Next Generation Microchannel Plate Detectors for High Spatial and Temporal Resolution

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- Characterisation of the TORCH 16x96 Multi Anode MCP-PMT
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- Development of a Charge Sharing Photon Timing/Imaging Detector
- **Instrument a capacitively coupled multi-anode readout using TOFPET2d ASIC**
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- **Can we avoid complicated calibration using Neural Networks?**
- **Can we even do it faster?**
- **Royal Commission for 1851 Industrial Fellowship with University of Leicester – Amelia Markfort**

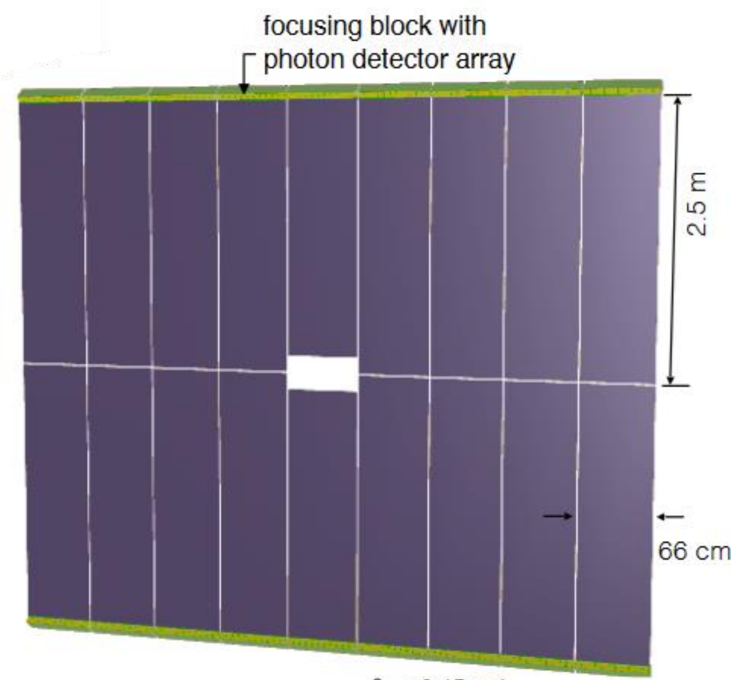
TORCH MCP Detector

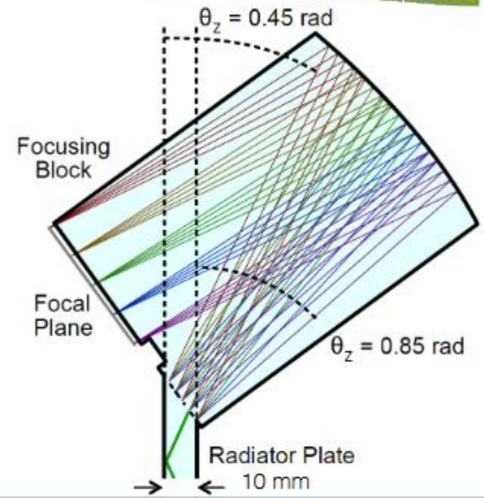
High density multi-anode MCP Photon detector characterisation

TORCH Cerenkov Particle ID Detector Concept

- Exploit prompt production of Cherenkov light in an array of fused-silica bars to provide timing.
- Cherenkov photons are propagated to detector plane via total internal reflection from the quartz surfaces.
- Cylindrical focussing block, focusses the image onto a detector plane with highly segmented photon detectors.
  - Used to correct for chromatic dispersion.
- Large area detector required to cover the full LHCb acceptance ($5x6m^2$).

