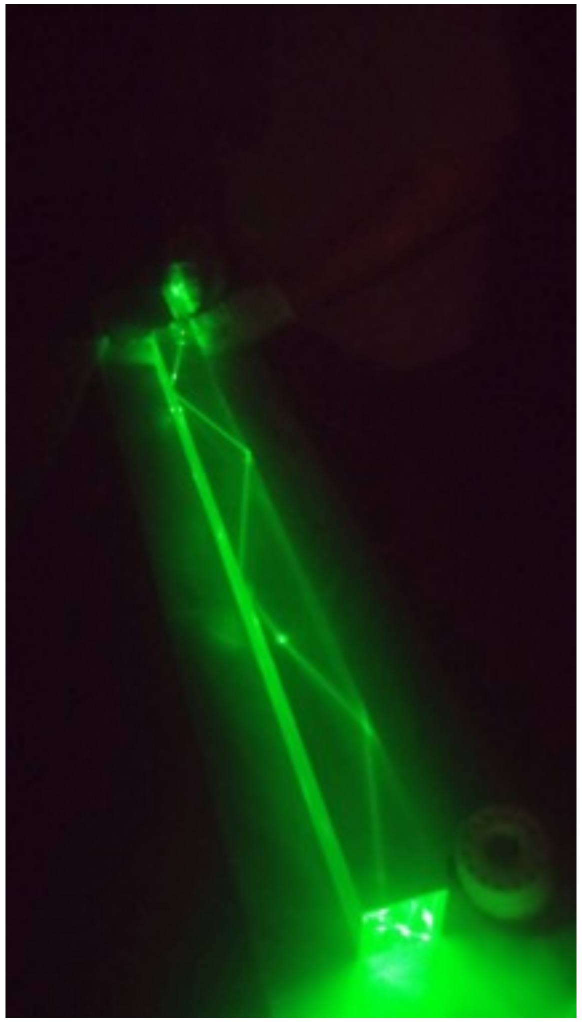
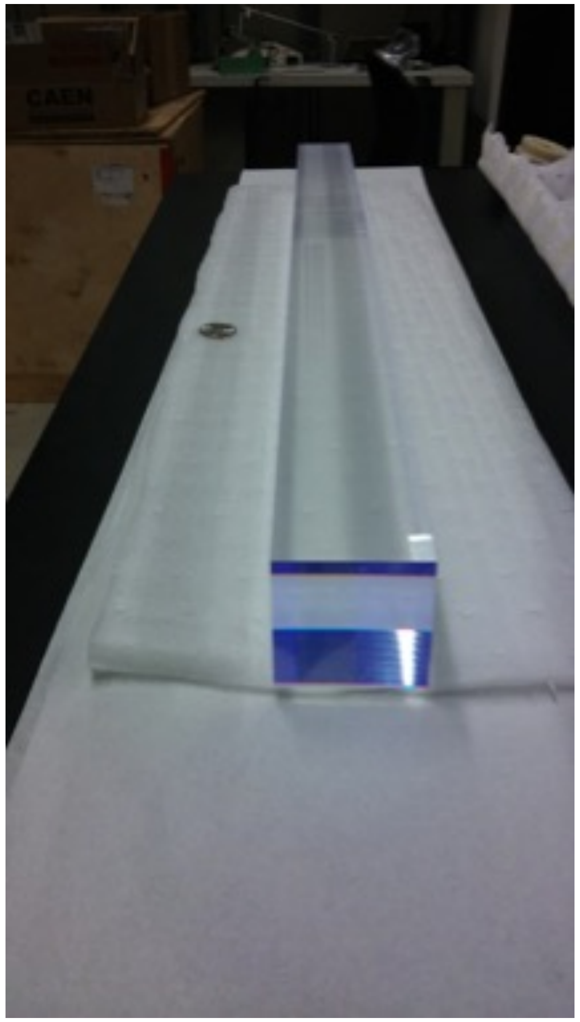
OSU Activities

OSU Facilities

- OSU has several prototype devices of interest to MilliQan
  - Four 2”x2”x80cm bars of Saint-Gobain BC408 plastic scintillator
  - A fifth scintillator bar incorporated with a Hamamatsu R7725 PMT
    - Assembled by Saint-Gobain





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OSU Facilities

- In addition to the R7725 PMT coupled to scintillator from Saint-Gobain:
  - Stand-alone R7725 PMT from Hamamatsu
  - Hamamatsu E5859-11 voltage divider base

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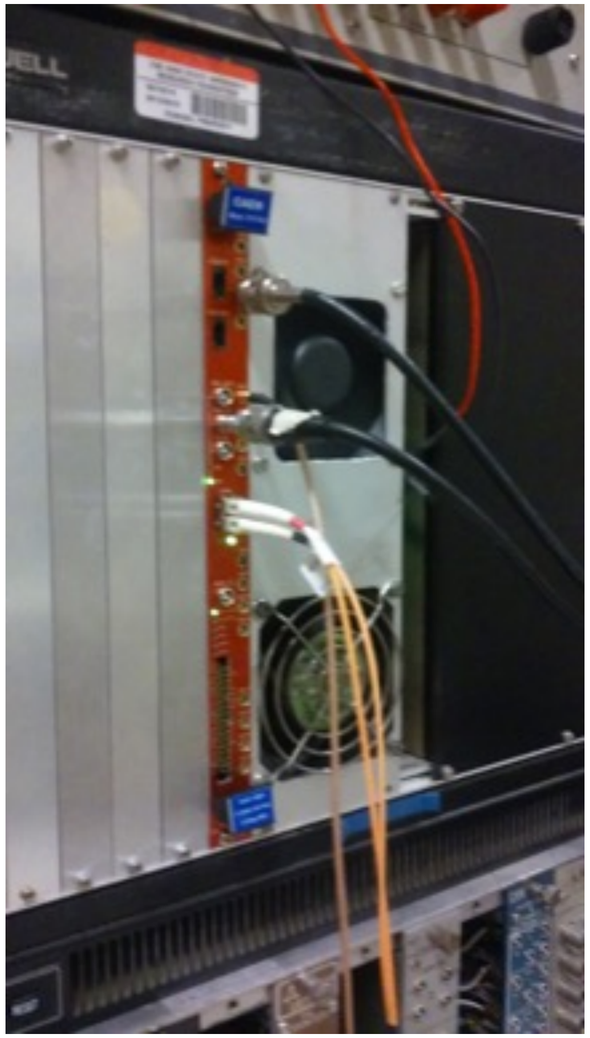
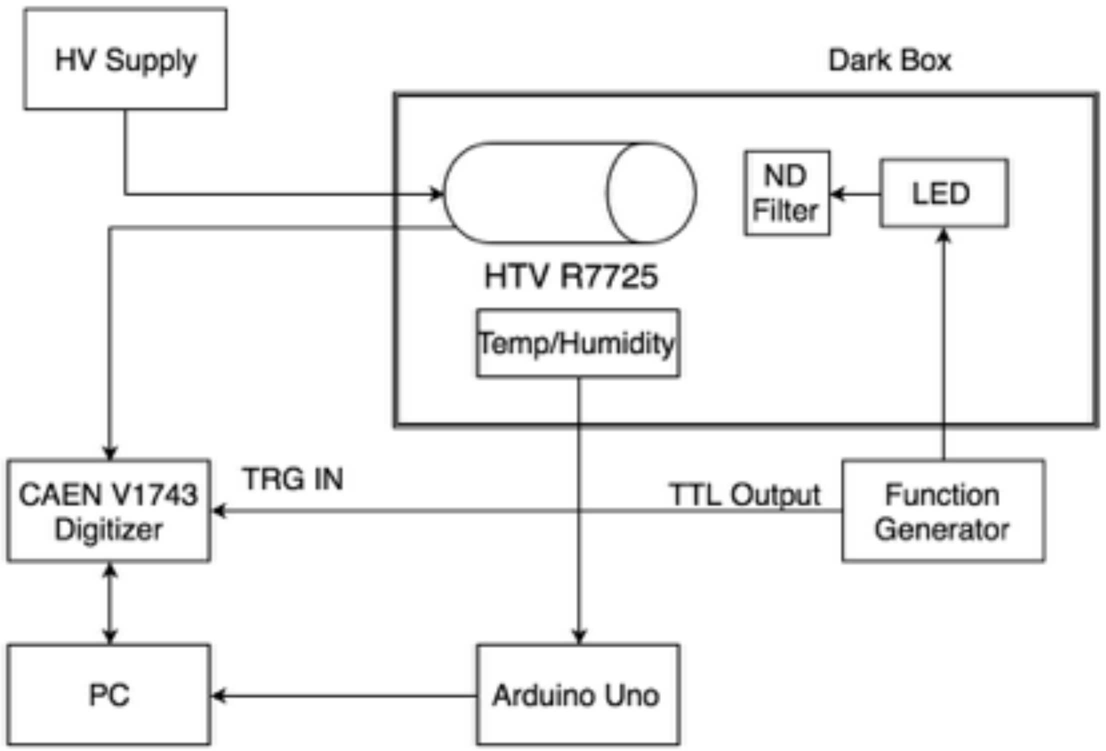
OSU Facilities

- We read out each device with a CAEN V1743 digitizer
- Connected to a PC by fiber optic connection to a CAEN A2818 optical controller





HV Supply

Dark Box

ND Filter

LED

HTV R7725

Temp/Humidity

CAEN V1743 Digitizer

TRG IN

TTL Output

Function Generator

PC

Arduino Uno

R7725 Dark Rate Measurements

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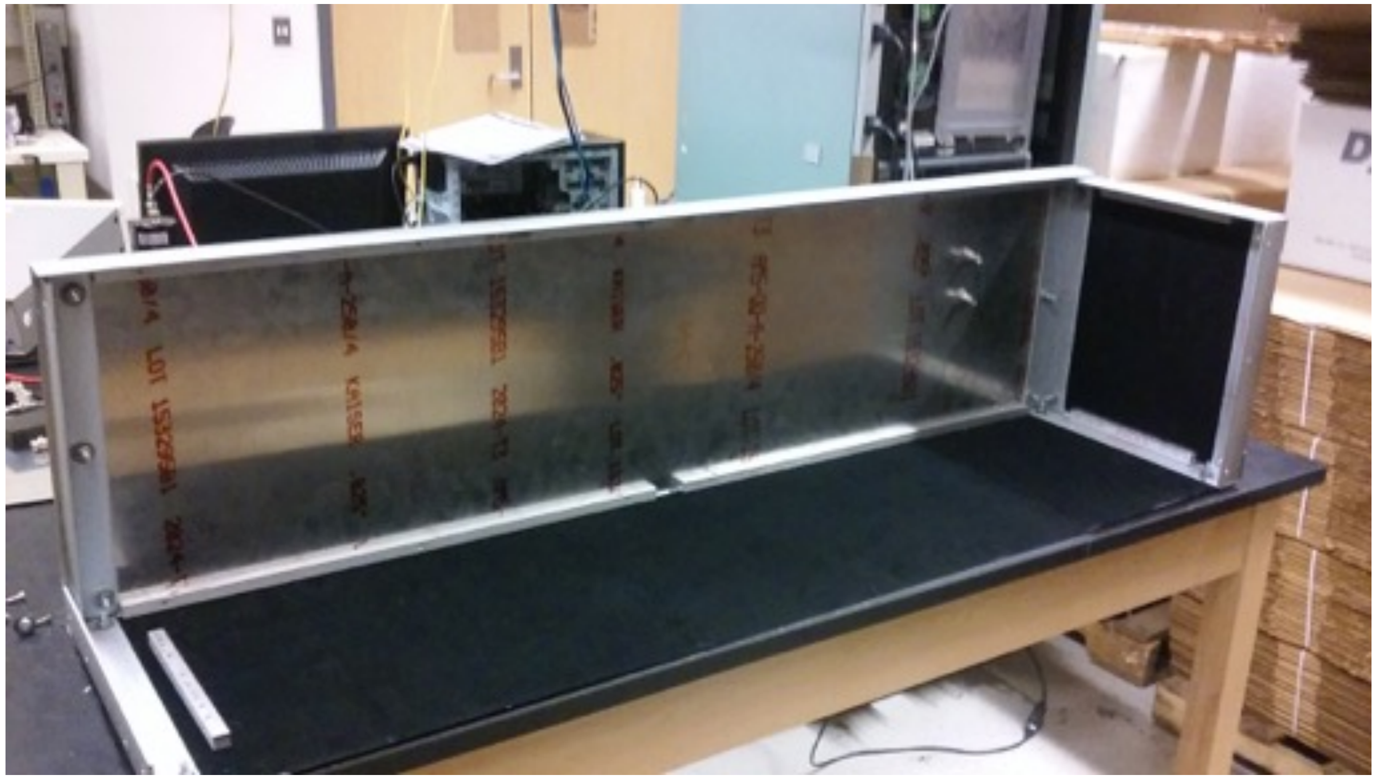
Light Shielding

- Over several months we have improved our HTV R7725 PMT
- Working to prevent ambient light from disturbing dark rate measurement



- Initially a metal tube with small amounts of electrical tape, within a larger metal box
    - Most of the box internally is covered with “black-out” paper

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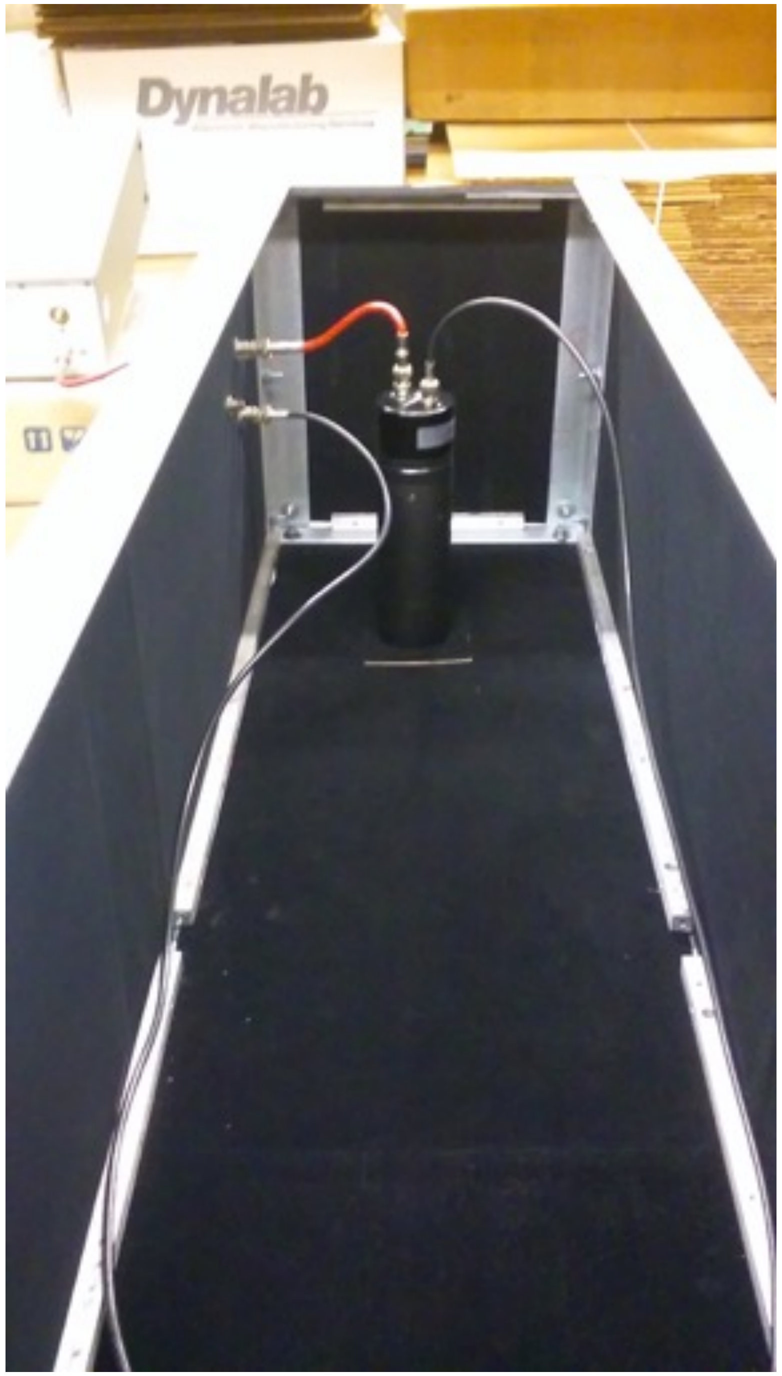
Light Shielding

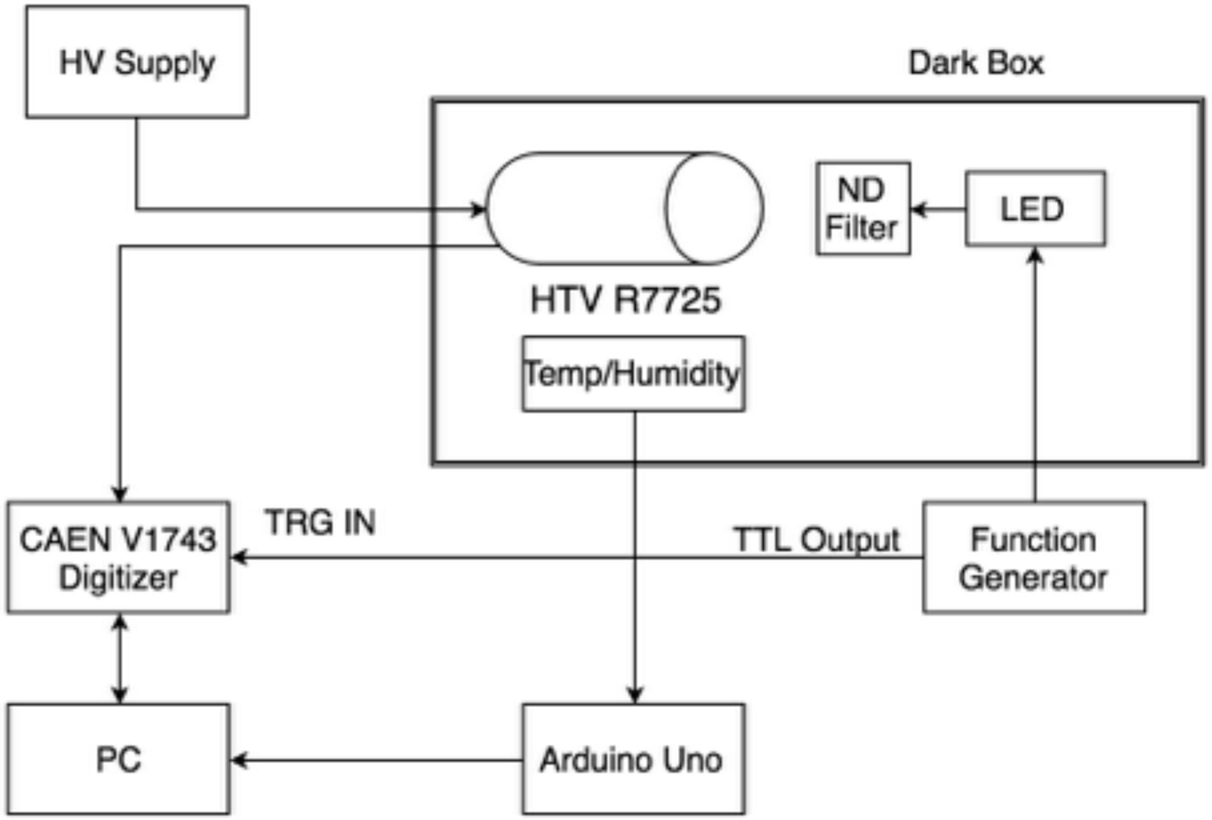
- Box designed to be large enough to accommodate PMT and scintillator

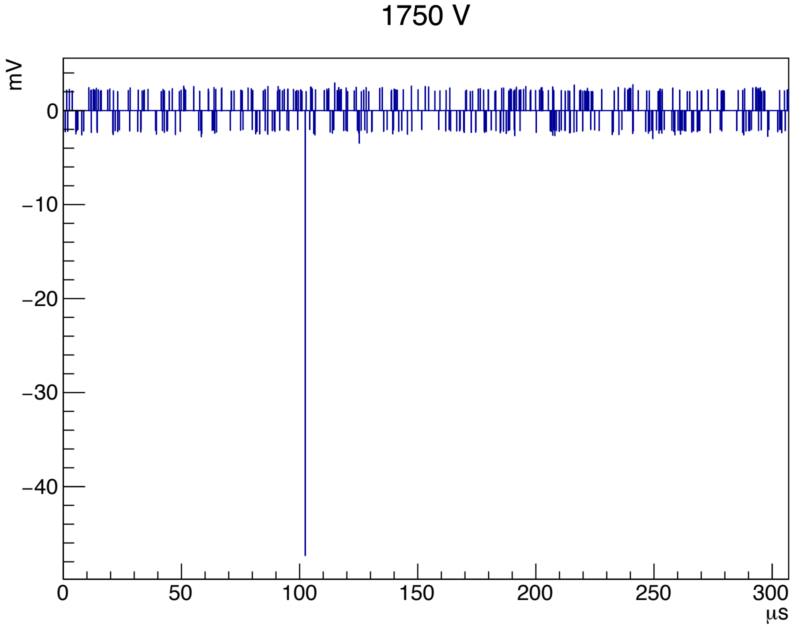


- Studio photography type “black-out” cloth

Dark Rate Measurement

- To observe the dark rate:
  - Trigger digitizer on TTL output of function generator (1500 Hz)
  - Configure digitizer for longest acquisition possible
    - 1024 samples @ 0.4 GS/s — 2.56 μs/event
  - Observe the amplitude of each event as the minimum sample in mV
  - Then the dark rate, above some threshold, is:





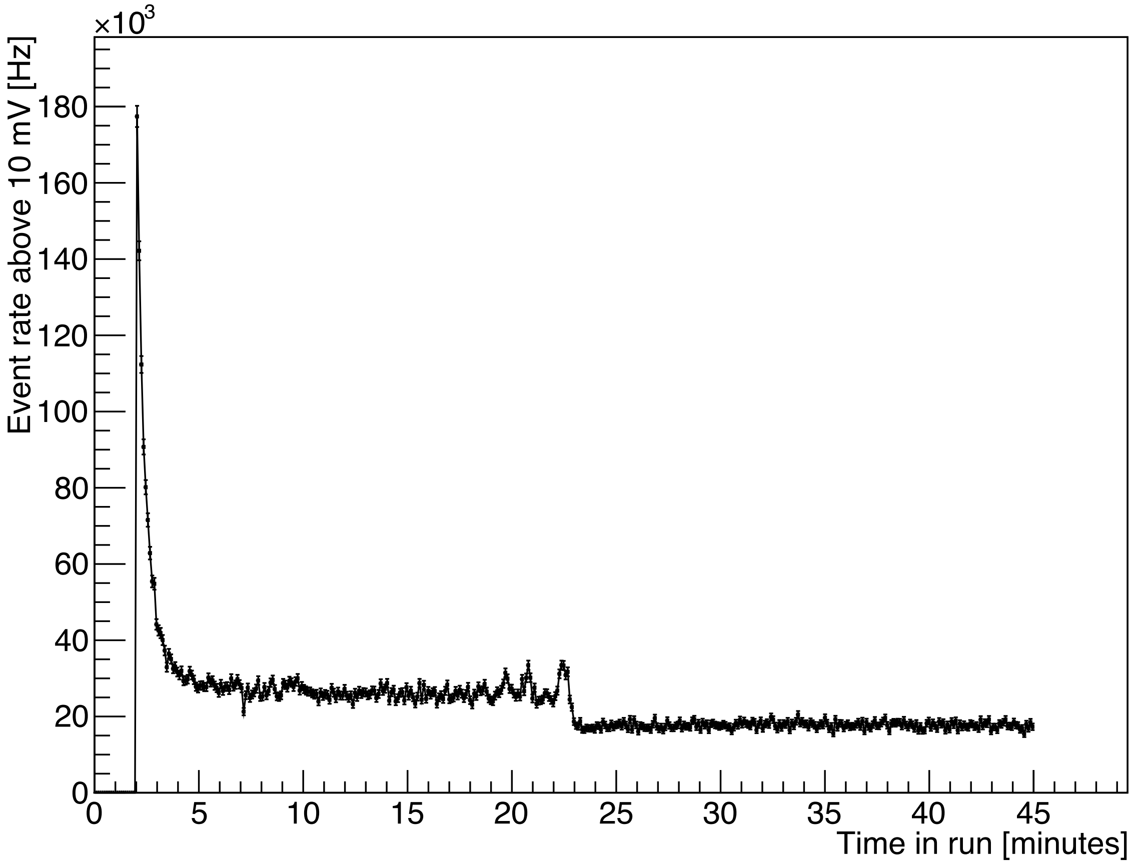
|sample| > 2 mV for 120 events

Events (amplitude > threshold) over the total acquisition time

where total acquisition time = N events times 2.56μs / event

Dark Rate Measurement

- Initial rate measurements were very high (20-30 kHz) and very unstable



- Sharp increase at the beginning is when the tube bias voltage is turned on
- We spent considerable time examining how repeatable this measurement was, and investigating the cause of the large drops in rate

