significantly higher triple coincidence rate for $N_{PE} < 5$. For $N_{PE} > 5$ the rate is comparable for all paths.

8.2 Radiation

To be filled ...

8.3 Cosmic/beam muon showers

To be filled (Brunel/Ryan) ...

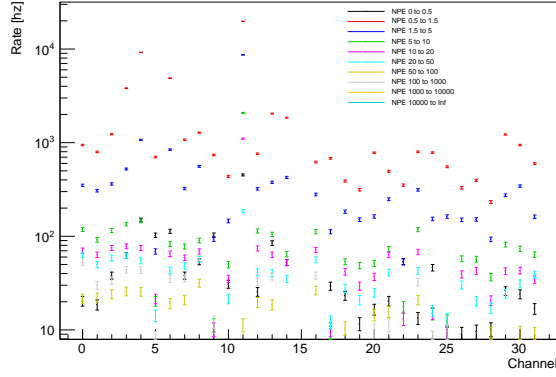


Figure 14: Single channel rate for an inclusive N_{PE} selection measured using zero bias runs.

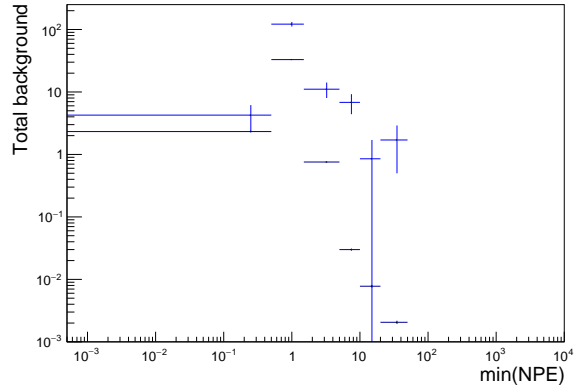


Figure 15: Background predictions for a signal like selection from dark rate is compared to the observation in the data taking period without beam.

8.4 Afterpulses

To be filled (Jan) ...

9 Interpretation

Signal efficiencies from injection tests and prototype interpretations

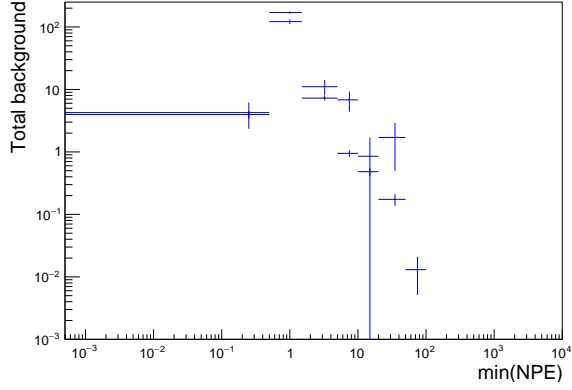


Figure 16: Background predictions for a signal like selection from the dark rate in each channel overlapping with a double coincidence in the two other channels for each path is compared to the observation in the data taking period without beam.

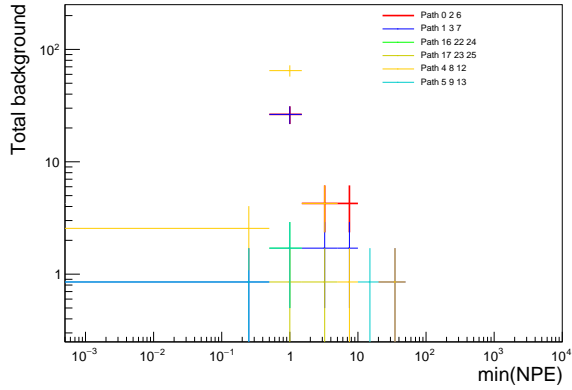


Figure 17: The minimal N_{PE} in the event during data-taking period without collisions for events passing the signal selection is shown for each pointing path through the demonstrator.

10 Summary

The alignment and calibration of the milliQan demonstrator have been detailed. The calibrated data have been used to search for fractionally charged particles with new exclusion sensitivity expected for masses between ~ 0.1

and 5 GeV and charges between ~ 0.02 and $0.1e$.

A LED bench studies

In this appendix the studies undertaken using PMTs coupled to an LED source are documented. The experimental setup is shown in Figure 18. The LED is a Thorlabs LED430L with a 430 nm wavelength and representative R878, R7725 and ET PMTs are studied. The DRS scope is triggered on the LED pulse meaning the PMT response falls in a well-defined time window and removing the need for pulse finding. The pulse areas for a range of R878 HVs are shown in Figure 19. The average N_{PE} input to the PMT can be controlled by varying the amplitude of the input LED pulse. This setup was used to study the SPE area, afterpulses and create an SPE template for pulse and signal injection tests.