For more details on the TORCH concept see **[NIM A 639 (1) (2011) 173]**

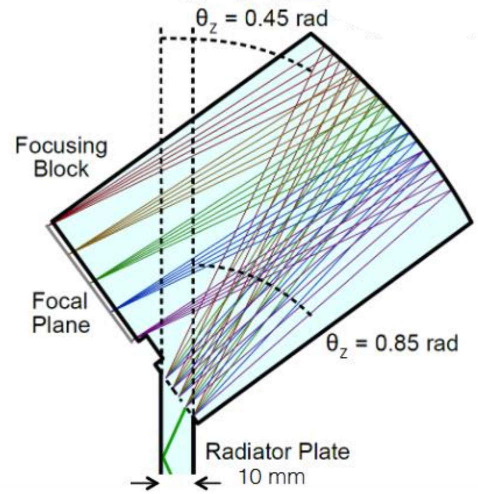


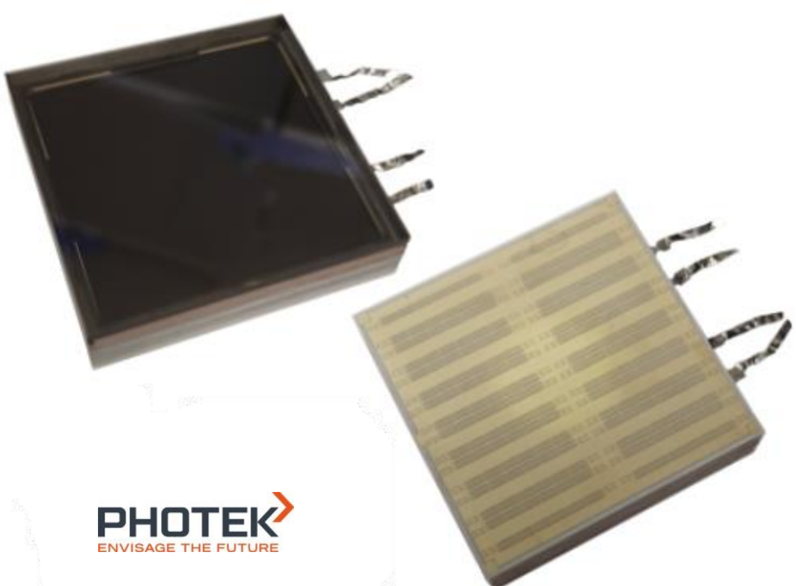


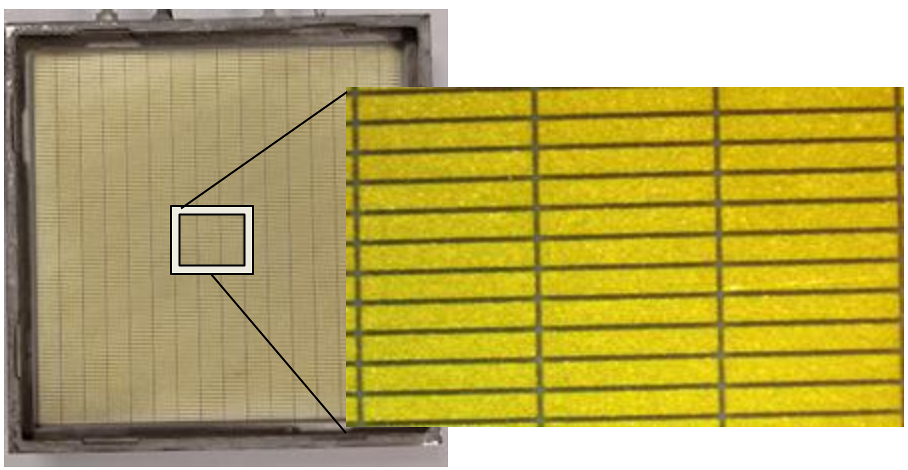
Credit: T.Blake – Pisa Meeting 2024

TORCH 16×96 Multi-anode MCP Detector

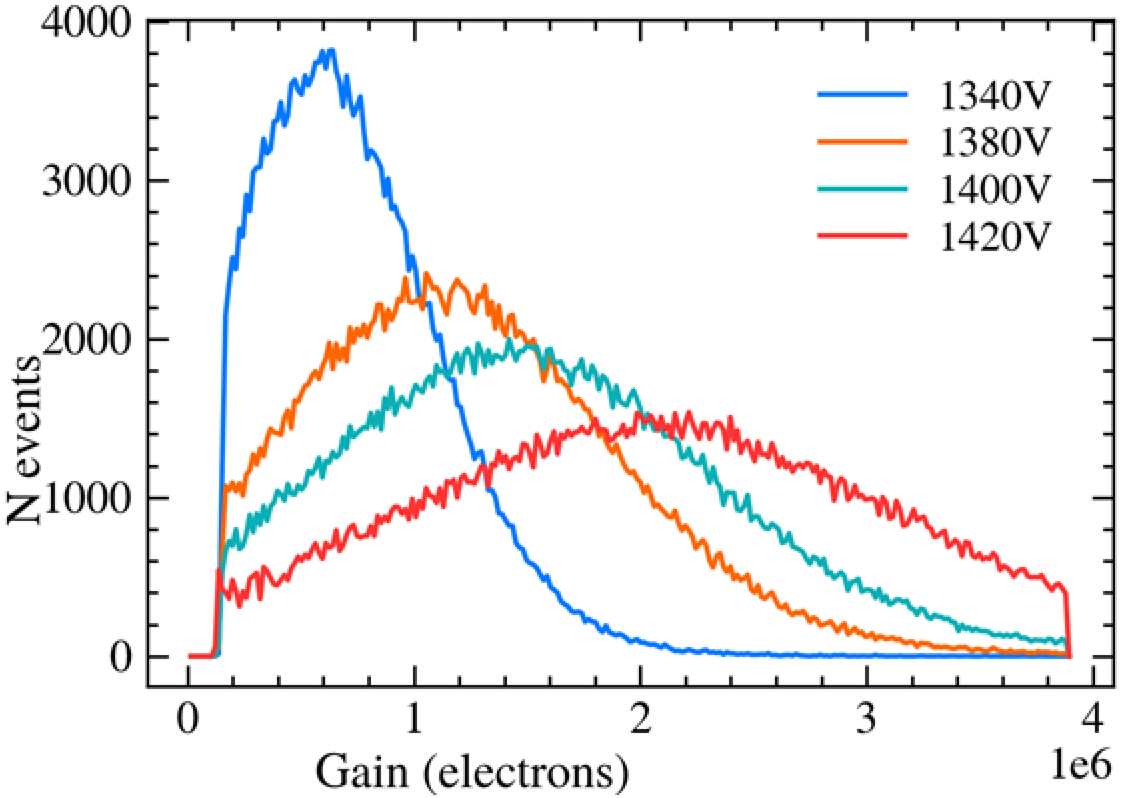
- 16×96 Anode layout, 53×53 mm^2 active area
- Fine pitch required in one direction
  - 552 µm pitch
  - Measure angle – Cerenkov/chromatic aberration correction
  - Also reduces occupancy for high rates
- In coarse direction 3312 µm pitch