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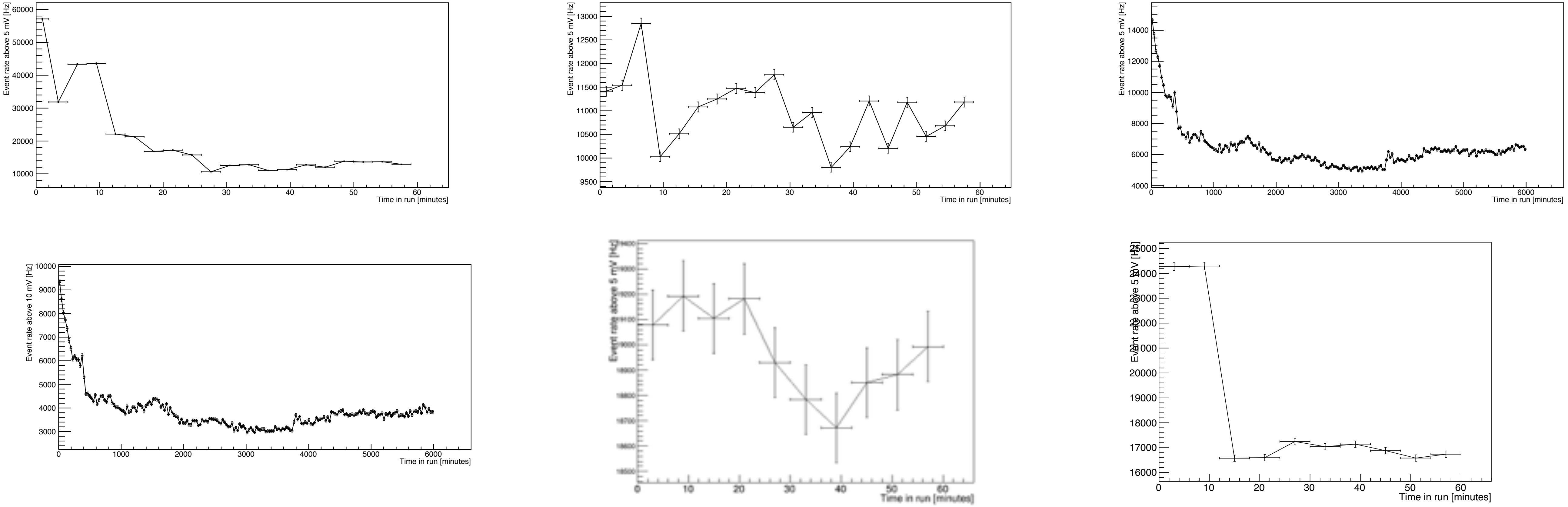
Dark Rate Measurement

- Many repeated measurements by several different users:

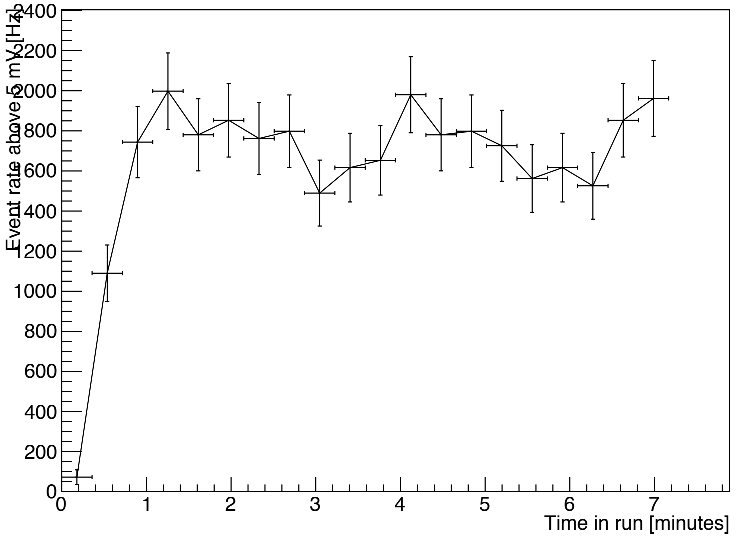


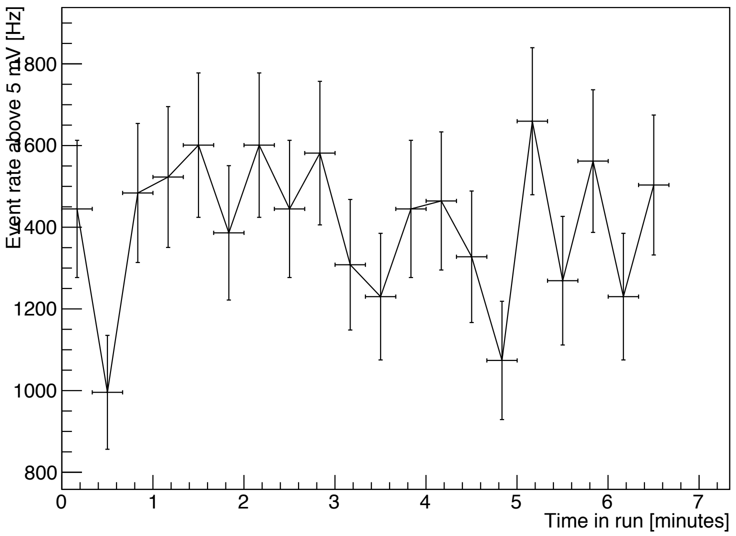
- After observing different rates for different users, and even rate changes within data-taking runs, we convinced ourselves that environmental factors were not being controlled
  - In particular we suspected a very large light leak

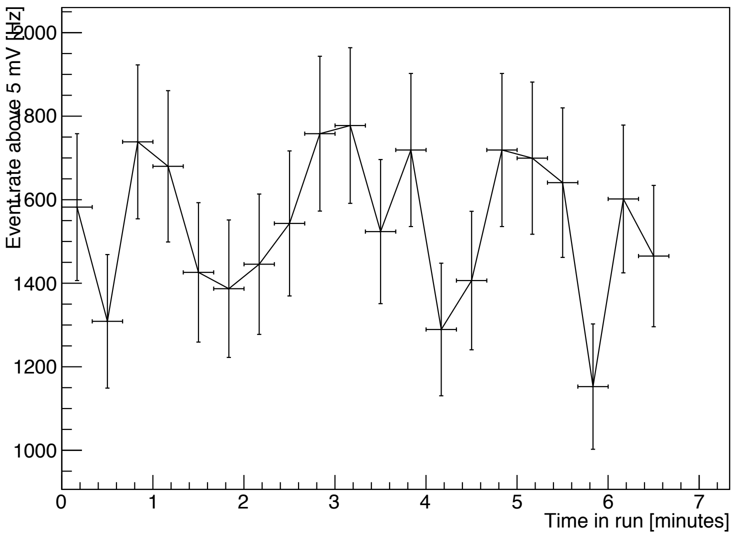
Dark Rate Measurement

- Applied a very aggressive amount of black electrical tape
- Not visible here: cathode window itself is covered with black-out paper and directly taped

- A large decrease in rate resulted, confirming the existence of large light leaks

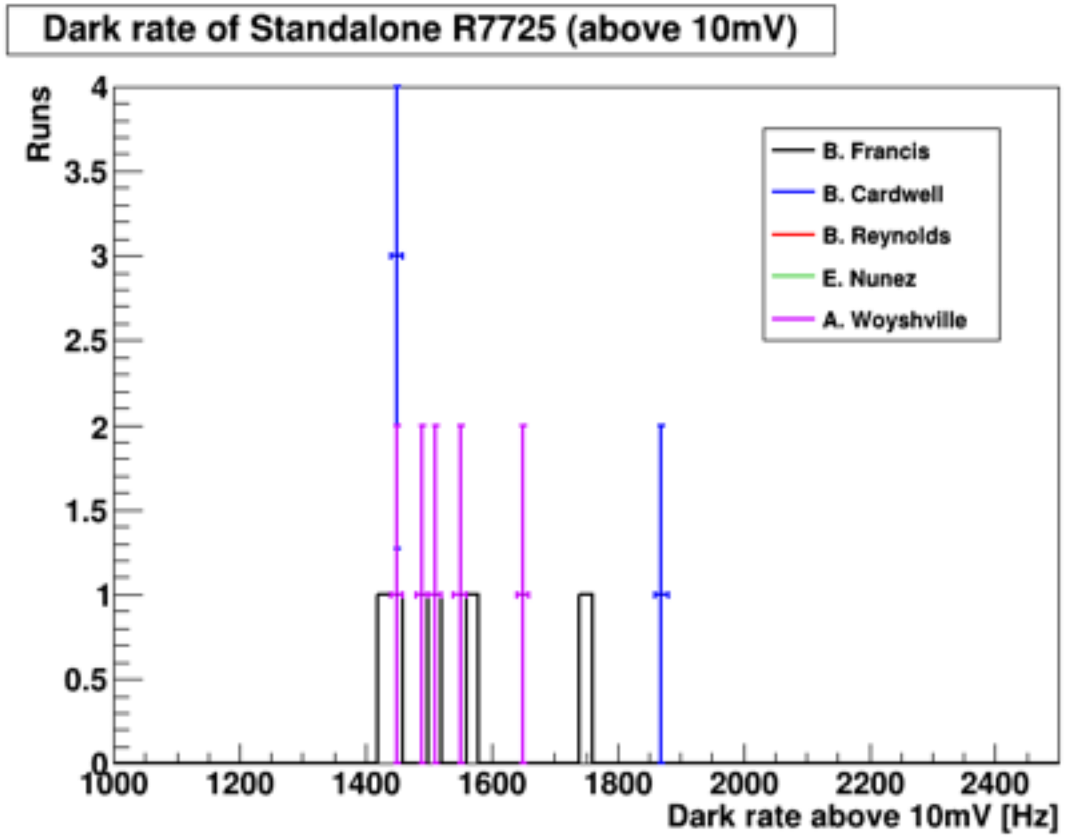






Dark Rate Measurement

- Here, several separate measurements recorded over several days, each for 30 minutes of real time (6.2 seconds total acquisition live time)



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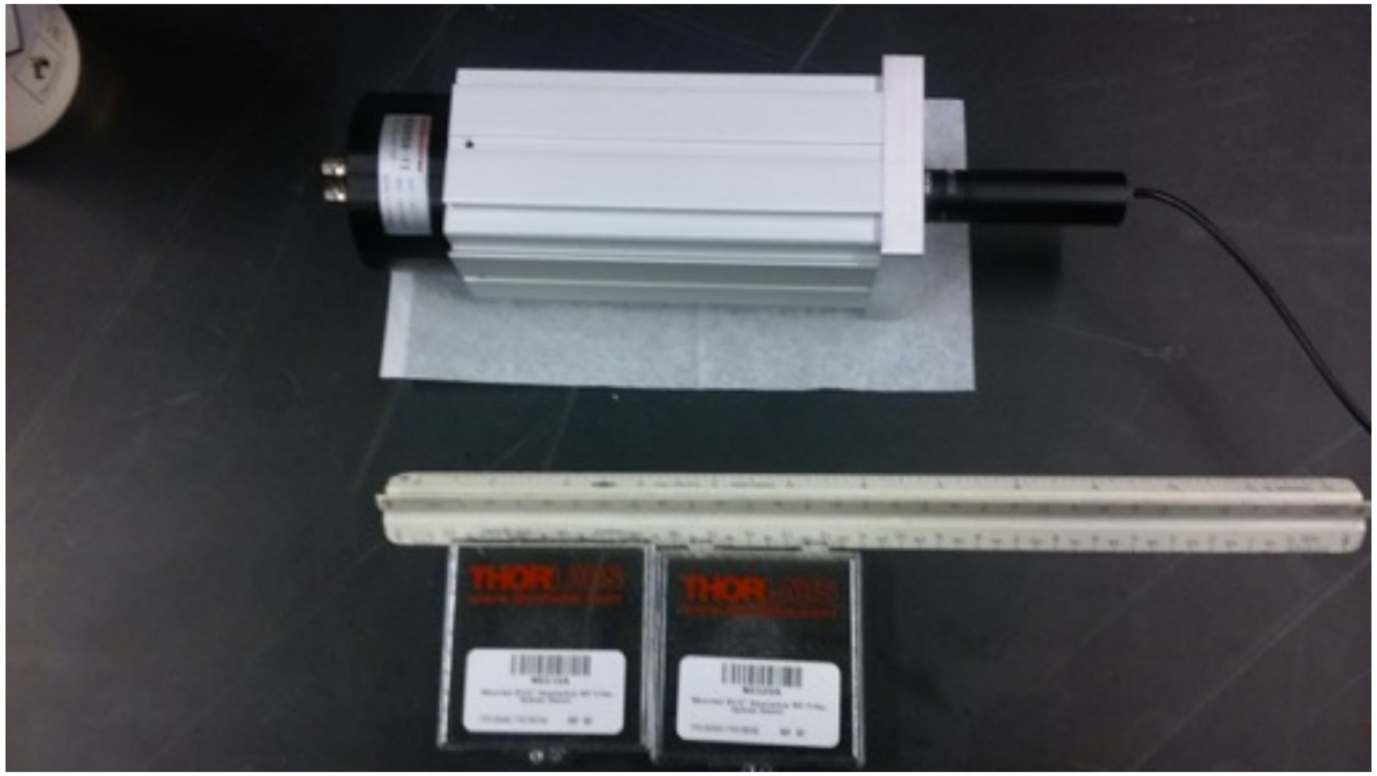
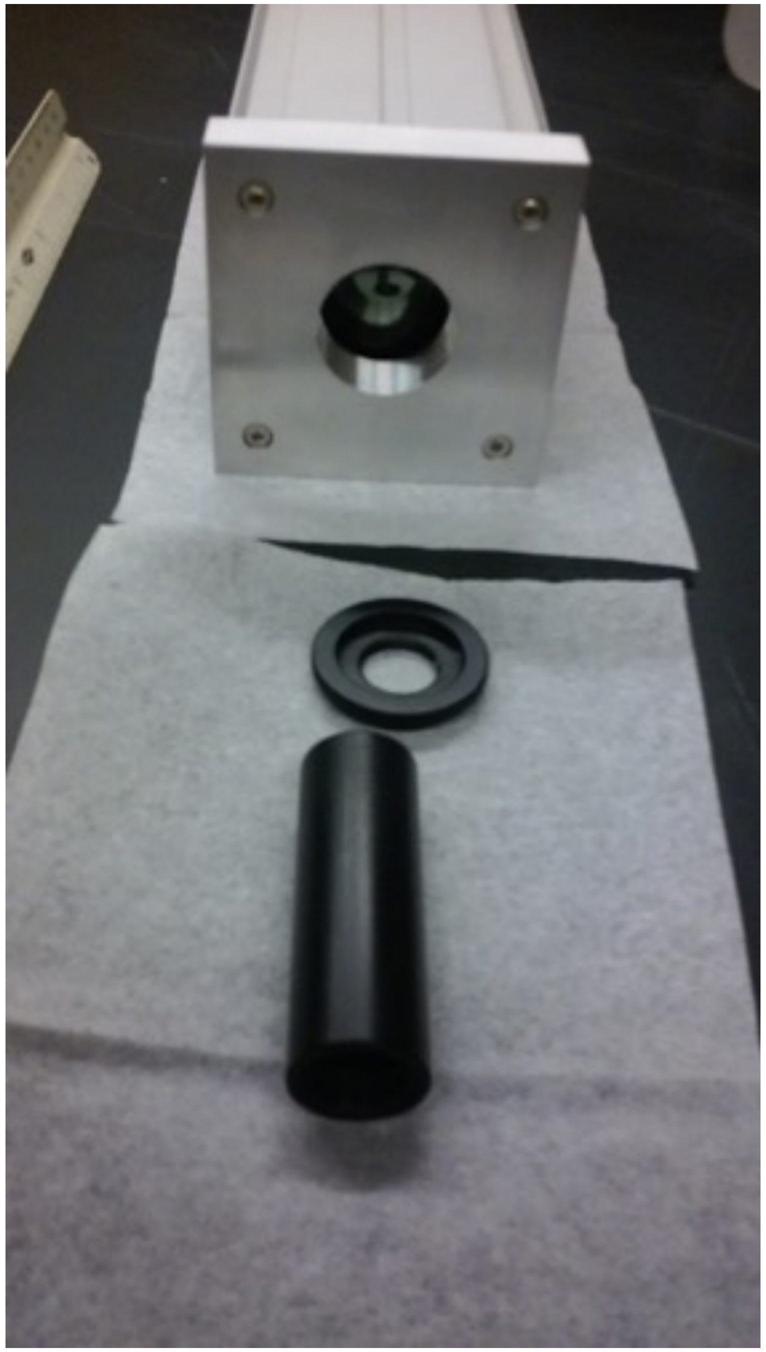
New PMT Enclosure

- Seeing that light leaks are easily missed, the next challenge was in coupling an LED and optical fiber without re-introducing large light leaks
- Constructed a new enclosure aiming to better control for environmental factors
  - Discrete neutral density filters (rather than a continuously variable one)
  - Tightly-fitting lens tube and LED mount from Thorlabs
    - No need for fiber coupling, LED directly faces PMT window
  - Temperature and humidity measurements
  - Tightly-fitting aluminum enclosure that can accept future cooling elements



New PMT Enclosure

- Thorlabs LED and filters:
  - LED430L — 430nm, 8 mW



- NE500A series neutral density filters:
  - NE510A (T=10^{-1}), NE530A (T=10^{-3}), NE550A (T=10^{-5})
  - Note: “OD5” —> optical density 5 —> T=10^{-5}
  - I will make heavy use of this notation!
    - “OD4” is a combination of OD3 and OD1

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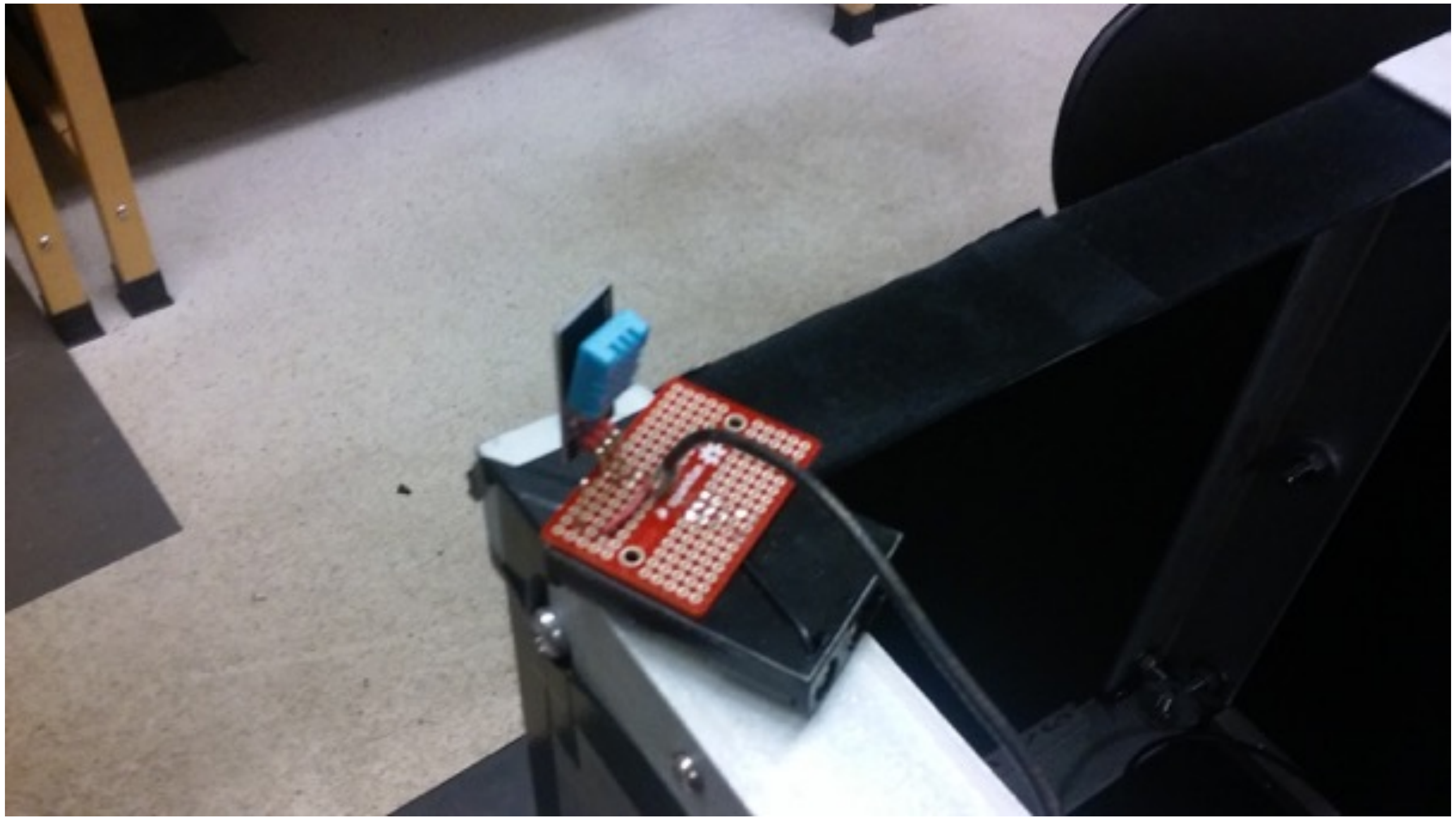
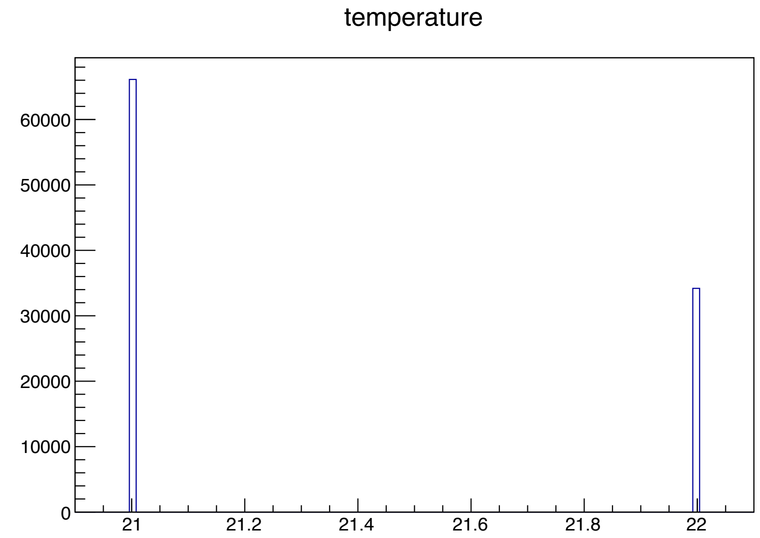
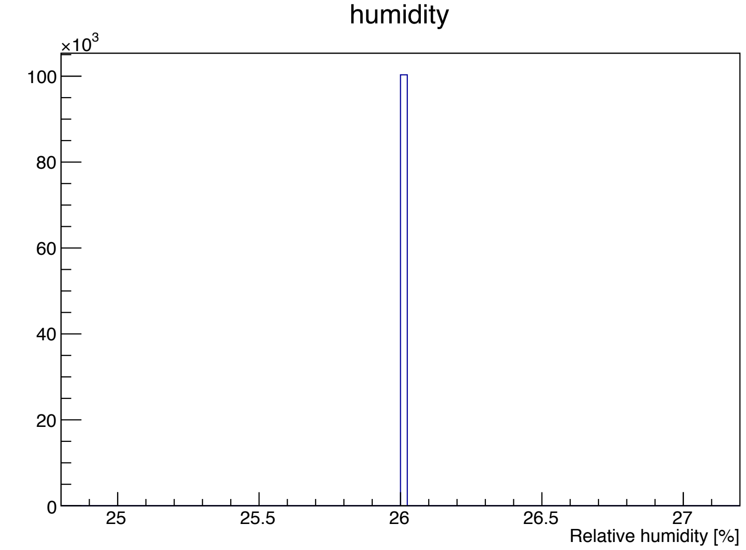
New PMT Enclosure