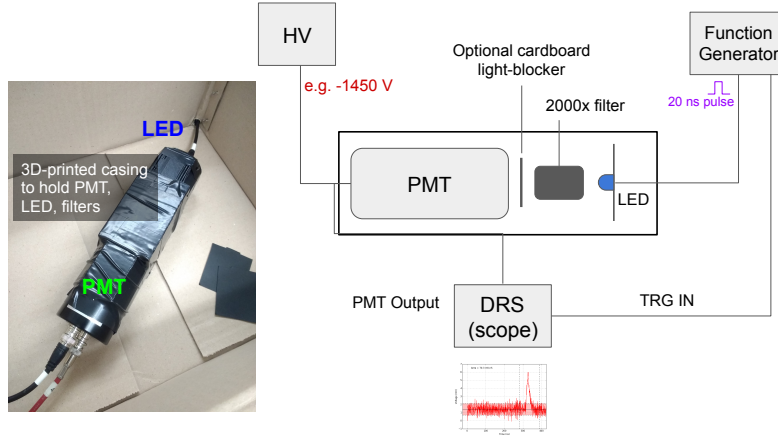


Figure 18: The experimental setup used for the LED bench studies.

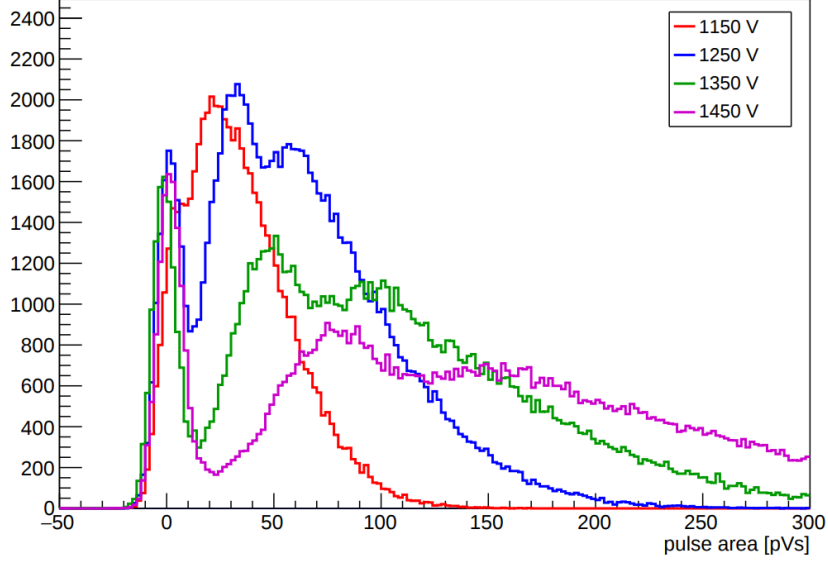


Figure 19: The area distributions for several R878 PMT HVs. The peaks correspond to 0, 1 and 2 SPEs and their separation increases with HV.

A.1 SPE area measurement

The calibration of the SPE area using an LED allows the impact of "partial" SPE pulses to be considered. Such pulses can occur in the PMT due to non-optimal trajectories such as the photon passing through the cathode and directly striking the first dynode or a PE skipping a dynode. The calibration procedure follows the method described in Ref. [1]. First, the zero SPE pulse area distribution is measured by taking data with the LED blocked. Next, the pulse area distribution is measured with the LED on and the zero SPE distribution scaled to match the left edge of this distribution. This is shown in Figure 20. The fraction of zero SPE events to be estimated and, assuming a Poisson distribution, the average N_{PE} from the LED can be calculated as $\langle N_{\text{PE}} \rangle = -\log(f)$.

The average SPE area can then be trivially calculated as $\langle \text{area}_{\text{on}} \rangle - \langle \text{area}_{\text{blocked}} \rangle / \langle N_{\text{PE}} \rangle$. The result of this procedure is shown in Figure 21 for a range of HV values. The measured value for 1450 V is in good agreement with the in-situ measurement of the R878s described in Section 5.1.

The measurement of the SPE area for an R7725 and an ET PMT is shown in Figure 22 and 23 respectively. In the case of the R7725 the SPE

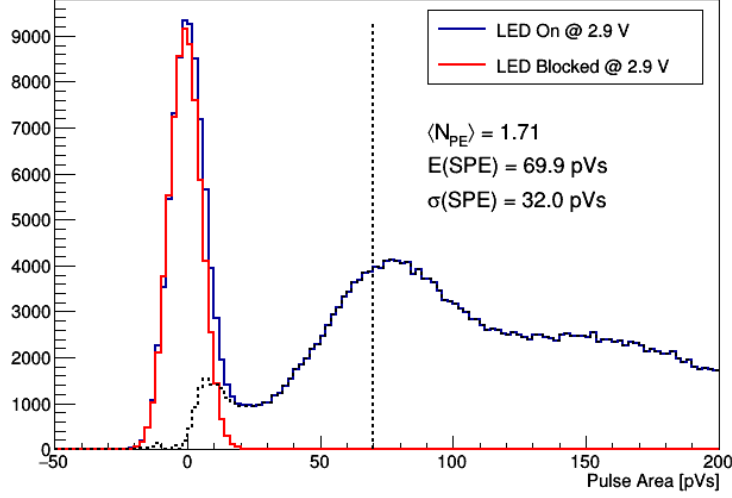


Figure 20: The pulse area distributions used to calibrate the SPE area for $HV = 1450 \text{ V}$.

area is significantly larger compared to the R878 and has a larger proportion of partial SPEs causing the mean response to be $\sim 20\%$ below the peak. In addition there is a significant disagreement with the in-situ measurement described in Section 5.1. This is likely due to the in-situ method neglecting the partial SPEs and the magnetic field in the cavern reducing the response by causing photoelectrons to be diverted.

A.2 Afterpulse characterisation

Afterpulses are caused by the production of positive ions in residual gases in the PMT tube. These ions return to the photocathode and produce a significant number of photoelectrons. The amplitude and time delay depend on the mass and charge of the ion as well as the position of the production of the ion. The time delay typically ranges from several hundred nanoseconds to a few microseconds or more. In the later case this can cause a correlated background in the detector if there are overlapping afterpulses from a single correlated source (which would lie outside of the trigger window).

The afterpulse behaviour was studied for the R878 and R7725 PMT considered in Section A.1. The time window was expanded to a microsecond

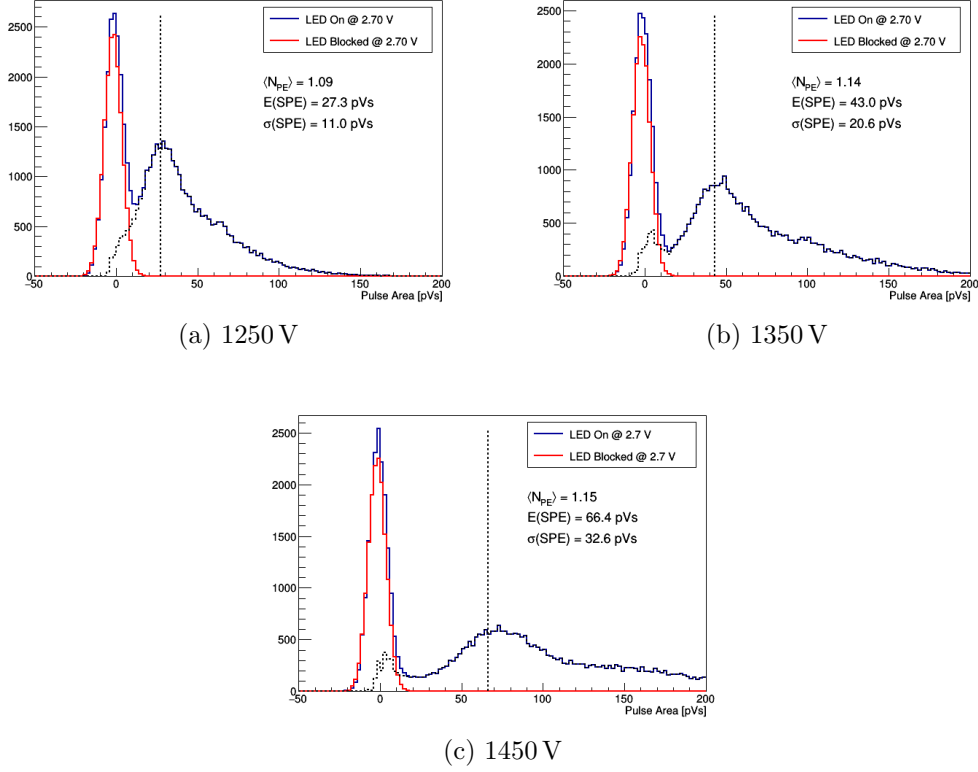


Figure 21: The pulse area distributions used to calibrate the SPE area of an R878 PMT for a range of HV values.

and the afterpulse spectrum measured by averaging the waveforms after subtracting the time of the initial pulse. The results are shown in Figure 24 for the R878 and R7725 PMTs. The R878 shows several peaks with the largest occurring at ~ 400 ns while the R7725 has a single large peak at ~ 500 ns. Finally, the average waveform for various HV values is shown in Figure 25a. The peak time is expected to follow an inverse square root HV dependance [2] and, while this requires further study, can be seen in Figure 25b.