- A simple DHT11 sensor provides temperature (± 1° C) and relative humidity (± 1%) measurements from inside the larger box
- Read out with an Arduino Uno that is integrated into the DAQ software and data stream



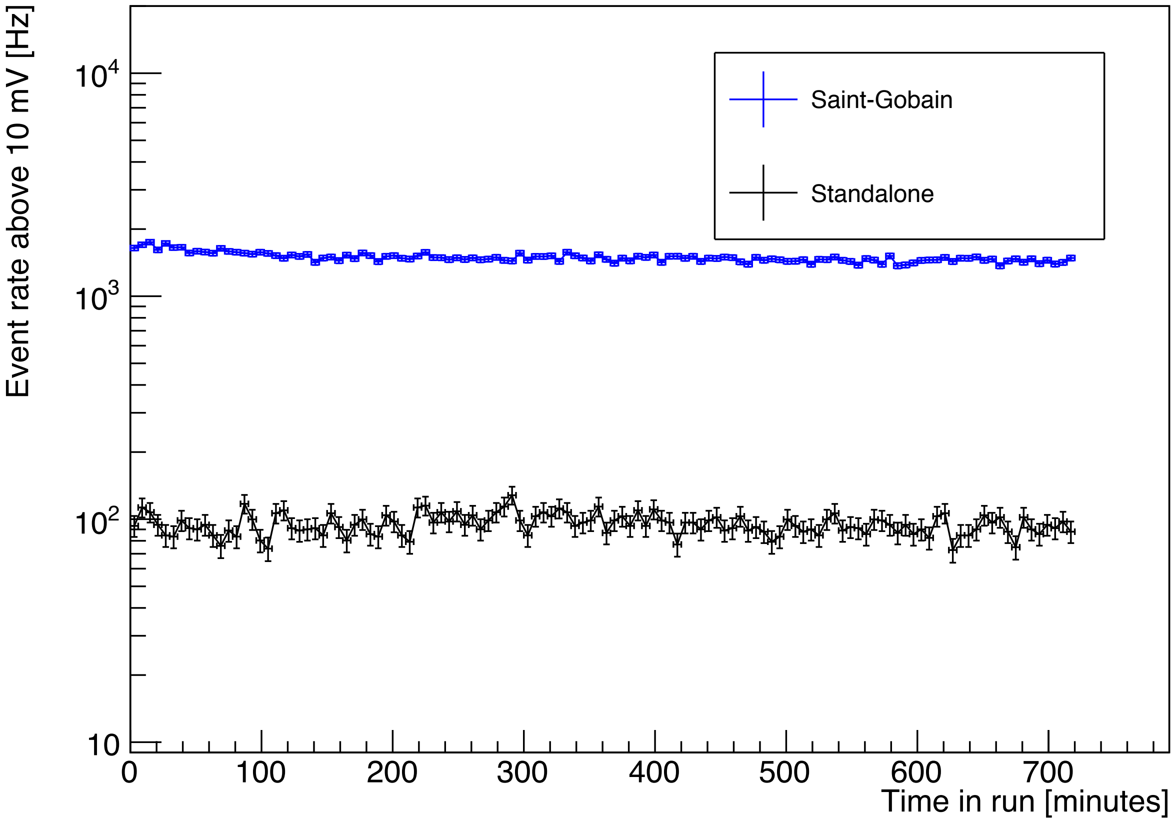




~60 seconds

New PMT Enclosure

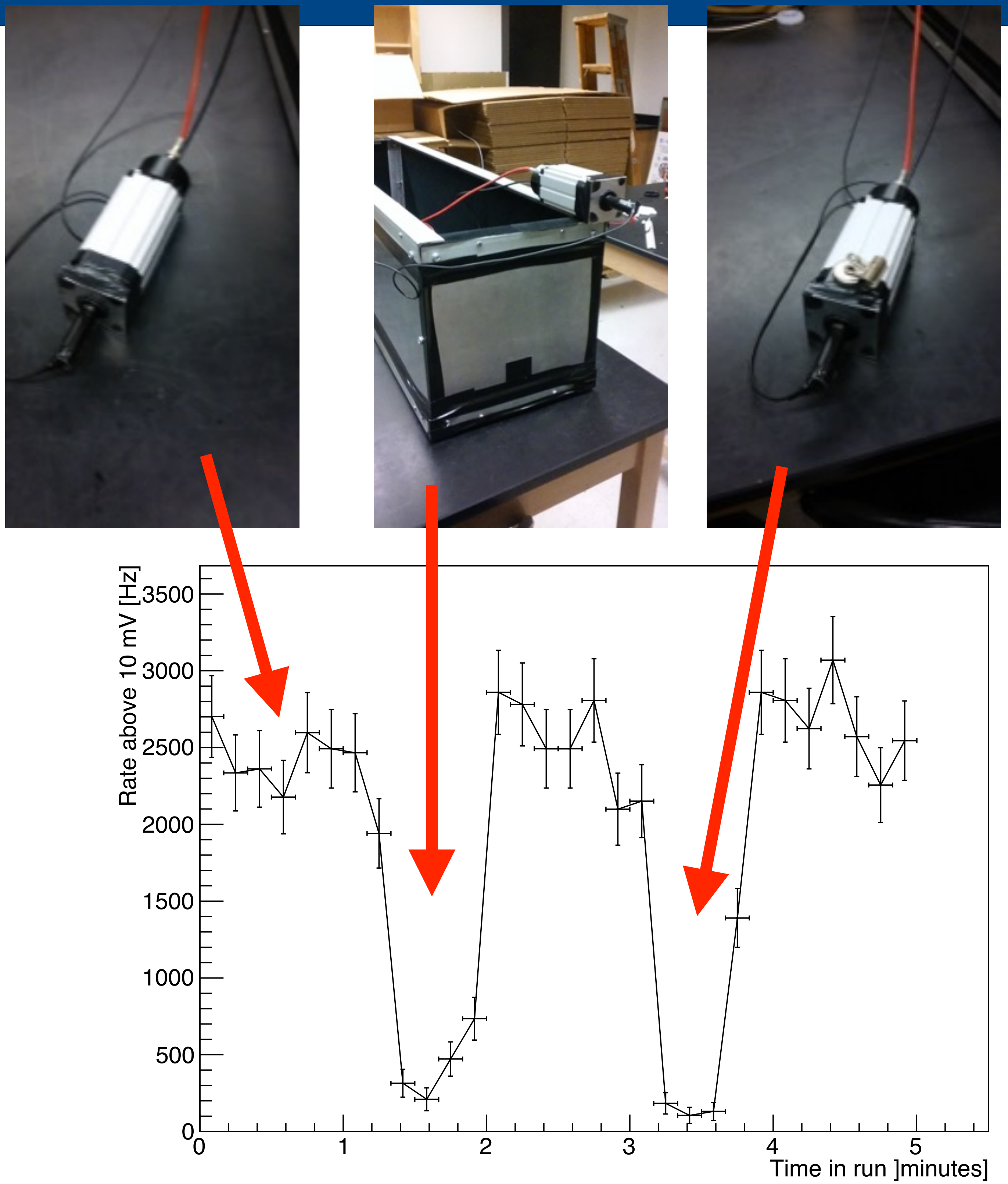
- With this new enclosure intended to be better light-proofed, we first measured the dark rate
- The new enclosure was intentionally left outside of the larger dark box to test for light-tightness



- A very low rate (100 Hz)!
- We very quickly observed that simply moving the enclosure to a different location increased this

New PMT Enclosure

- Happened to have placed photocathode above the edge of a steel component of the dark box
- Placing a magnet near the photocathode similarly reduces this
- In both cases, applying LED light does not give observable signals
- Not surprising that a magnetic field would reduce the gain and dark rate
    - Is however surprising that this material would cause a similar effect
- Need to acquire a gauss meter and measure the field in this particular areas
- For the time being we avoid placing the enclosure on large metal objects



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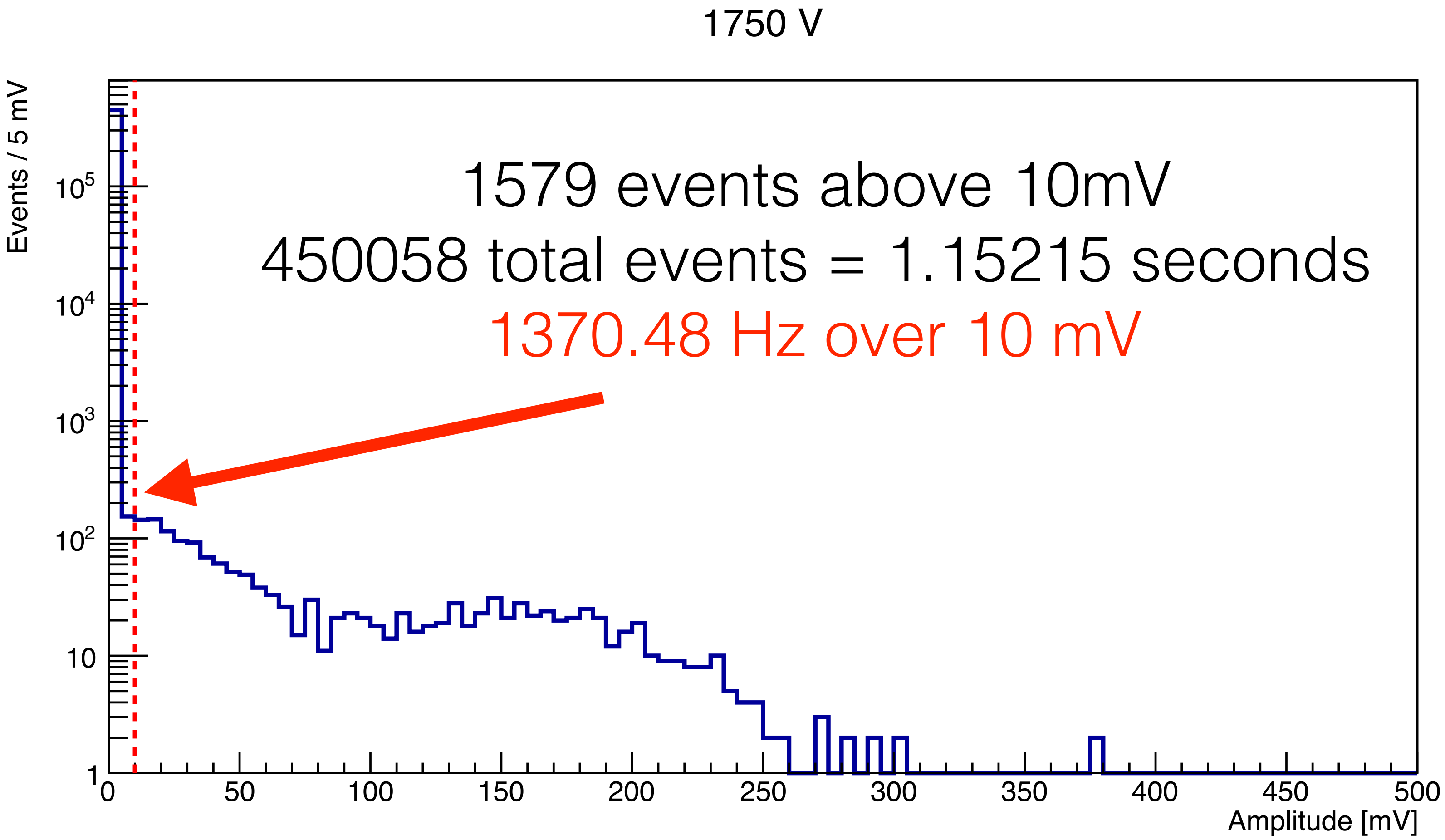
Dark Rate Measurement

- With this new enclosure (avoiding known areas that drastically reduce the gain of the PMT), the observed dark rates are slightly lower than with the previous enclosure (very taped-up)
- An example at the recommended bias voltage, -1750 V:



1579 events above 10mV
450058 total events = 1.15215 seconds
1370.48 Hz over 10 mV

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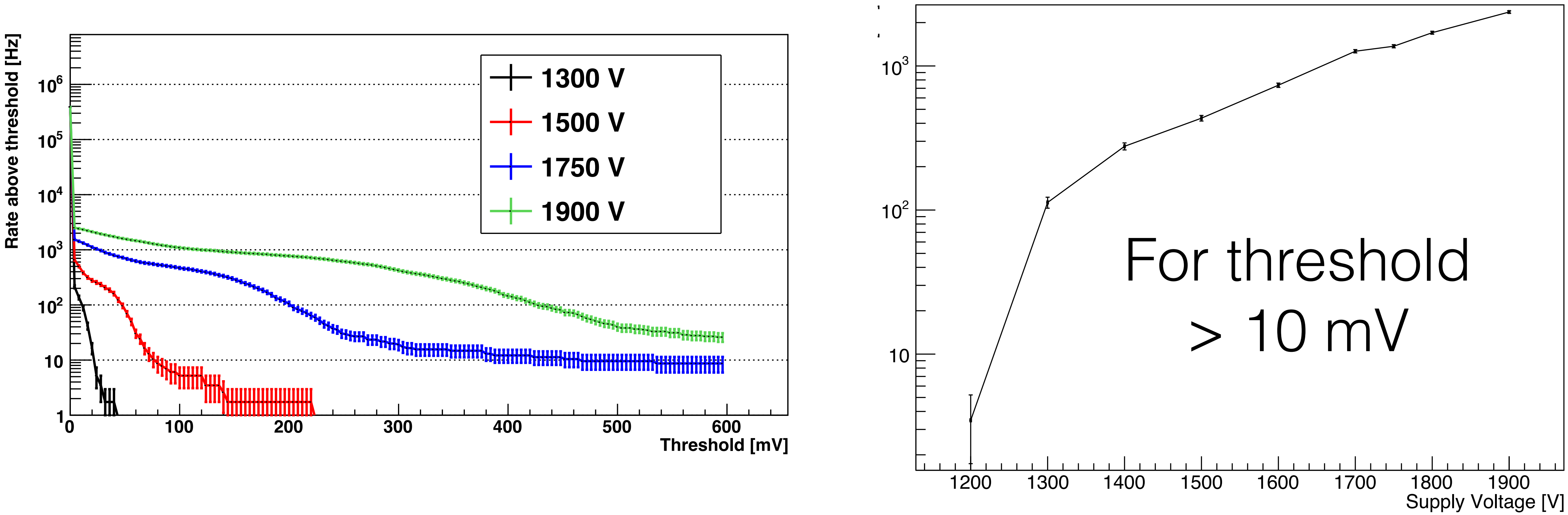
Dark Rate Measurement

- Performing this measurement over a range of PMT bias voltages:



For threshold > 10 mV

- Ultimately, a rate of 1 kHz should be possible given appropriate choice in trigger threshold
- The LOI quotes an expected rate of 500 Hz per channel, which should be achievable with some cooling

Dark Rate Measurement

- Of course, this threshold is an arbitrary choice
- A more meaningful threshold, and thus dark rate measurement, is found relative to the single photoelectron (SPE) response

R7725 Single Photoelectron Response

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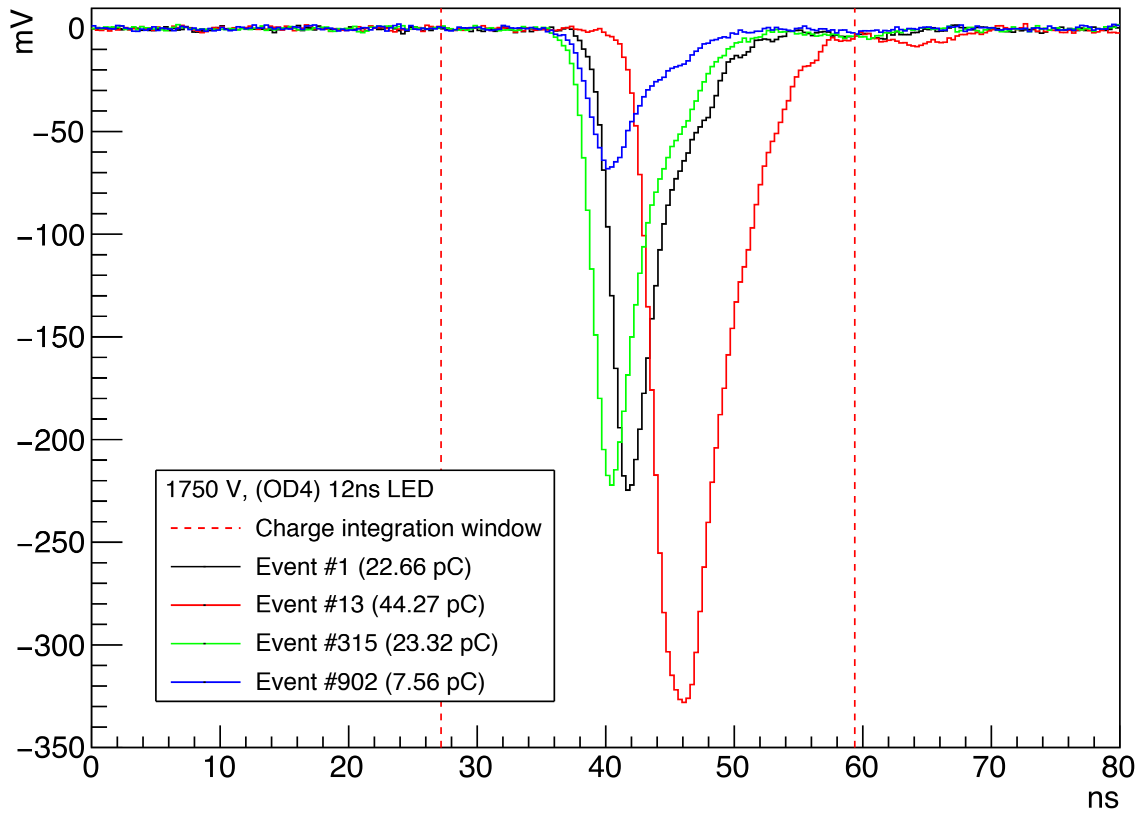
Calculating charge with V1743

- While waveform amplitude is a directly triggerable quantity and of interest for the dark rate, the total charge is of more interest when calculating PMT gain
- To calculate the charge for a given waveform, define a charge integration window:



- And integrate as:

$$\text{Charge [pC]} = 10^9 \frac{\text{pC}}{\text{mC}} \cdot \sum_i \frac{V_i\,[\text{mV}] - \text{baseline}}{50\ \Omega} \frac{1\ \text{s}}{3.2\times10^9}$$

- where the “baseline” is the average voltage in the first 16 samples of the waveform

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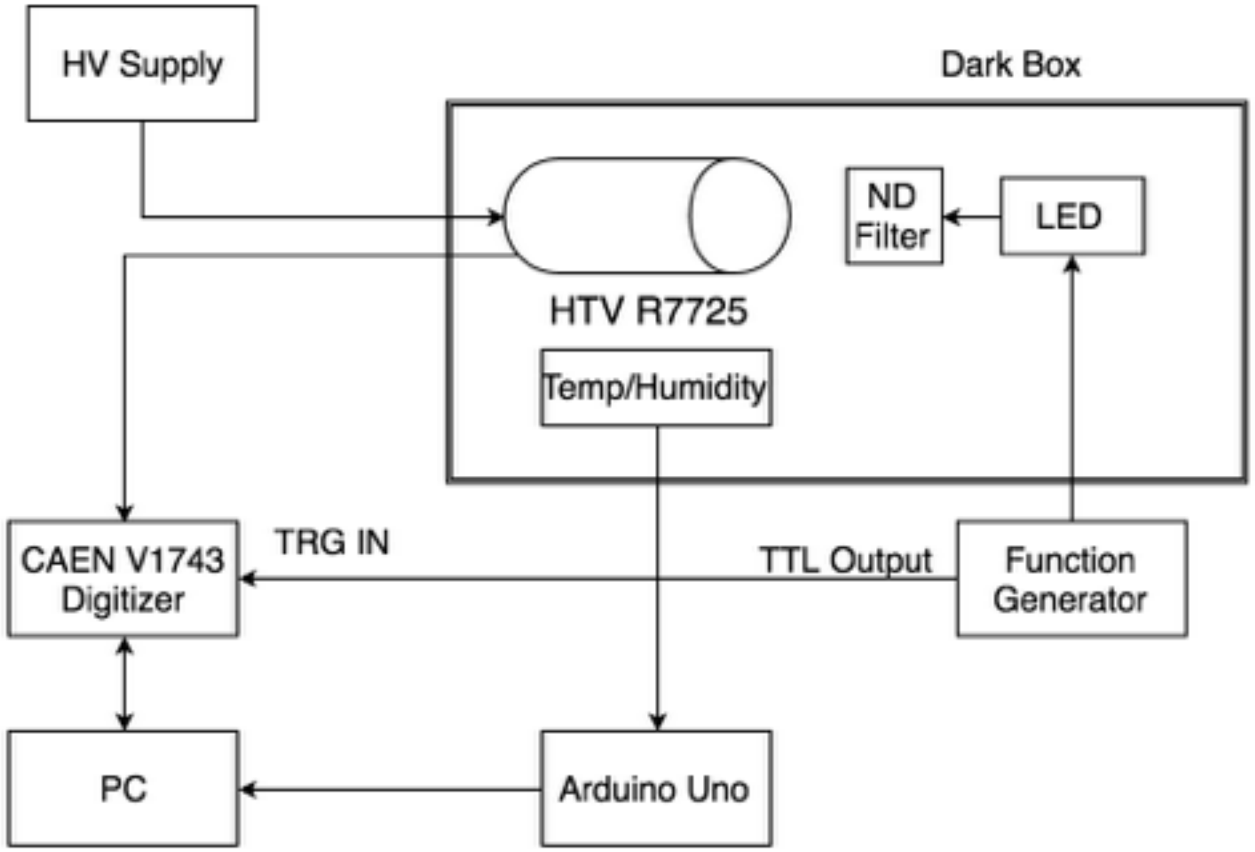
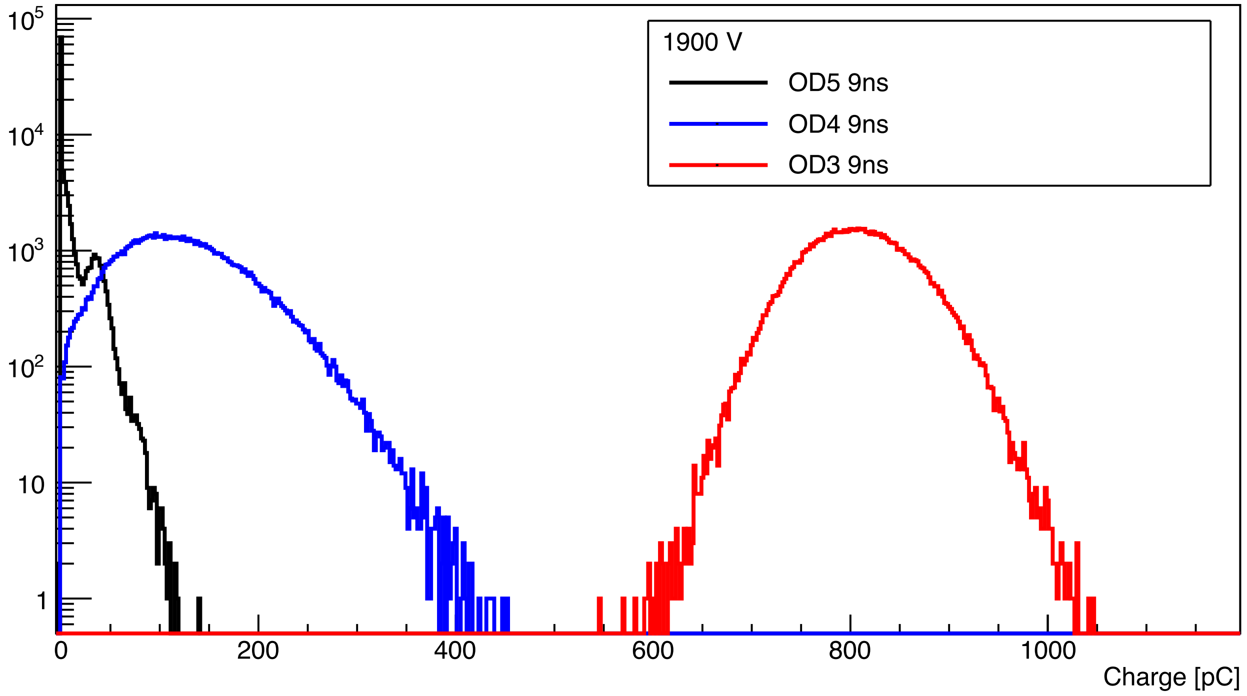
Observing the SPE