A.3 SPE pulse shape and area spectrum

The LED is finally used to measure the average SPE waveform and are spectrum. This is carried out for an R878 and R7725 PMT. The pulse

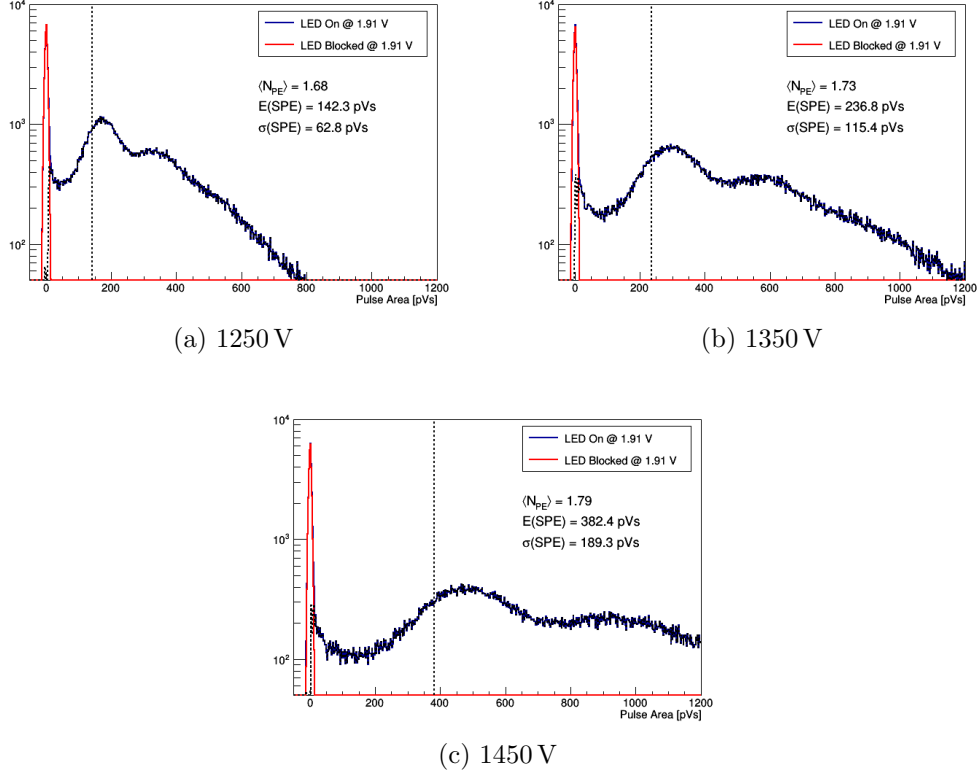


Figure 22: The pulse area distributions used to calibrate the SPE area of an R7725 PMT for a range of HV values.

shape is measured by averaging many individual pulses and the resultant templates are shown in Figure 26. The average waveform for the R7725 is significantly narrower than for the R878. The SPE area spectrum is measured by using a very low LED intensity to eliminate contamination from 2 or more SPE events. The zero PE component is then subtracted following the same procedure in A.1 and the resultant SPE area distribution for the R7725 shown in Figure 27. There is an exponential tail from suboptimal trajectories at low pulse areas and a Gaussian core around ~ 500 ps. The contamination from 2 or more SPE events is $\sim 3\%$.

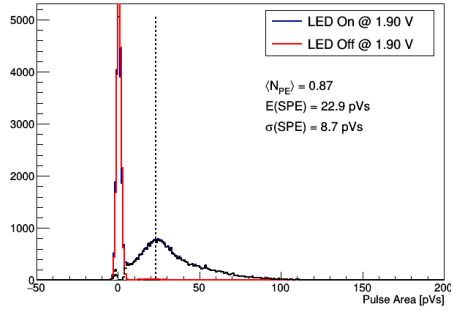


Figure 23: The pulse area distributions used to calibrate the SPE area of an ET PMT for a HV of 1700 V.

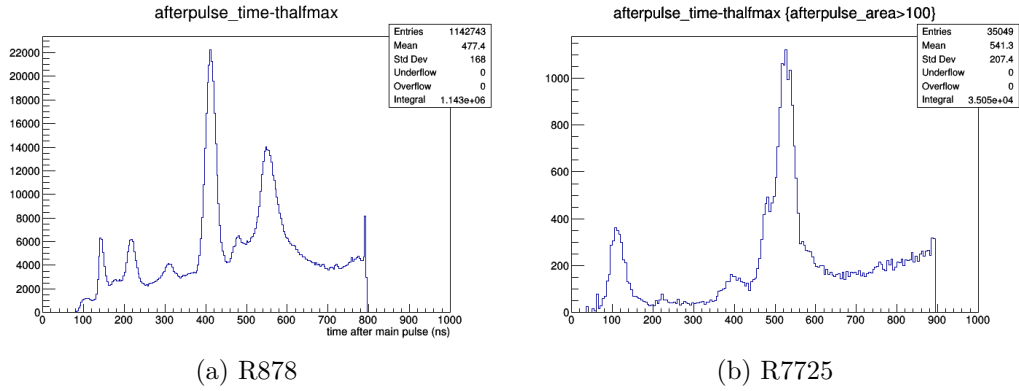


Figure 24: The average waveform spectrum for two PMTs. The peaks correspond to afterpulses.

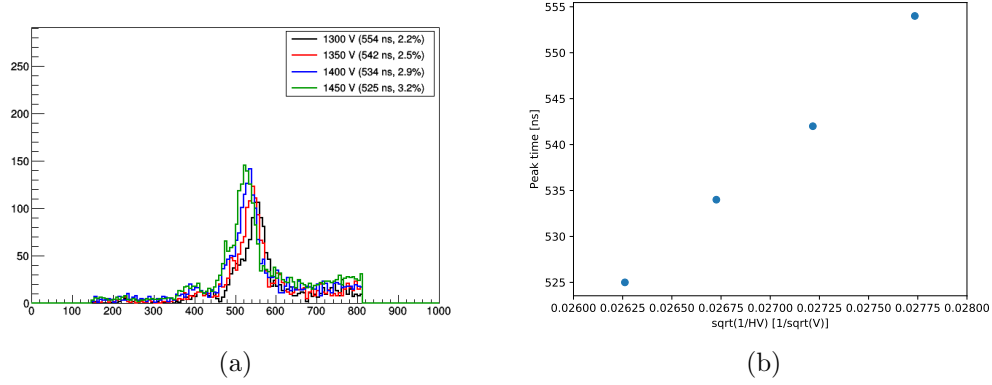


Figure 25: (a) The average waveform spectrum for the R7725 PMT for several HV values. (b) The peak time follows an inverse square root dependence with the HV.

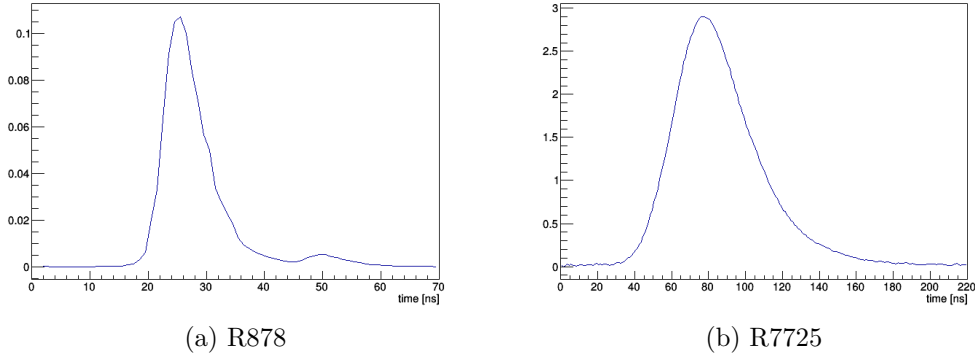


Figure 26: The average waveform spectrum for the R7725 PMT for several HV values. The peak time follows an inverse square root dependence with the HV.

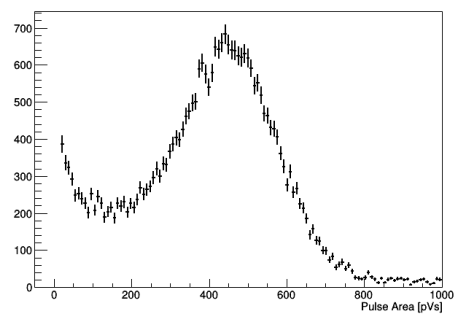


Figure 27: The measurement of the SPE area spectrum for an R7725 PMT.

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