- To observe the single photoelectron (SPE) response:
  - Drive the LED with 3V “square” pulses at 1800 Hz for short periods of time
    - Function generator has rise/fall time of 2.5ns, less square at short widths
  - Configure the digitizer for its maximal sampling rate (3.2 GS/s) and shortened record length (256 samples) to handle 1800 Hz incoming trigger rate
  - Trigger on the LED driving signal (TTL output to V1743 TRG IN)

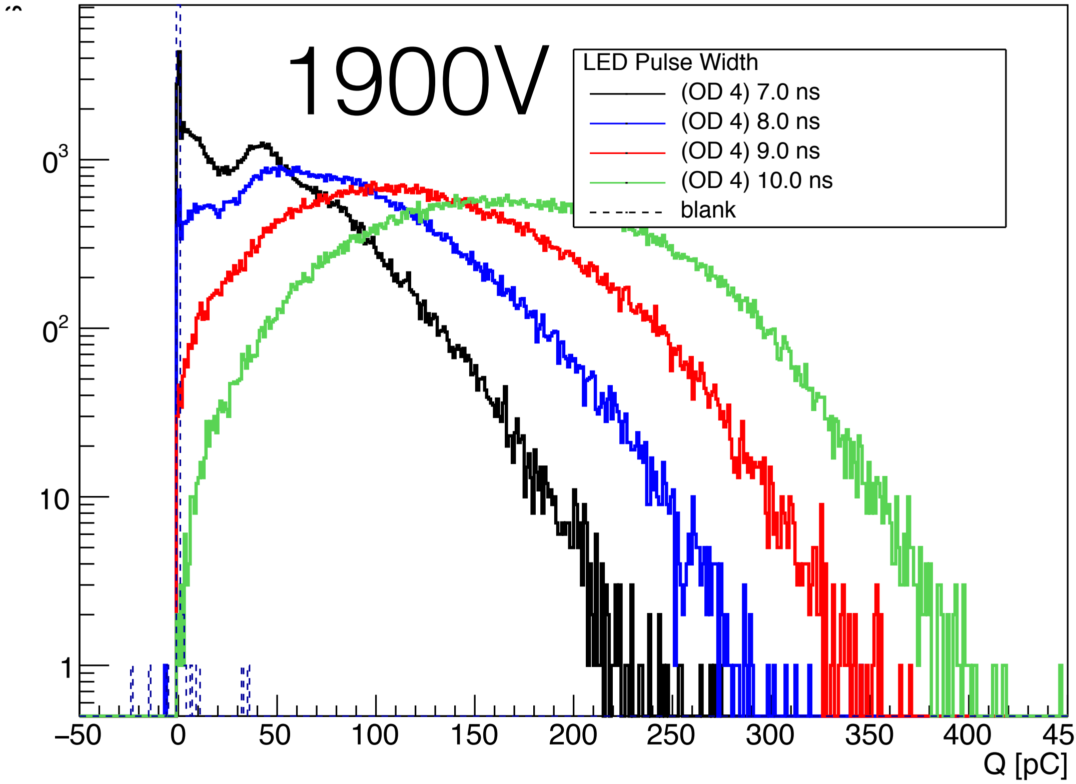


Observing the SPE

- Several “knobs” to adjust the light intensity:
  - LED driver pulse width
  - Optical density of neutral density filters
    - Have 3 different filters to combine (OD1, OD3, OD5 — Transmission ~ 10%, 0.1%, 0.001%)
- Additionally a “knob” to adjust the PMT gain, the supply voltage
  - Range from 1200 V to 1900 V (max rating is 2000 V, recommended 1750 V)



Adjusting ND filters



Adjusting LED width

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Calculating SPE Response

- We attempt several separate methods to determine the single photoelectron (SPE) response:
  - Method 1 — in the many-PE (gaussian) regime, scale the mean charge of distributions with the light intensity
    - Altering intensity with the LED pulse width or by changing ND filters
  - Method 2 — functional fits of the charge distribution
  - Method 3 — “Model Independent Approach” paper method

- Some definitions first:
  - μ, <NPE> — average number of photoelectrons
  - Q_1, σ_1 — single photoelectron charge and width
  - Q_∞, σ_∞ — large NPE, overall distribution mean
  - c.f. Bellamy et al — *Nucl. Inst. and Meth. for Phys. Res. A 339 (1994) 468-476*

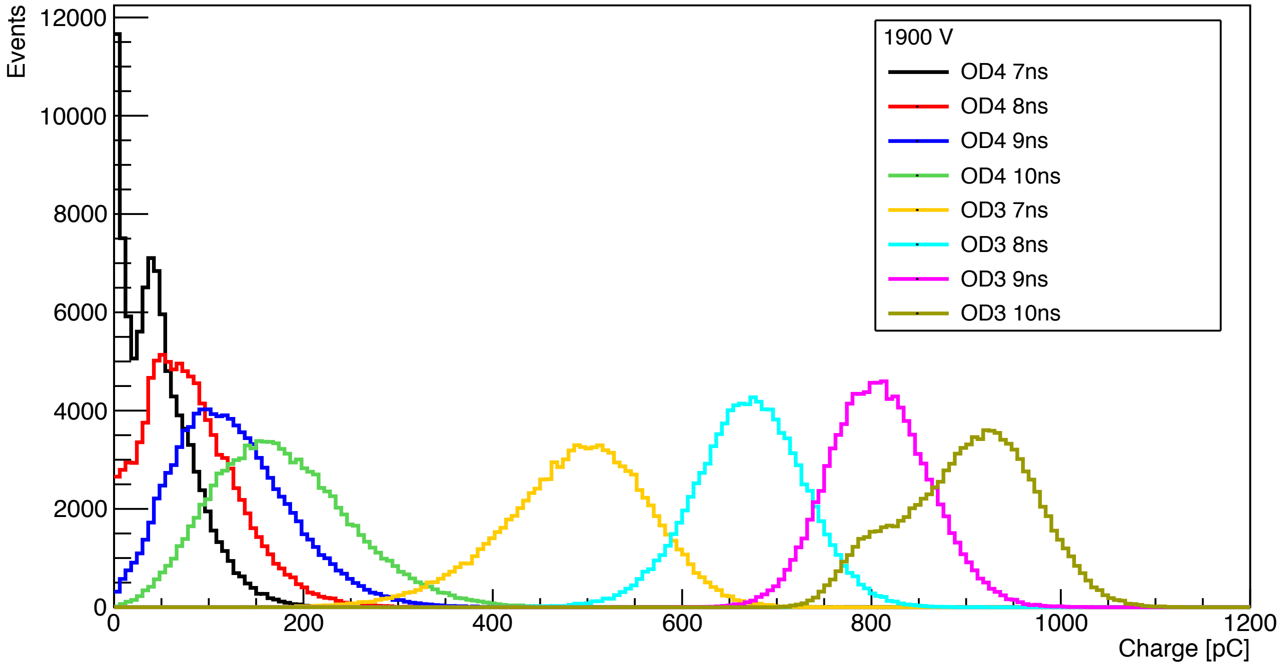
SPE: Gaussian Regime

- Method 1:
- In the limit of large <NPE>, the poisson distribution of NPE approaches gaussian
- Charge distribution approaches a gaussian with*

$$Q_\infty = \mu Q_1$$

$$\sigma_\infty = \sqrt{\mu(\sigma_1^2 + Q_1^2)} \quad \longrightarrow \quad \left(\frac{Q_\infty}{\sigma_\infty}\right)^2 = \frac{Q_1^2}{\sigma_1^2 + Q_1^2} \cdot \mu$$

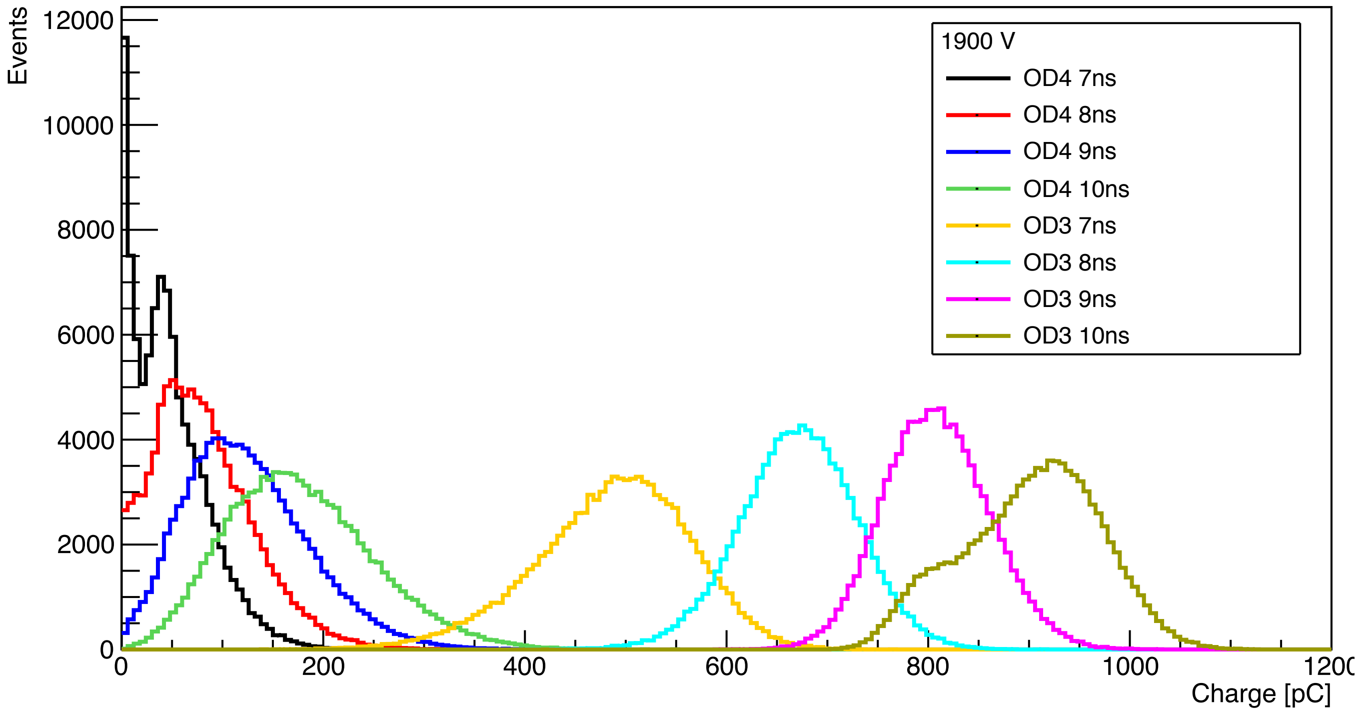
- So we take several datasets at high gain (1900 V) and higher LED intensities
  - Using ND filter densities of OD4 and OD3

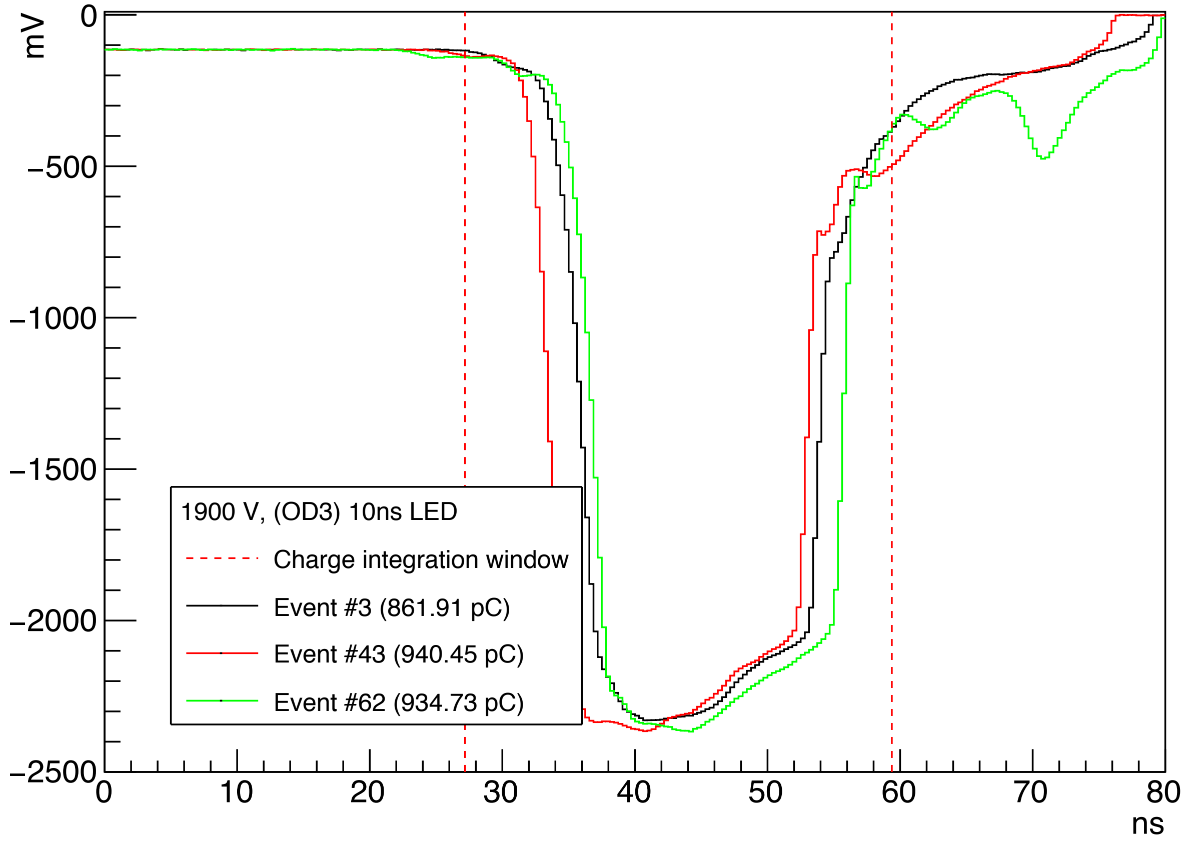


*c.f. Bellamy et al

SPE: Gaussian Regime

- In this range of LED intensities, only OD3 7-9ns and OD4 10ns appear fairly gaussian
- For the OD3 at 10ns dataset, very long and large pulses disturb the charge calculation by falling outside the defined integration window





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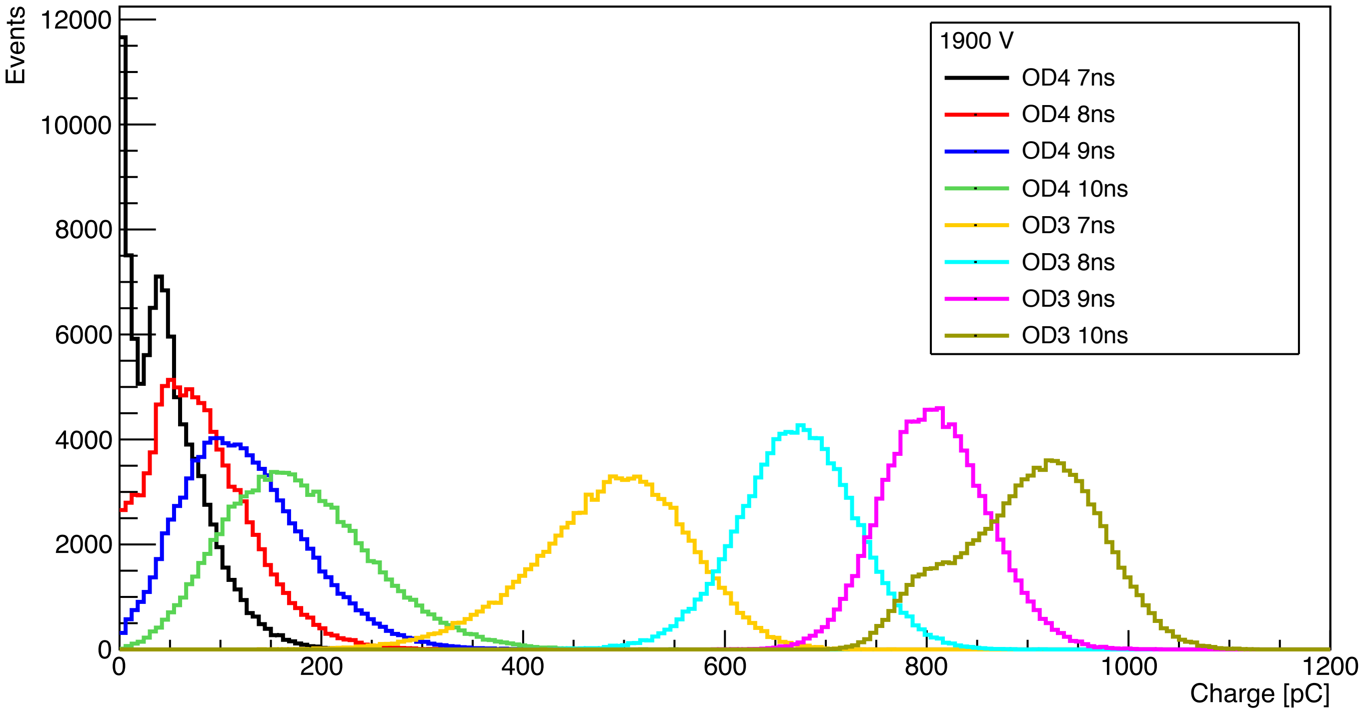
SPE: Gaussian Regime



	Mean (pC)	Width (pC)	(Mean/ Width)^2
OD4 9ns	124.6	61.2	4.1
OD4 10ns	177.5	72.7	6.0
OD3 7ns	487.0	76.9	40.1
OD3 8ns	670.7	58.1	133.4
OD3 9ns	808.2	52.3	239.2

For gaussians:

$$\left(\frac{Q_\infty}{\sigma_\infty}\right)^2 = \frac{Q_1^2}{\sigma_1^2+Q_1^2}\cdot\mu$$

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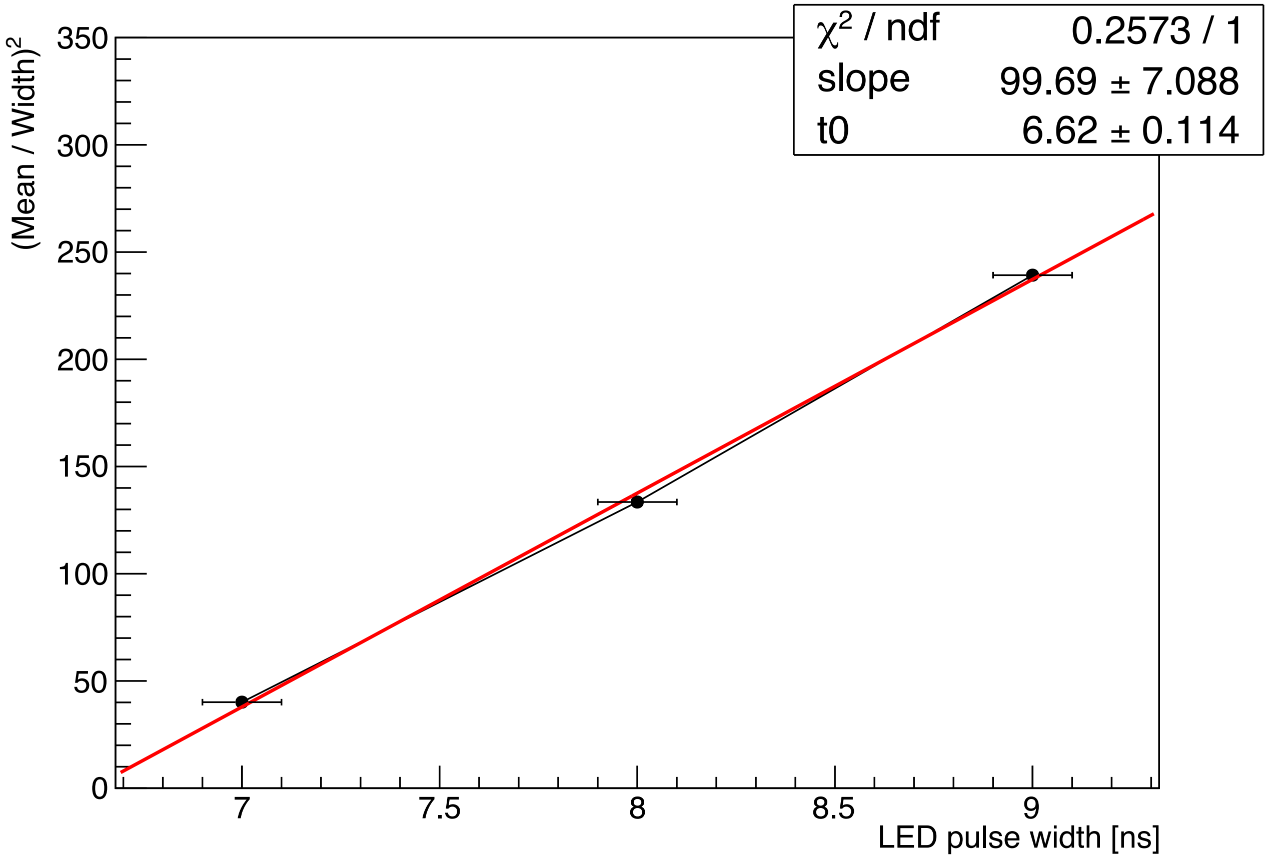
SPE: Gaussian Regime

- Varying LED pulse width:
  - Assuming it takes time **t0** for the LED to reliably begin emitting light
  - and assuming each nanosecond of LED light gives **α** pC of charge, then expect

$$\left(\frac{Q_\infty}{\sigma_\infty}\right)^2 = \frac{Q_1^2}{\sigma_1^2+Q_1^2}\cdot\alpha\cdot\left[\text{Pulse width} - t_0\right]$$



- Varying LED pulse width for OD3 at 1900V:
  - Quite linear
  - However the slope of this line is still a product of the light intensity and the SPE parameters
  - Cannot extract SPE here without calibrating the light source

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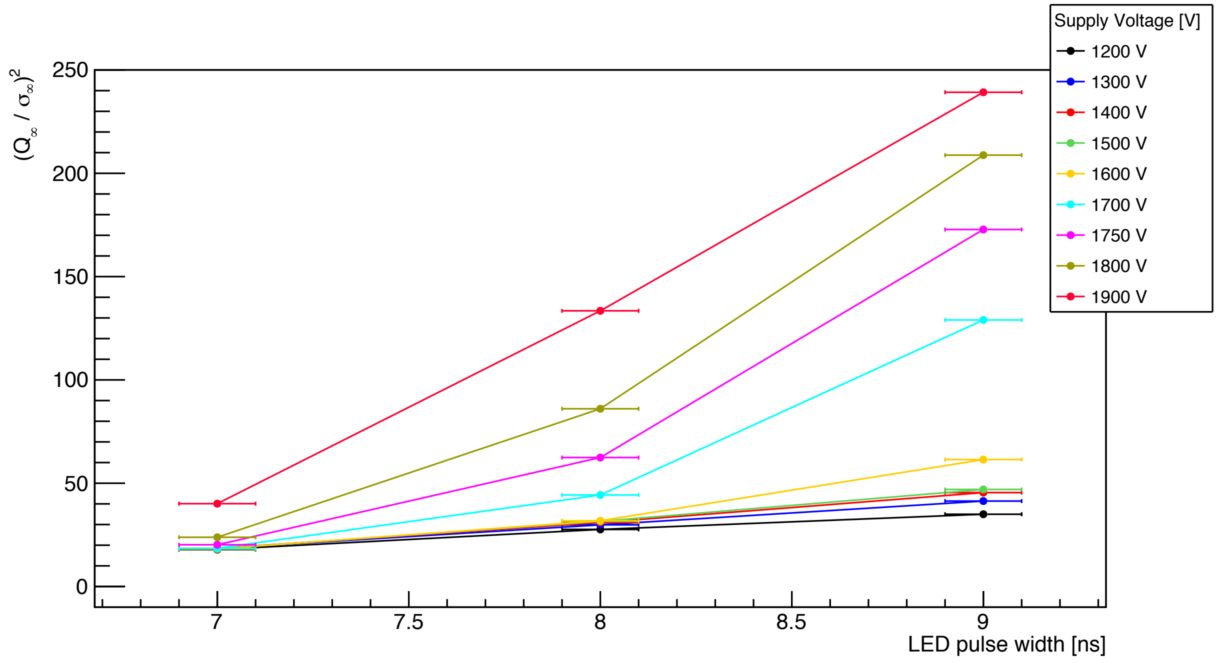
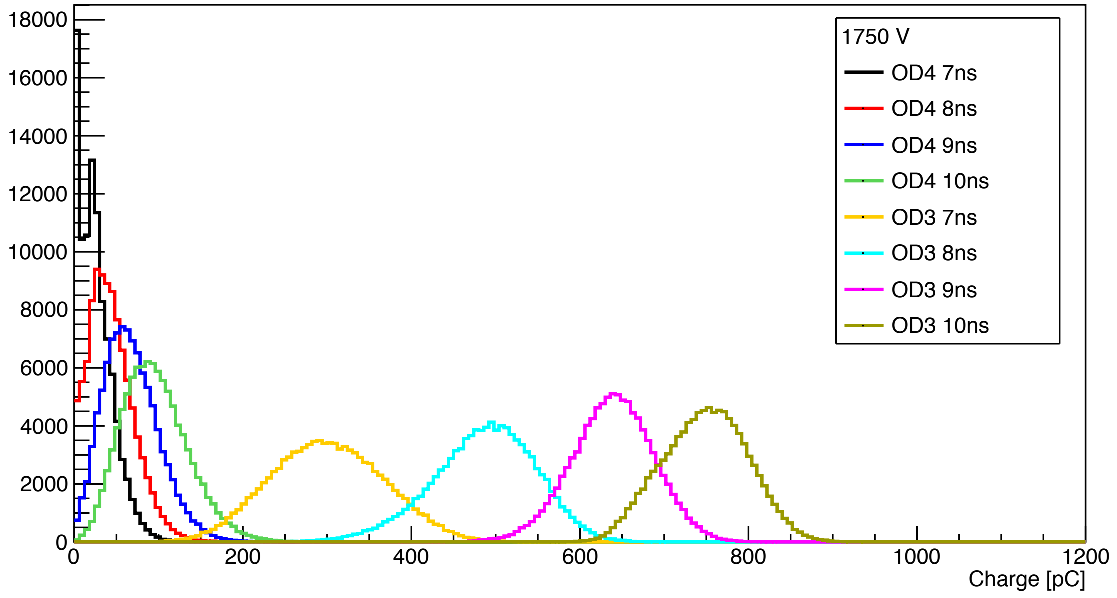
SPE: Gaussian Regime

- Lower PMT supply voltages however do not show this linear behavior:



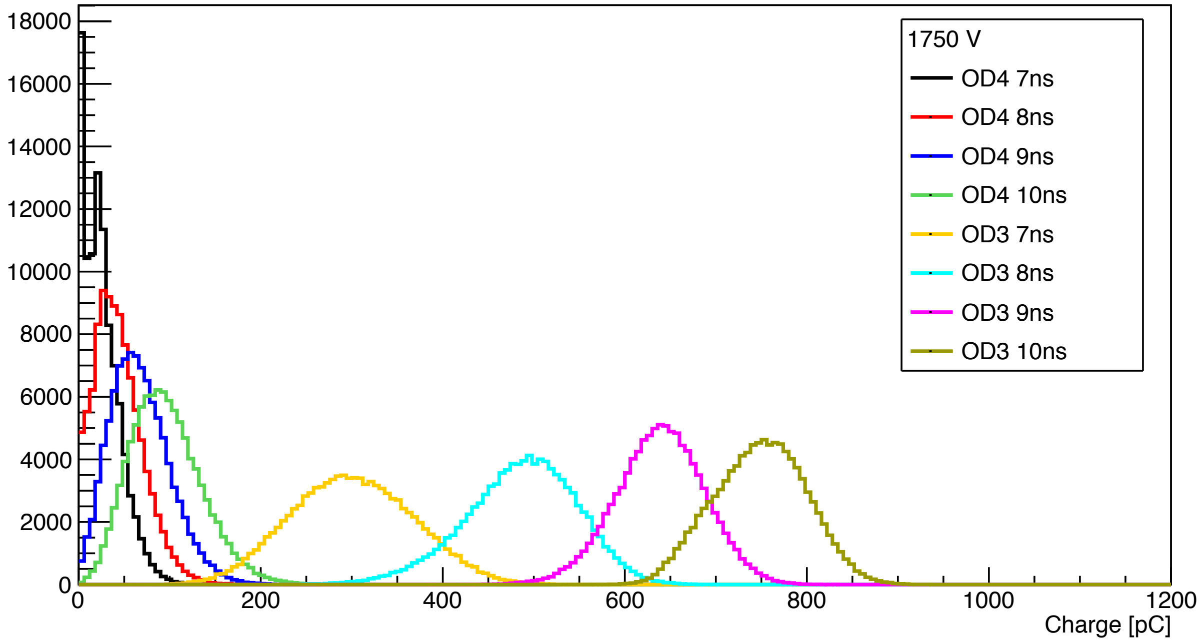


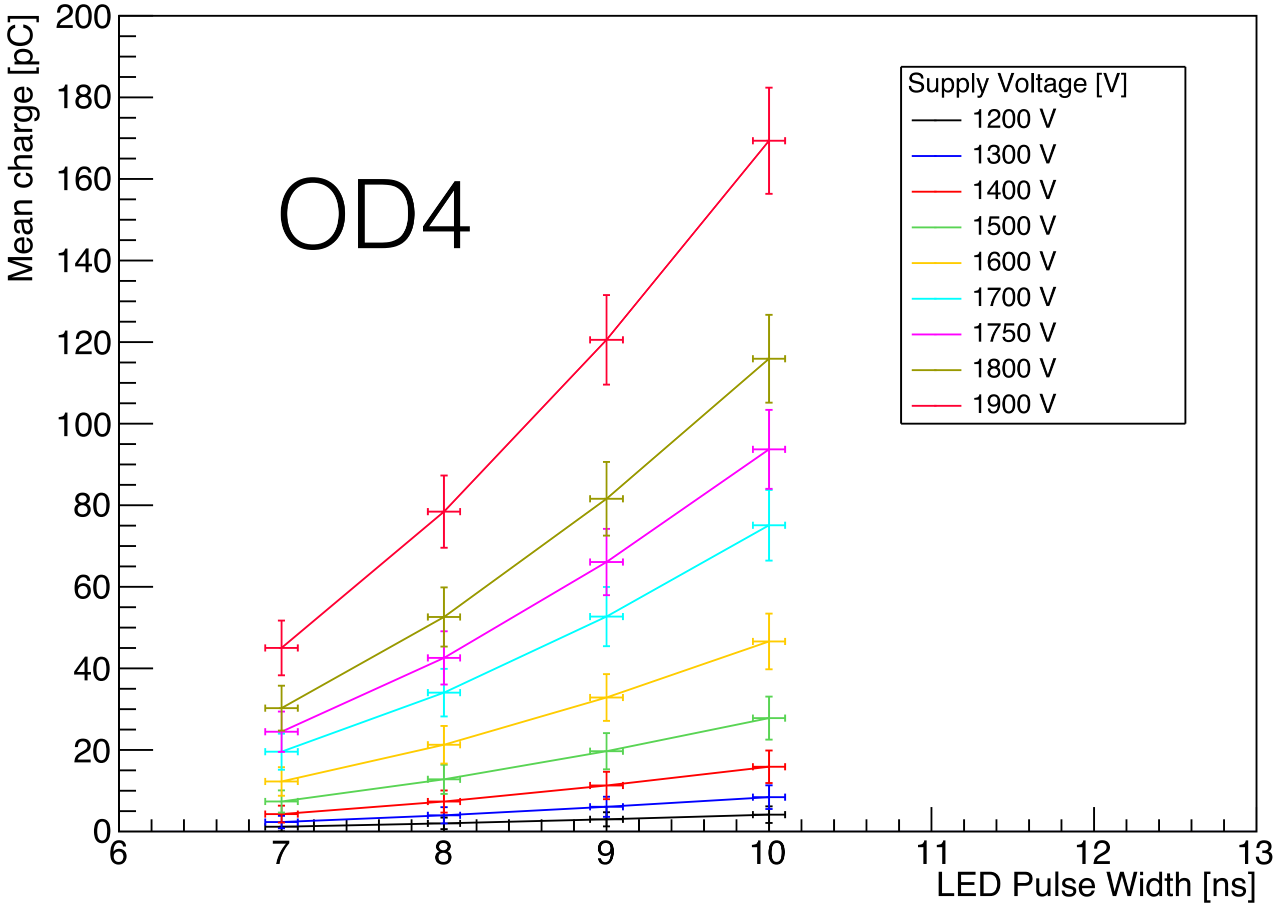
- Not clear why this is the case
- Something else that should scale with light intensity is the means of these distributions:

$$Q_\infty = \mu Q_1$$

SPE: Gaussian Regime

- Plot the evolution of the mean charge with light intensity
- Appears to be fairly linear with LED pulse width





$$Q_\infty = \mu Q_1$$

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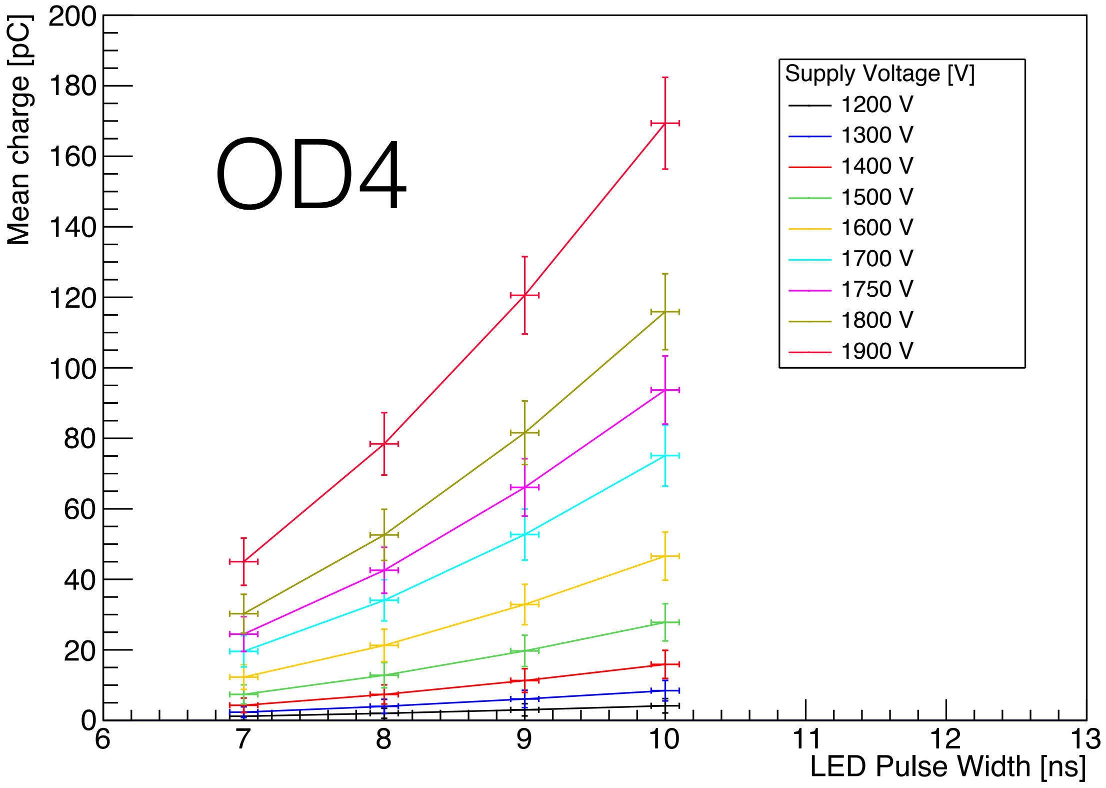
SPE: Gaussian Regime

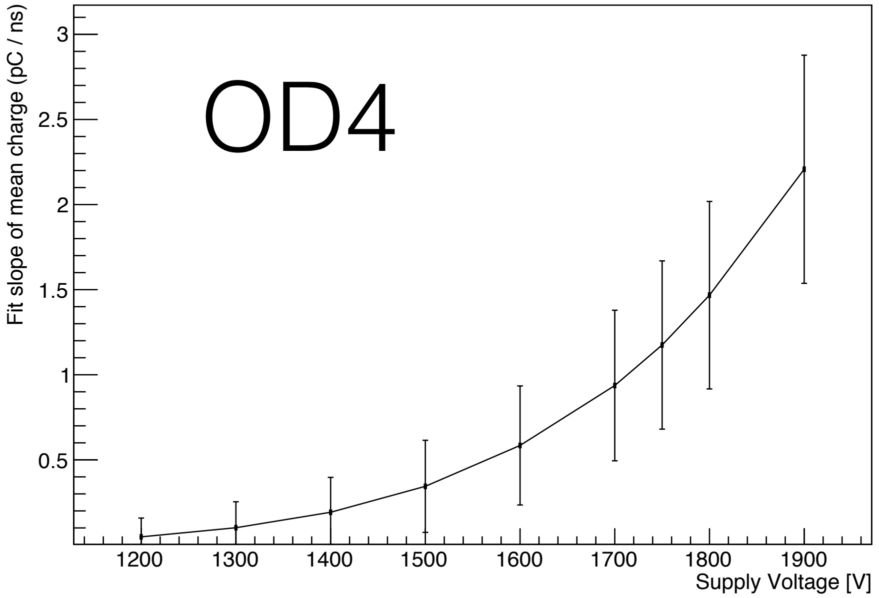
- Fitting each of these to a line:
  - Scales well at all supply voltages

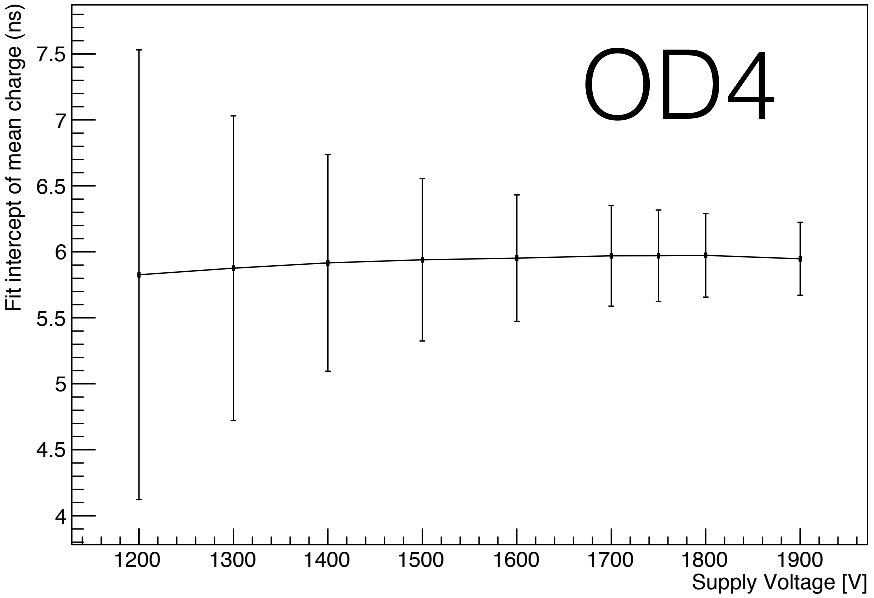
$$Q_\infty = Q_1 \cdot \mu$$

$$= Q_1 \cdot \alpha \cdot \left[\text{Pulse width} - t_0\right]$$

  - For 1900V:
    - Slope = 2.2 ± 0.7 pC/ns
    - Intercept = 6.2 ± 0.7 ns
  - Compare to intercept of previous fit: 6.6 ± 0.1
  - Again cannot separate SPE from light source



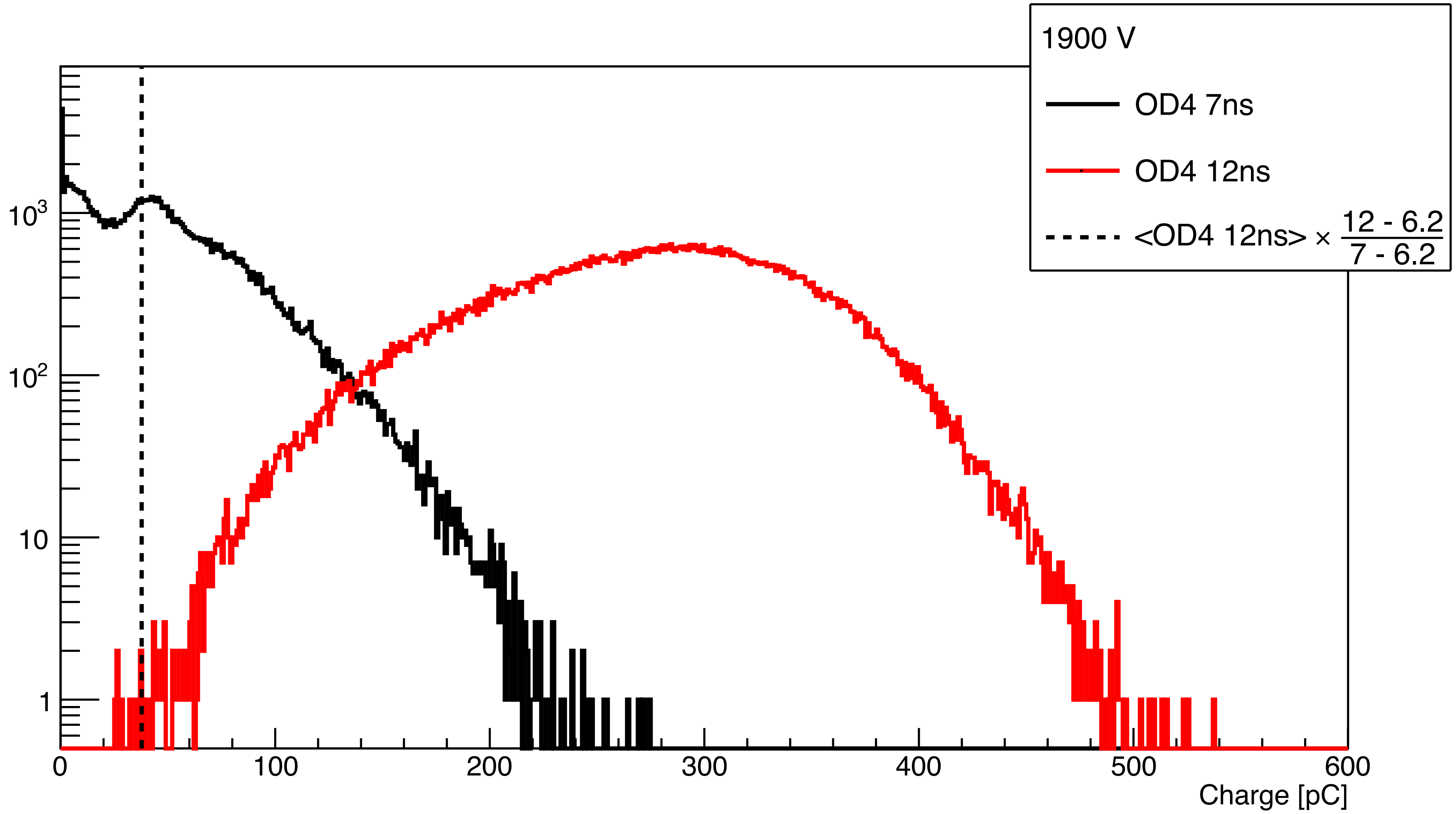




SPE: Gaussian Regime

- Using the previous fit as a relationship between LED pulse width and expected mean charge, perhaps this can isolate the SPE
- With the same ND filters, scale the mean charge of a large-NPE distribution down to a small-NPE distribution

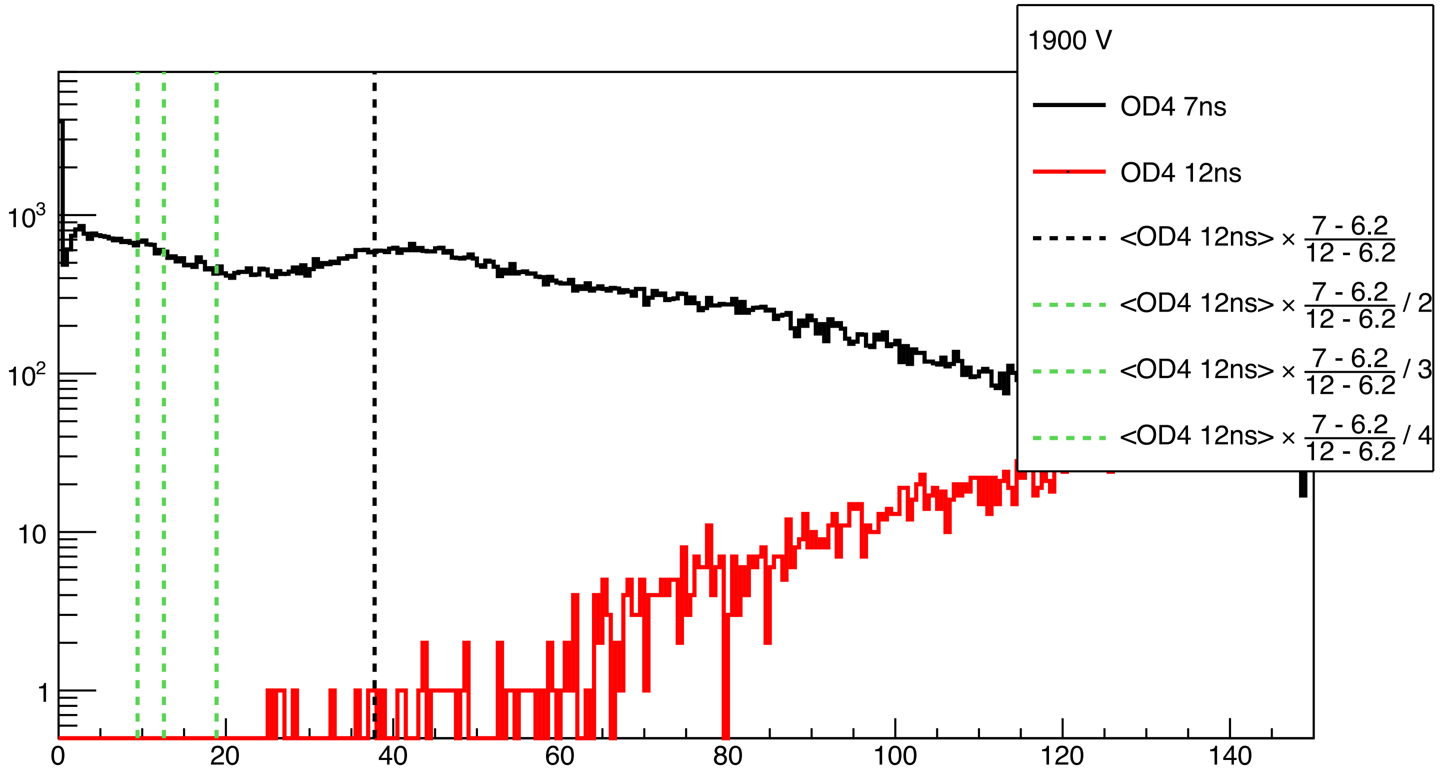
$$< Q_{12\mathrm{ns}} > \;\approx\; \frac{2.2(12-6.2)}{2.2(7-6.2)} < Q_{7\mathrm{ns}} >$$



SPE: Gaussian Regime

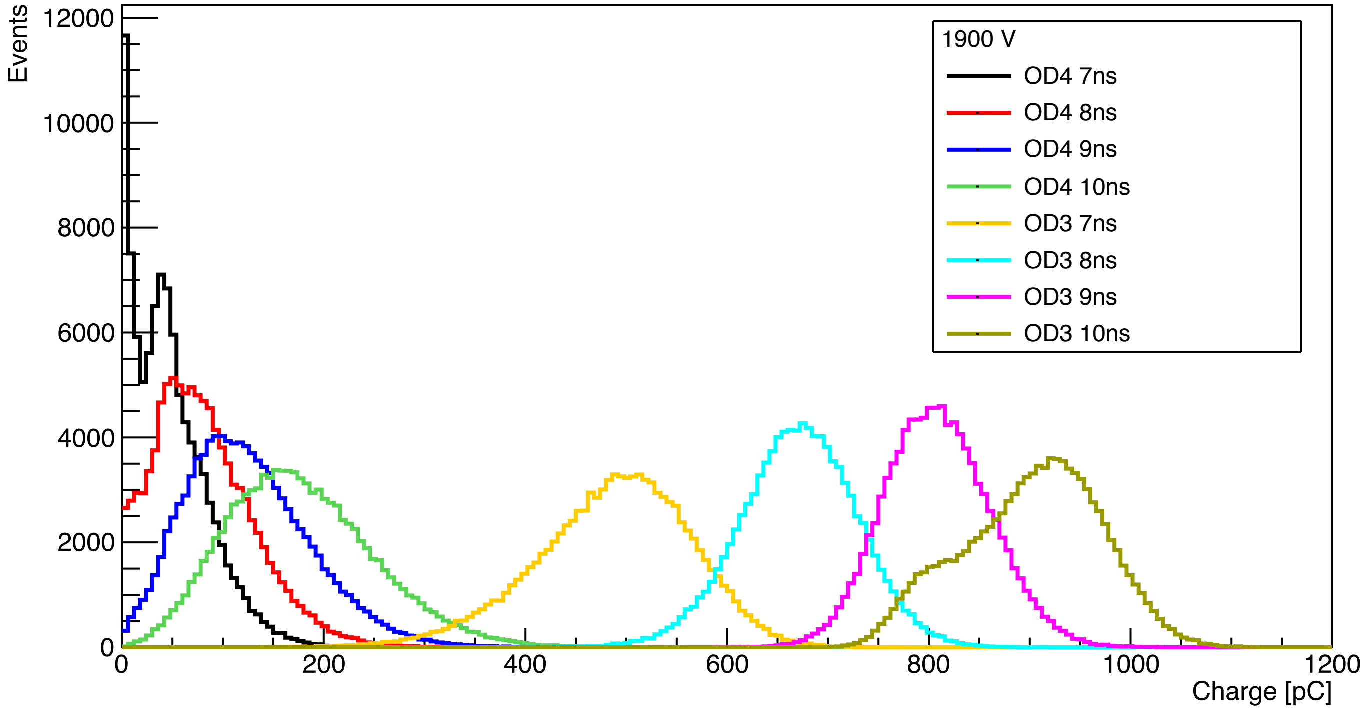
$$< Q_{\mathrm{12ns}} > \approx \frac{1}{7.3} < Q_{\mathrm{7ns}} >$$

- This appears to scale down to the peak charge, but this does not guarantee you the SPE
- If the larger-NPE distribution had 30 PEs on average, for example, this method gives you a mean of ~ 4.1 PE
- In fact if the larger-NPE distribution somehow has less than 7.3 NPE on average, this method gives you something less than the SPE
  - Projected mean: 37.8 pC
  - Actual mean: 45 pC



SPE: Gaussian Regime

- One other scaling to consider, changing ND filters
- "OD4" is the combination of OD3 and OD1, so to change from OD3 to OD4 the OD1 filter is added
  - Expect a 10-fold decrease in light intensity



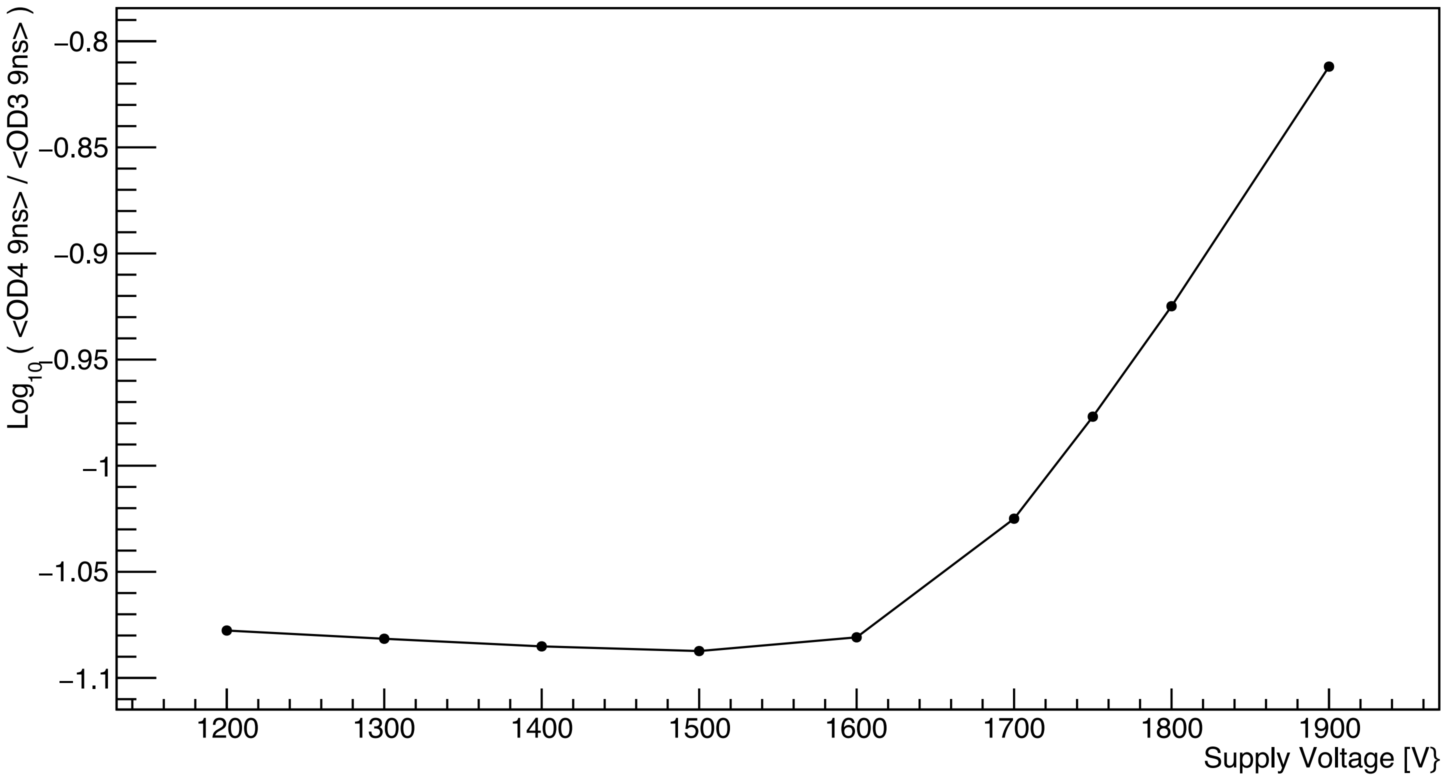
	Mean (pC)
OD4 9ns	124.6
OD3 9ns	808.2
Ratio of OD4/ OD3	0.15

$\mathrm{Log}_{10}(0.15) = -0.82$

OD1 ~ OD 0.82 ?

SPE: Gaussian Regime

- Keeping the same LED pulse widths, adding an OD1 neutral density filter should decrease the mean charge by a factor of 10
  - This decrease should be the same at all PMT supply voltages



- Not clear why this is not a constant, or why it deviates from -1.0
  - For OD3 and OD4, 9ns should be well into larger NPE values so as to be fairly gaussian

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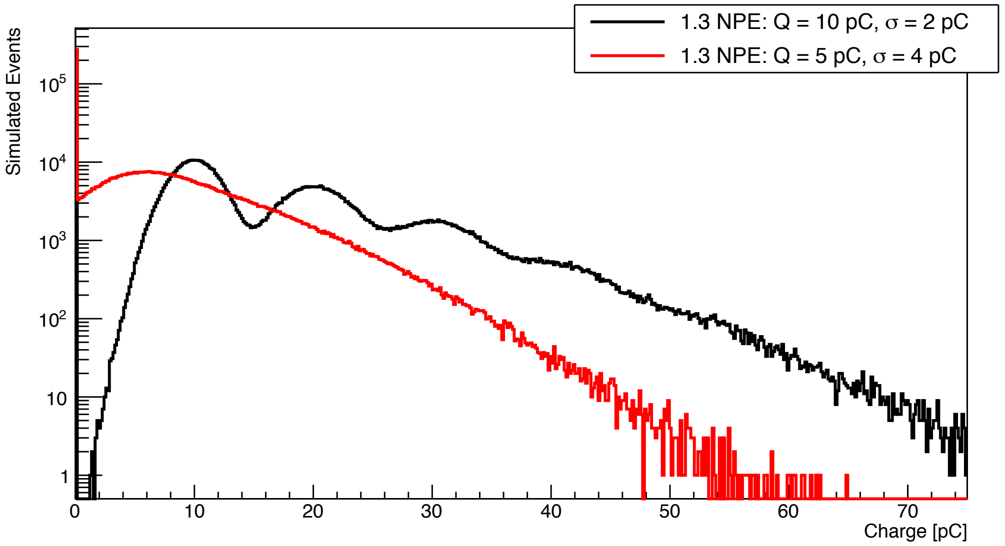
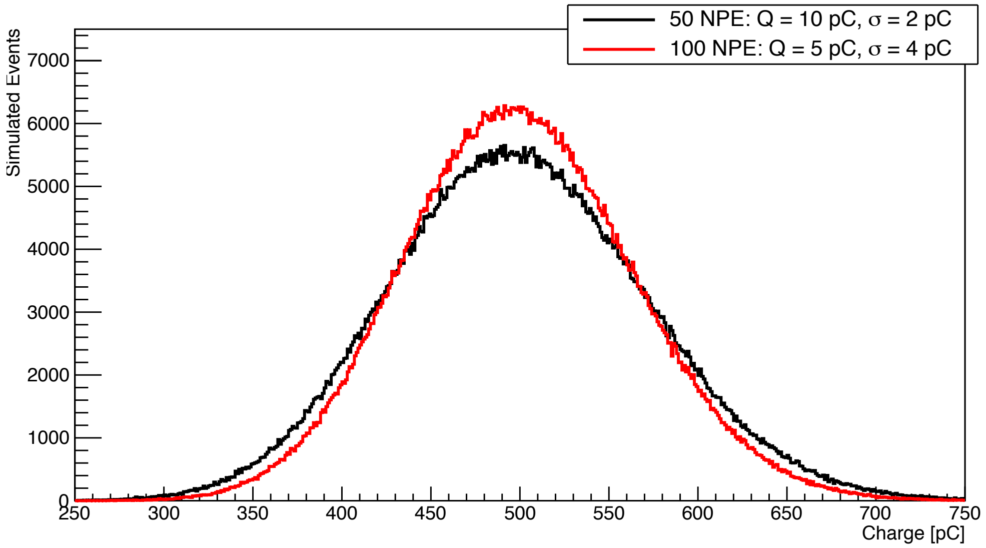
SPE: Gaussian Regime

- Difficulties aside, working in the gaussian regime does not seem to isolate the SPE response
- Shown below, two different SPE responses with different <NPE>:
  - Simulated by RNG shooting NPE from poisson, and charge per PE from gaussian distributions





- Easily distinguished at low NPE, but possible for distributions to be very similar at large (yet different) NPE

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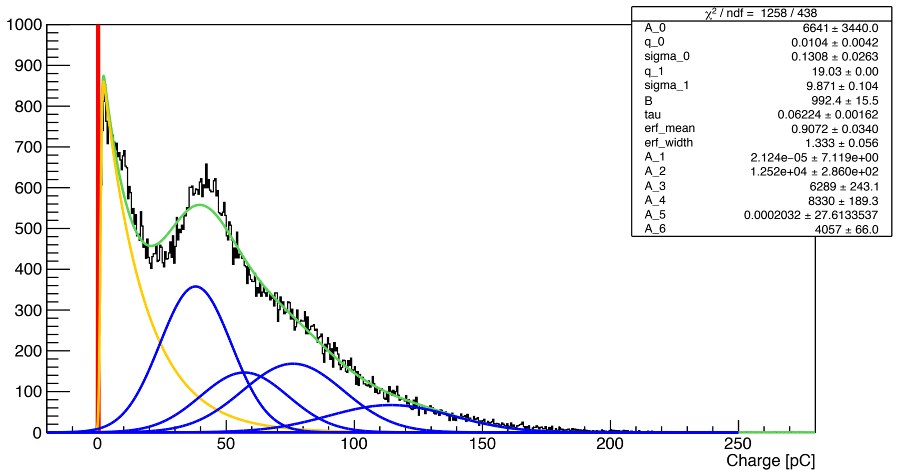
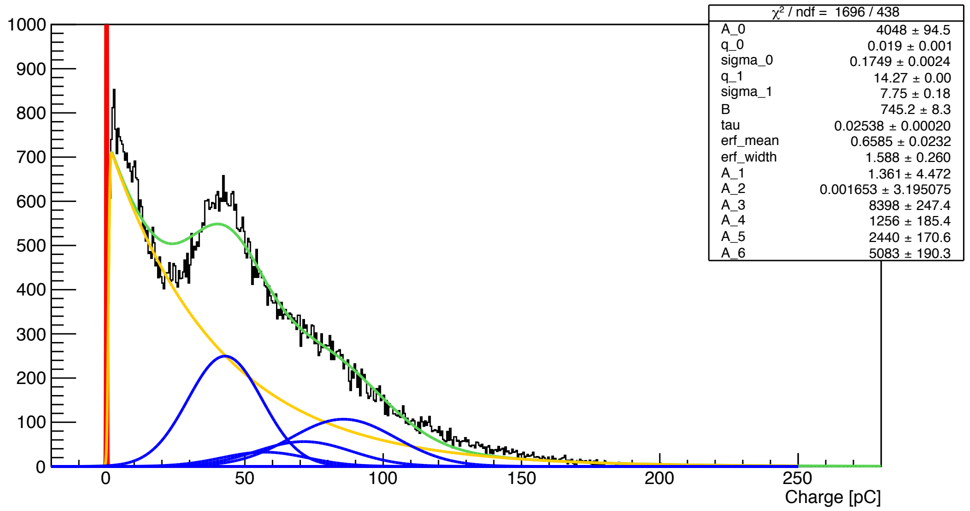
SPE: Functional Fit

- Method 2: assume a functional form of the expected distribution and extract the SPE parameters
  - Gaussian pedestal
  - Exponential background
  - Sum of several signal gaussians: Gaus(x, i * Q1, sqrt(i) * sigma1)
    - Without the constraint on peak spacings and width, fits fail to converge as yet
- Even with these assumptions and constraints, fit is very dependent on initial conditions
- For OD4 7ns at 1900 V:



Initial Q1 value = 16 pC
—>
Q1 = 19 pC

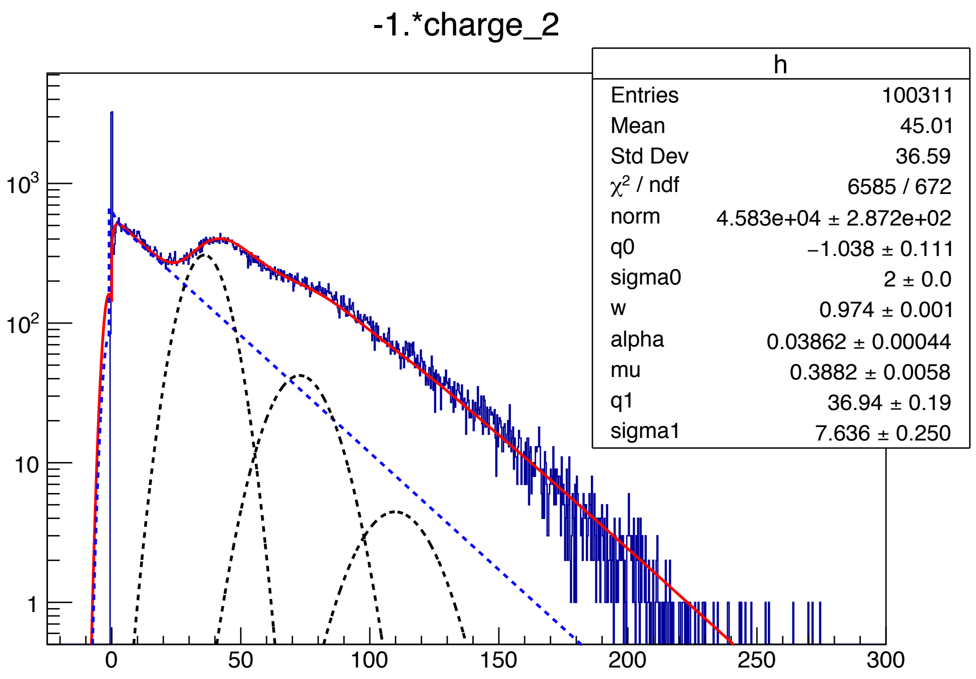


Initial Q1 value = 12 pC
—>
Q1 = 14 pC

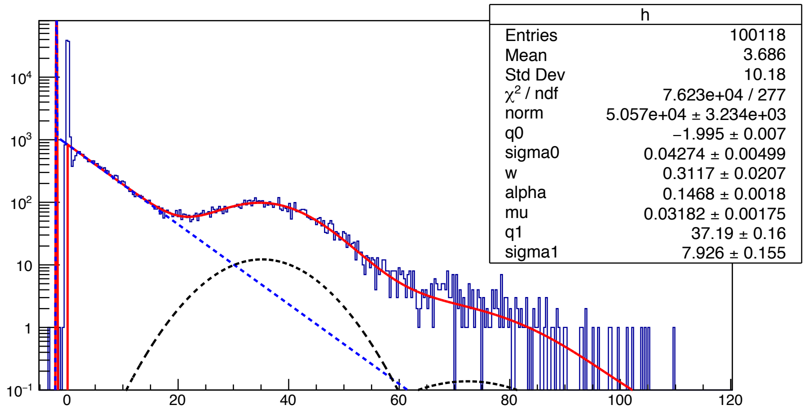
- Safe to say that this method is not yet working
- Consistently if you initialize the SPE peak below the peak at ~45, the fit returns lower-N peaks as having nearly zero events

SPE: Functional Fit

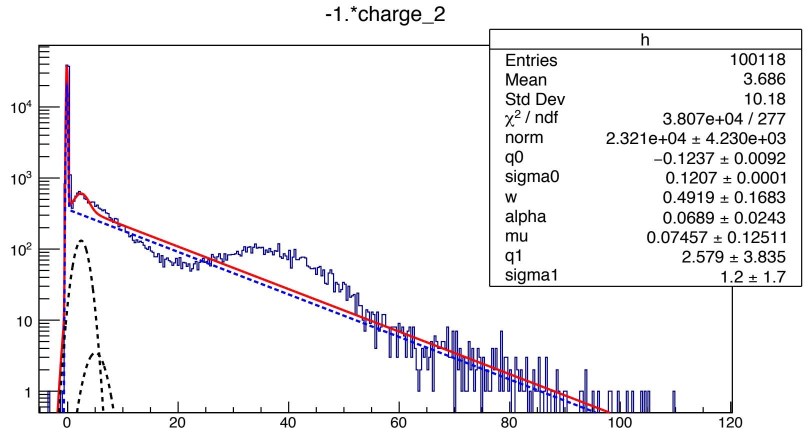
- A much more complicated functional form is described in Bellamy et al
  - Fully convolutes exponential background with each signal peak



OD4 7ns 1900V



Initial peak 40 pC



Initial peak 20 pC

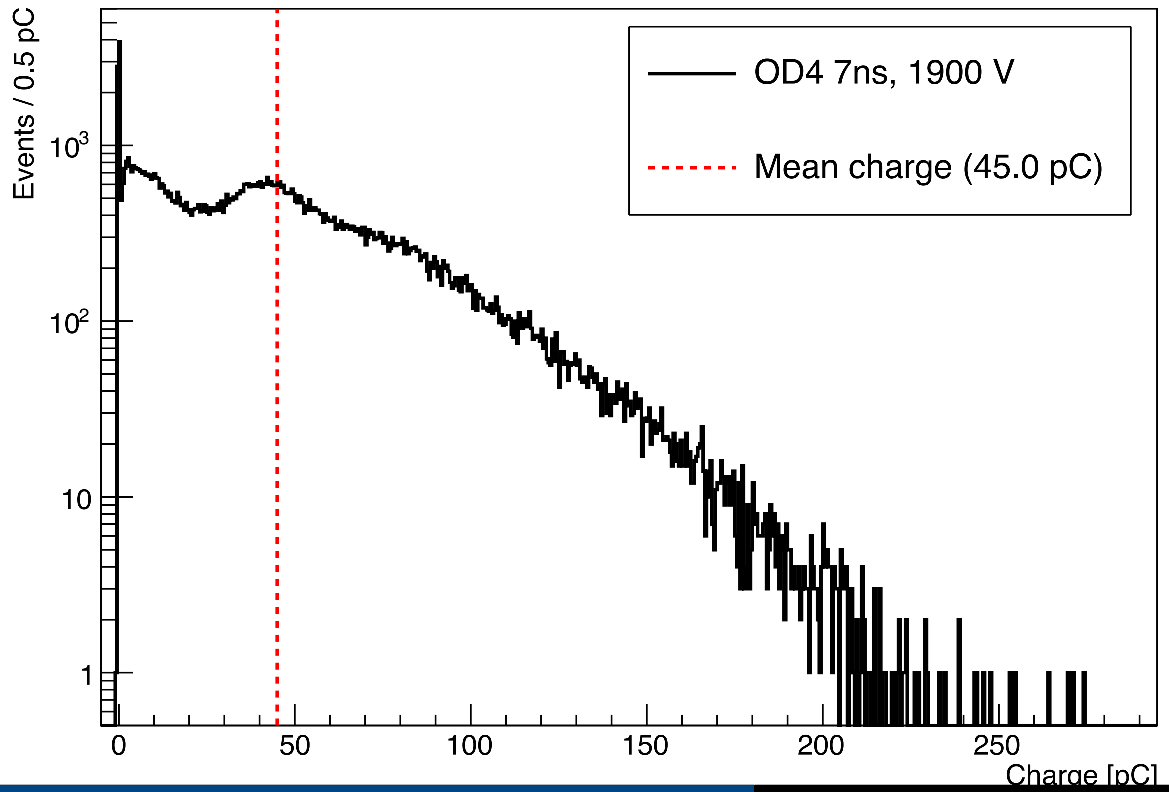
OD5 8ns 1900V

- In some instances this seems reasonable, but still is highly dependent on initial conditions
- Still involves some bias of suggesting the visible peak is the SPE peak

SPE: MIA

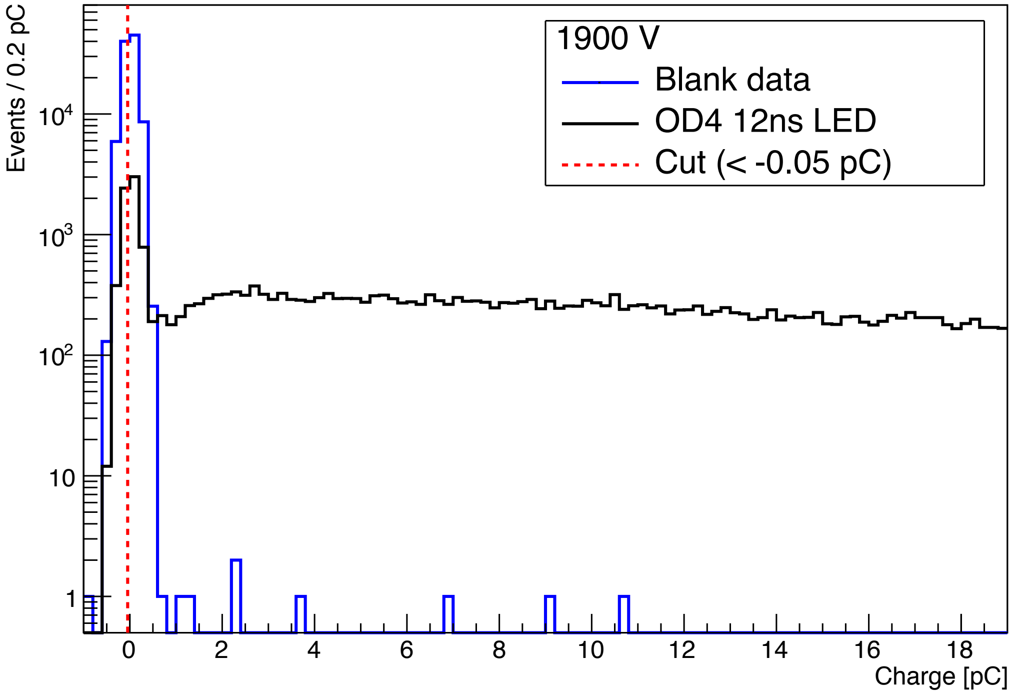
- Method 3: “Model Independent Approach” (MIA)
  - https://arxiv.org/abs/1602.03150
  - Method essentially has two ingredients:

  - 1) From a “blank”, no-LED dataset, use a low-charge cut to define ‘zero PE triggers’
  - 2) Compare the mean and variance of the “blank” dataset to that of an LED-on dataset



MIA SPE Response

- To calculate (https://arxiv.org/abs/1602.03150):
  - Define a charge cut such that ε ~ 1/3 in blank data (LED is turned off)
    - This 1/3 is arbitrary and its choice a source of systematic uncertainty
  - Take the same number of blank and LED events
  - Assuming the average N(PE) λ is low and Poisson-distributed, the occupancy λ is directly related to the likelihood of observing zero PEs:



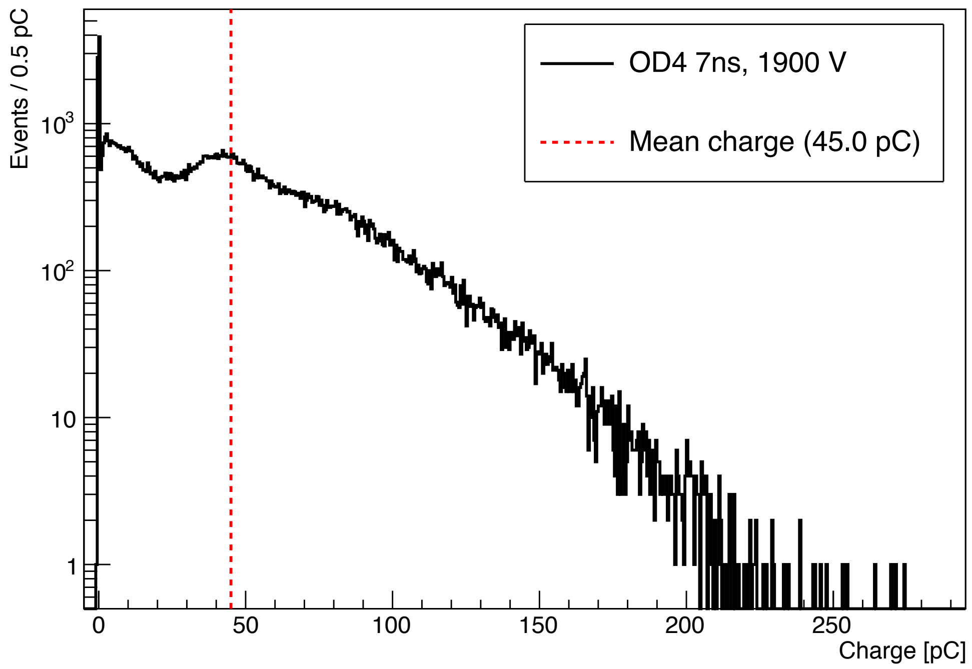
$$\begin{aligned}\lambda &= -\ln\left[L(0)\right]\\ &= -\ln\left[N_{\mathrm{LED}}(Q < \mathrm{cut}) \times \frac{1}{\epsilon_{\mathrm{blank}} N_{\mathrm{blank}}}\right]\\ &= -\ln\left[2010 \times \frac{1}{0.32975 \cdot 100{,}000}\right]\\ &= 2.80\end{aligned}$$

MIA SPE Response

- Now with λ, and the assumptions that:
  - The signal and background distributions are uncorrelated and
  - Signal is a repeated convolution of the SPE:
- Then:

$$E[\psi] = \frac{E[\mathrm{LED}] - E[\mathrm{blank}]}{\lambda}$$

$$V[\psi] = \frac{V[\mathrm{LED}] - V[\mathrm{blank}] - E^2[\psi] \cdot V[\lambda]}{\lambda}$$



$$E[\psi] = \frac{45.0 - 0.013}{2.80} = 16.09\ \mathrm{pC}$$

$$V[\psi] = \frac{1338.6 - 0.43 - 16.09^2 \cdot 2.80}{2.80} = 219.6\ \mathrm{pC}^2$$

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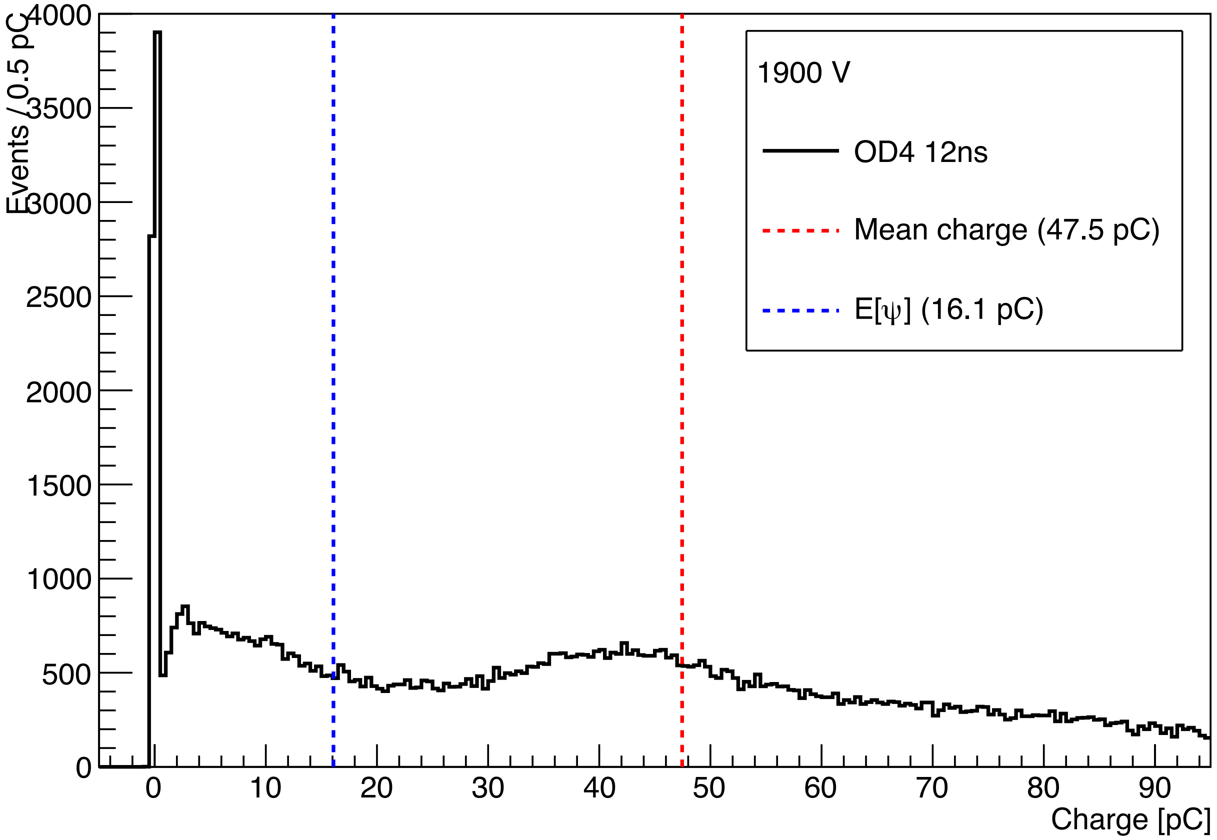
MIA SPE Response



$$E[\psi] = \frac{45.0 - 0.013}{2.80} = 16.09 \text{ pC}$$

$$V[\psi] = \frac{1338.6 - 0.43 - 16.09^2 \cdot 2.80}{2.80} = 219.6 \text{ pC}^2$$

- This method consistently derives an SPE expectation well below the observable peak, with a very large width

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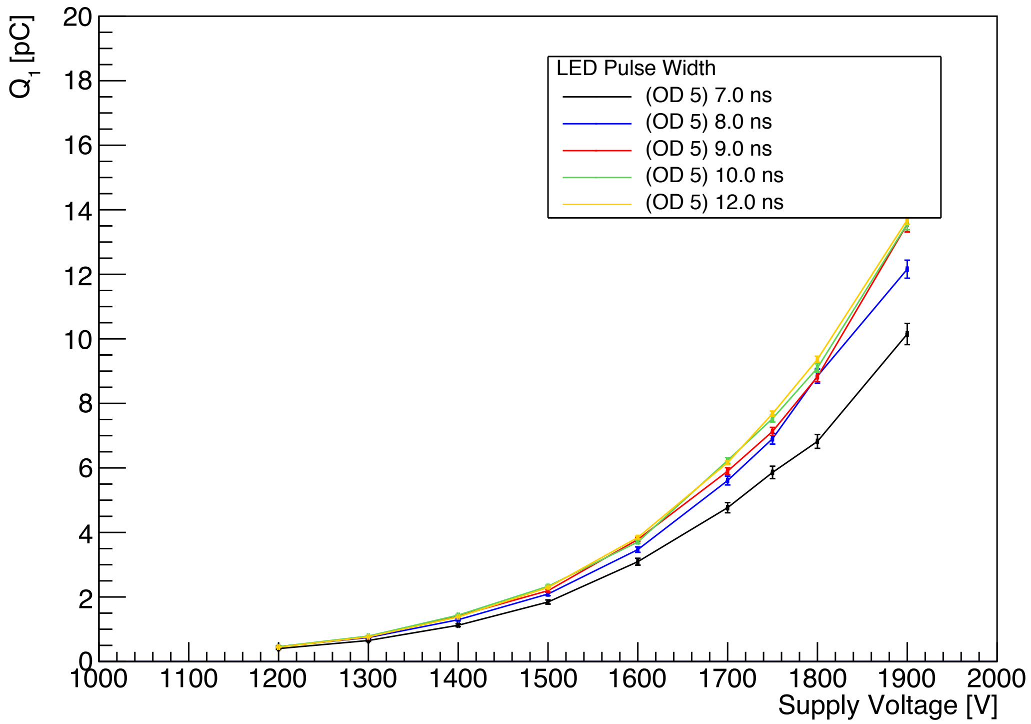
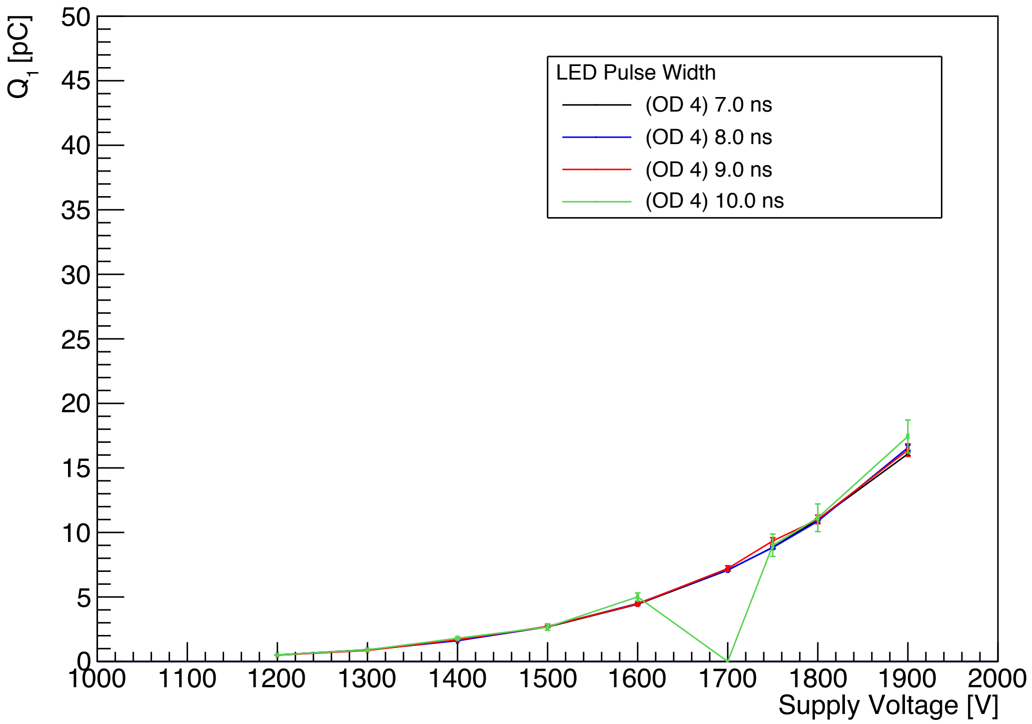
MIA SPE Charge



OD5



OD4

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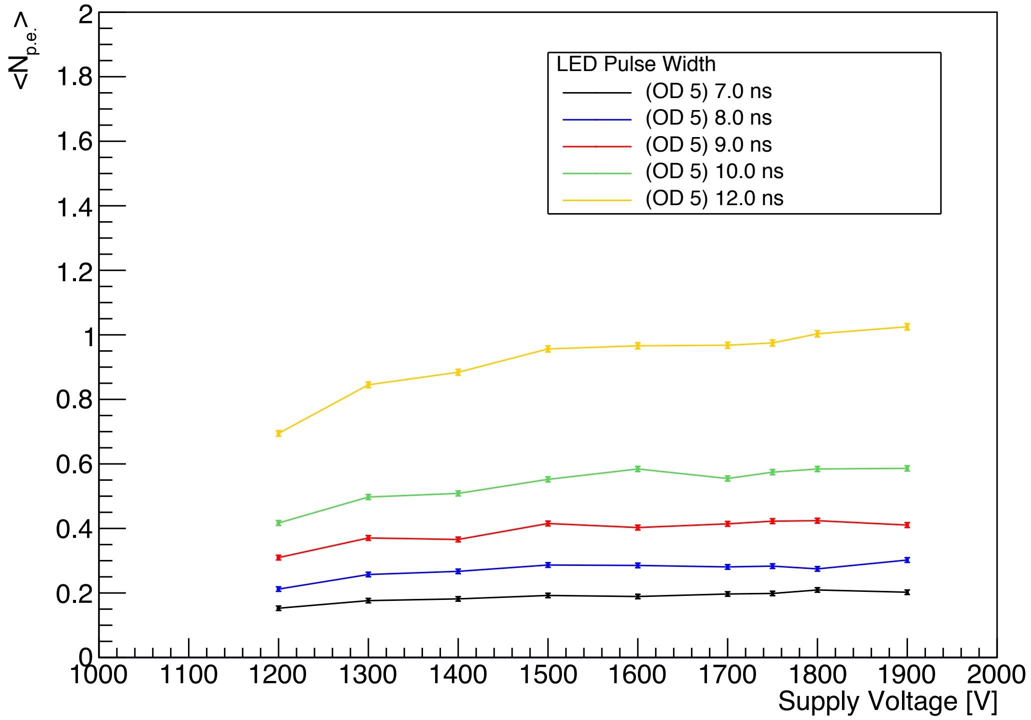
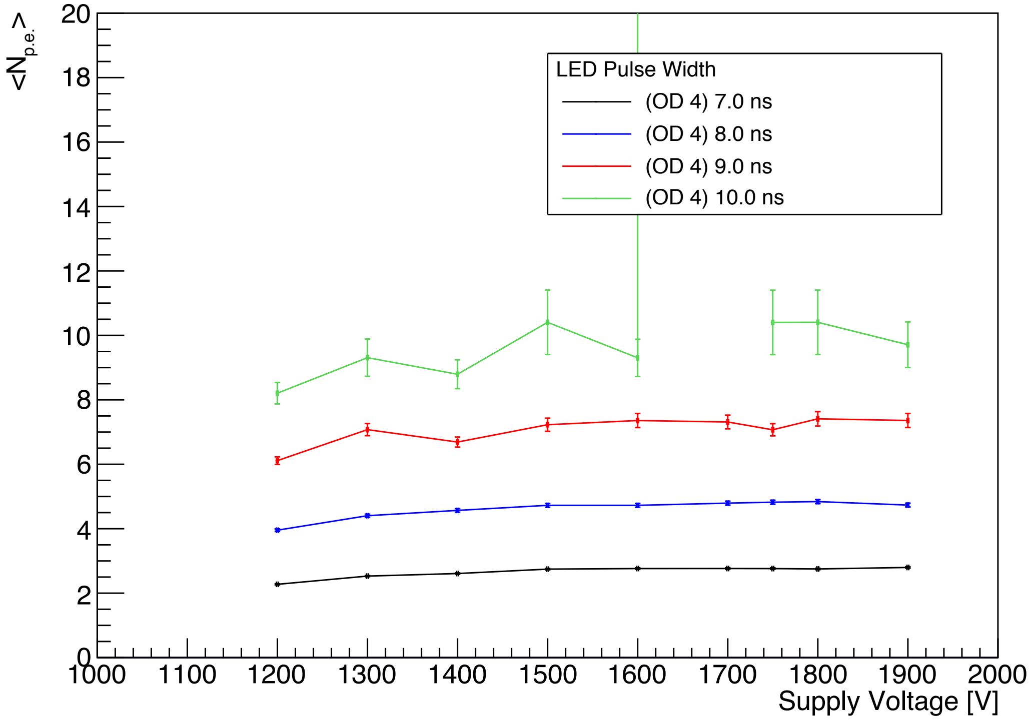
MIA SPE NPE



OD5



OD4

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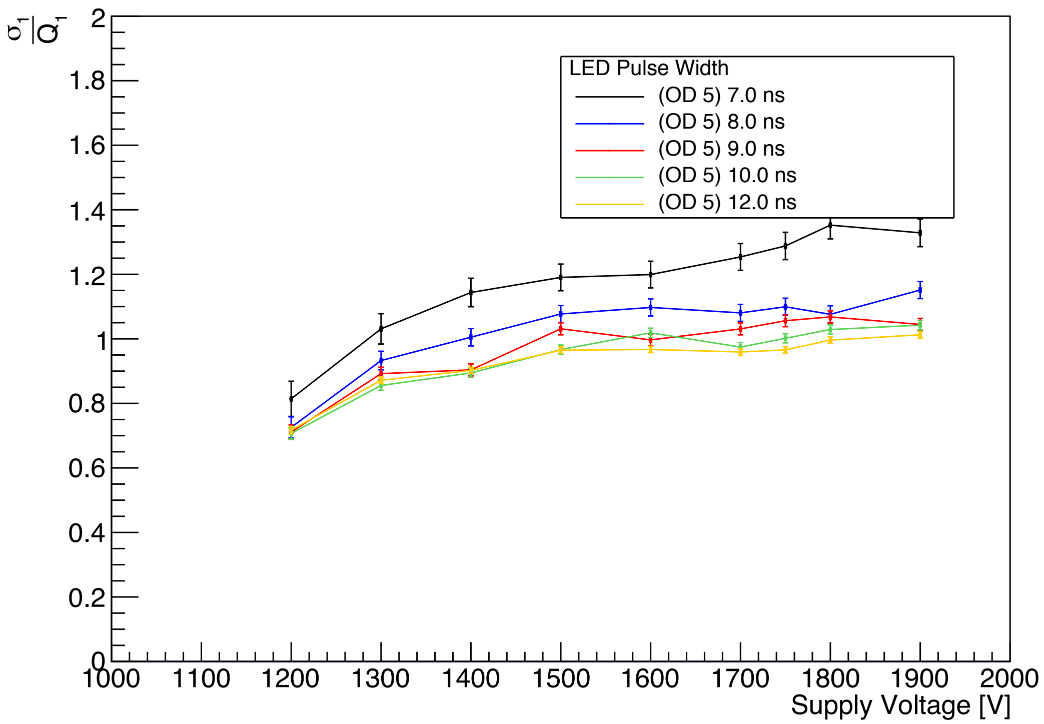
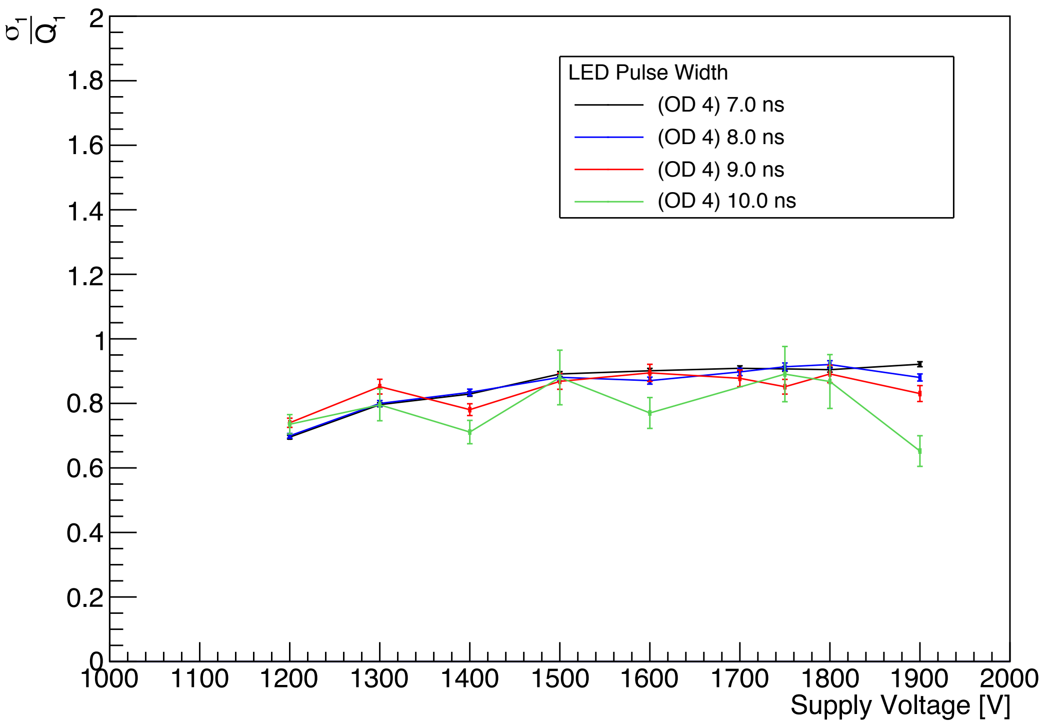
MIA SPE Resolution (Width / Peak)



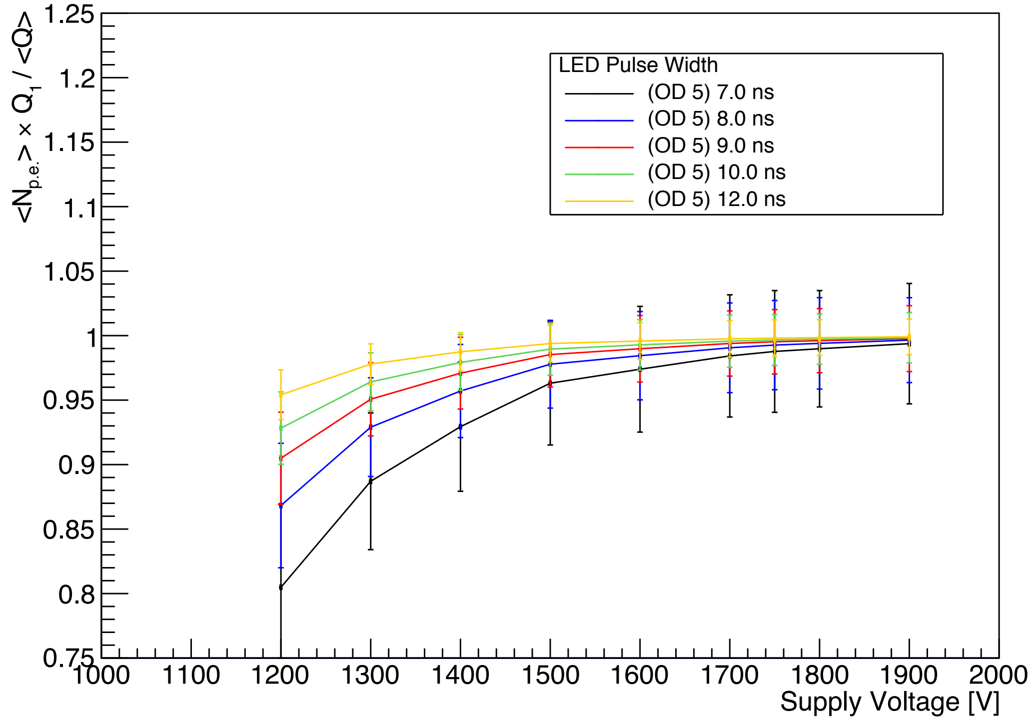
OD5



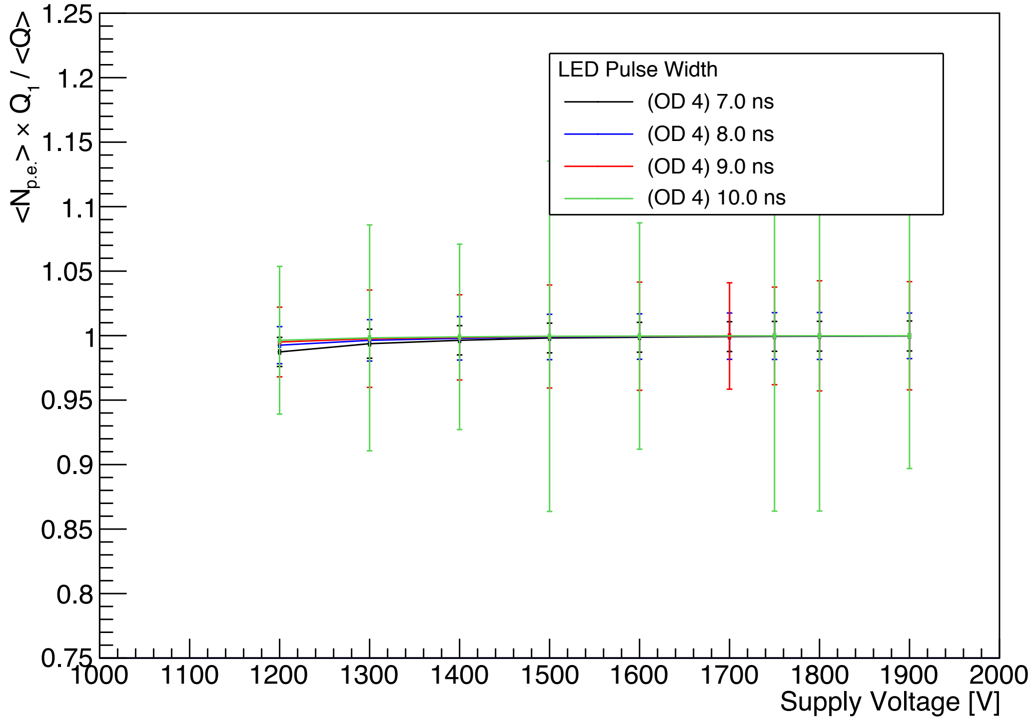
OD4

MIA SPE Approaching Distribution Mean

- As the gain and light intensity are increased, this method does approach <NPE>*Q1 —> mean charge of the distribution



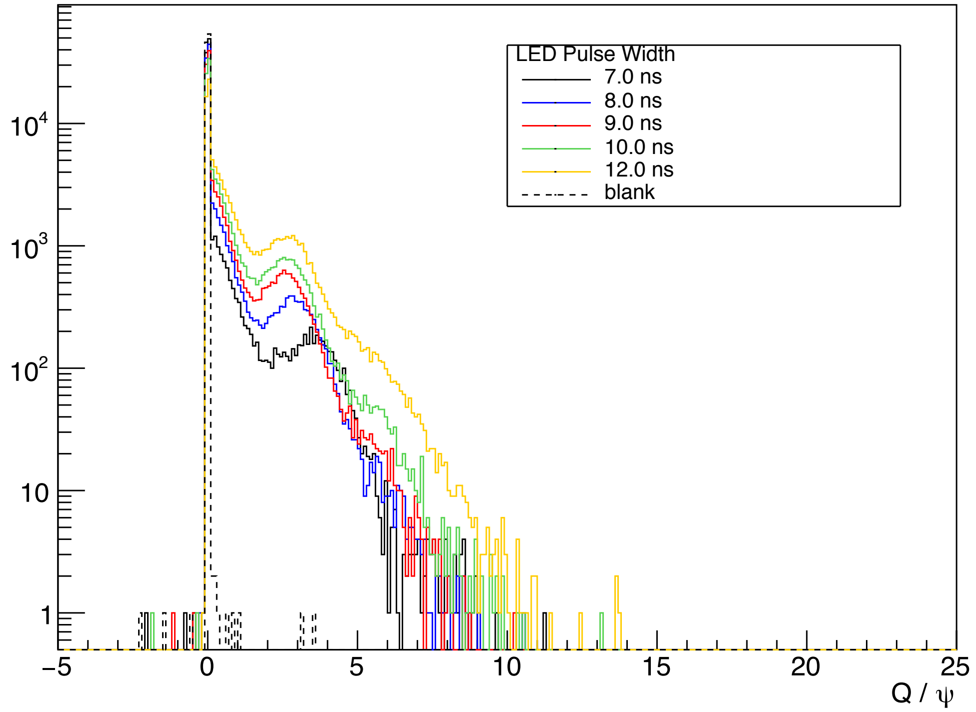
OD5



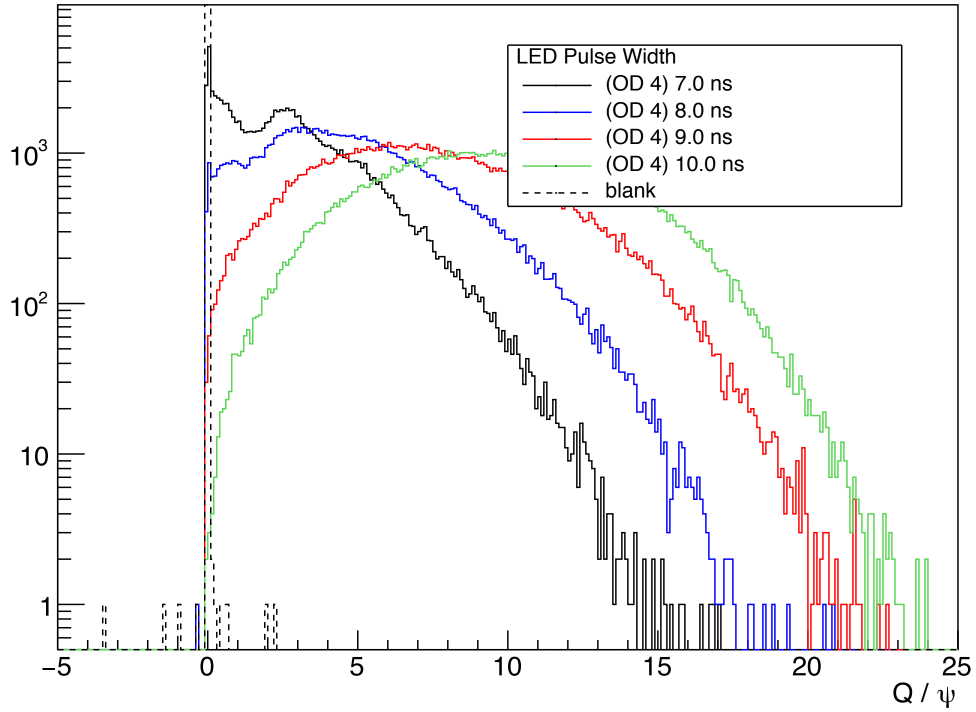
OD4

MIA SPE

- Scaling the charge distributions by the calculated single photoelectron charge does not seem to produce noticable photoelectron peaks
- Charge / (SPE charge) should be ~ NPE



OD5



OD4

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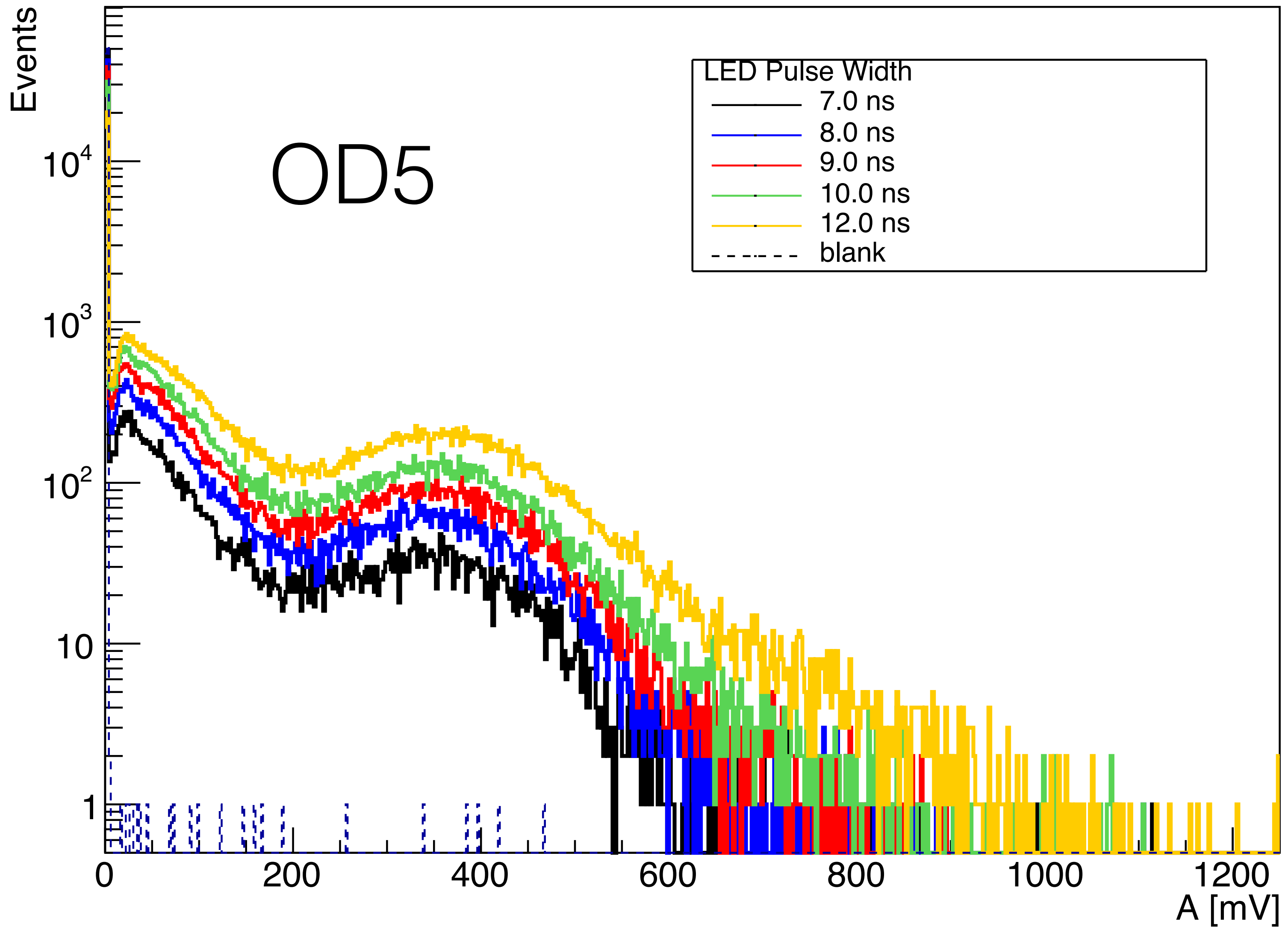
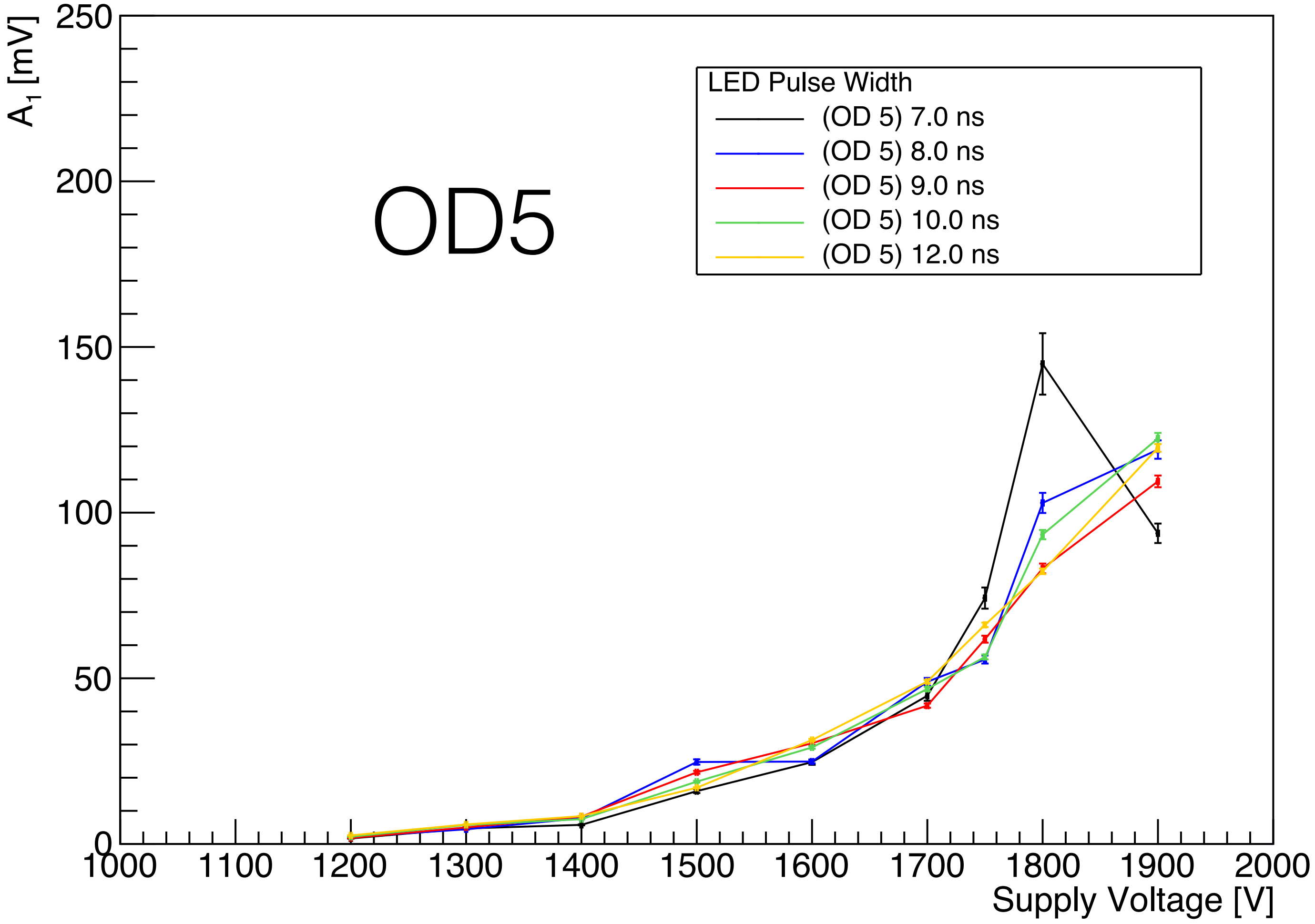
Dark Rate from MIA SPE

- To tie these results into the dark rate, which results from a trigger threshold in amplitude, can apply this method also to amplitude:



Dark Rate from MIA SPE

- The results of this method in amplitude less clean in their evolution with voltage, LED width



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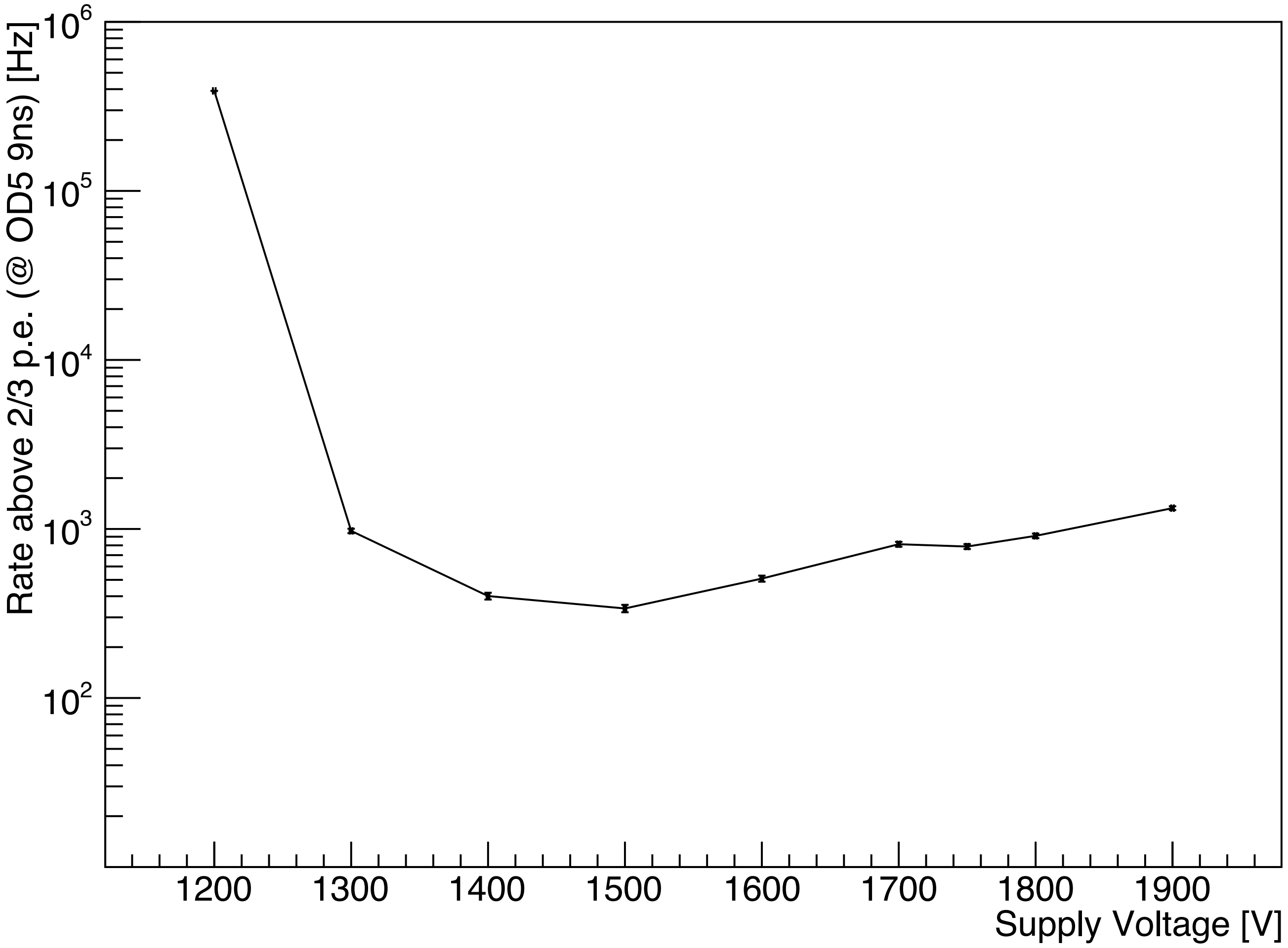
Dark Rate from MIA SPE

- Despite this, still attempt to use these expectations to form a trigger threshold
- Using one set of results (OD5 9ns) versus voltage, express the dark rate relative to a threshold 2/3 of these values



- Considering the MIA likely underestimates the distribution peaks, this is likely an overestimate of the rate at 2/3 PE

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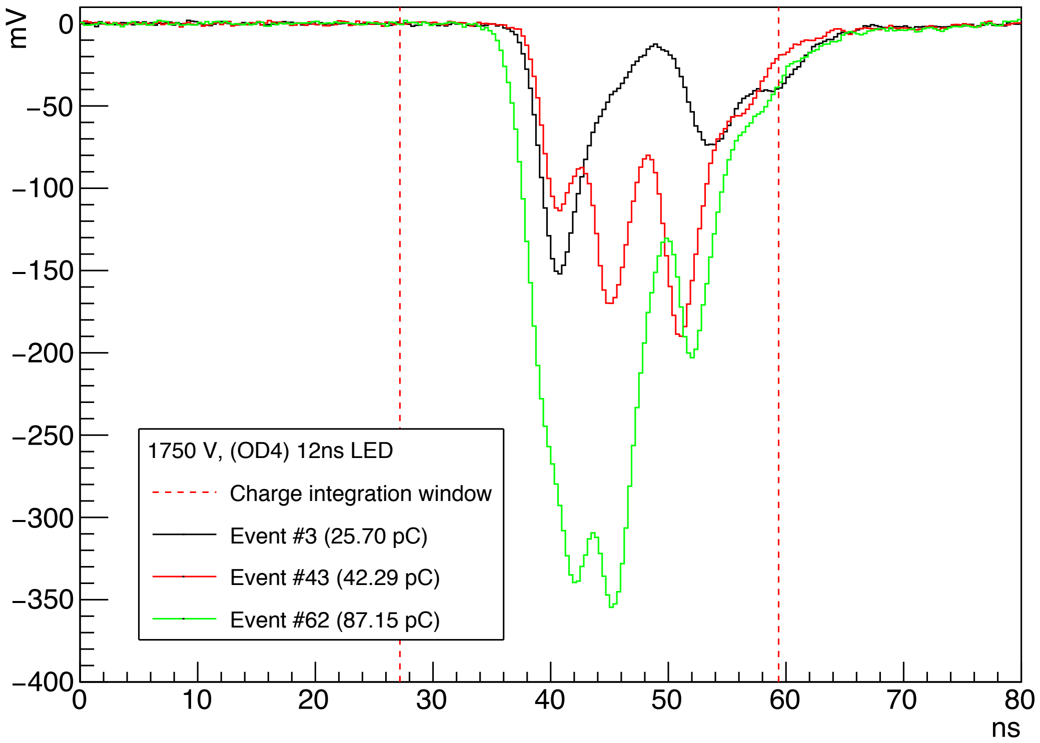
Backup

Calculating charge with V1743

- At higher gains and larger light intensities, you begin to observe very large-amplitude, long width signals
- For example at 1750 V, a 12s LED pulse with OD4 gives roughly 5% of events looking as:



- And for even larger signals the dynamic range of the V1743 can become saturated
- For these types of signals the amplitude underestimates the total amount of “signal” present
- It is best to examine both amplitude and charge

Dark Rate from Peak Amplitude

- Simply just look at the amplitude of the peak