Global Gain Measurement – All pixels connected



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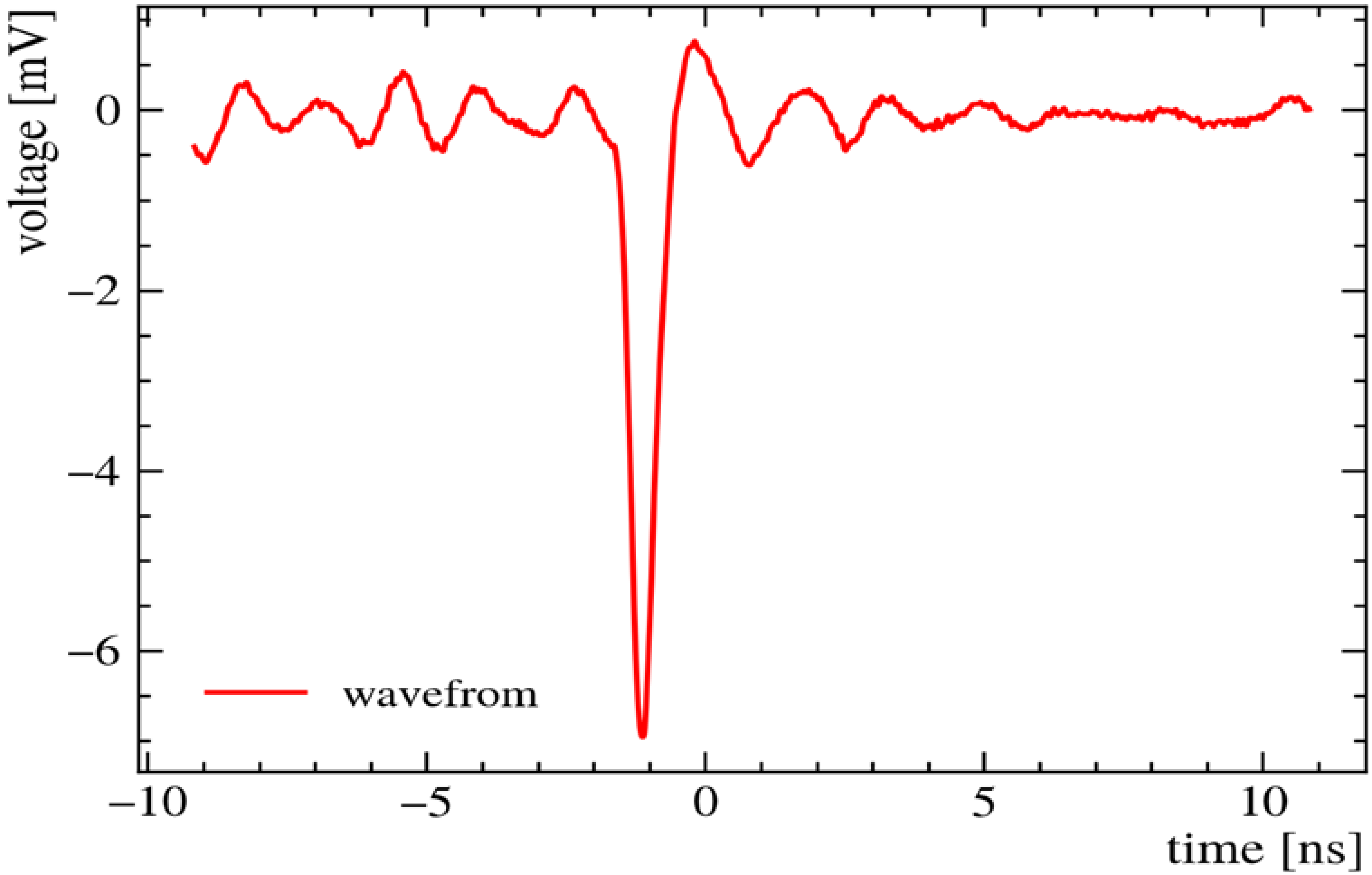
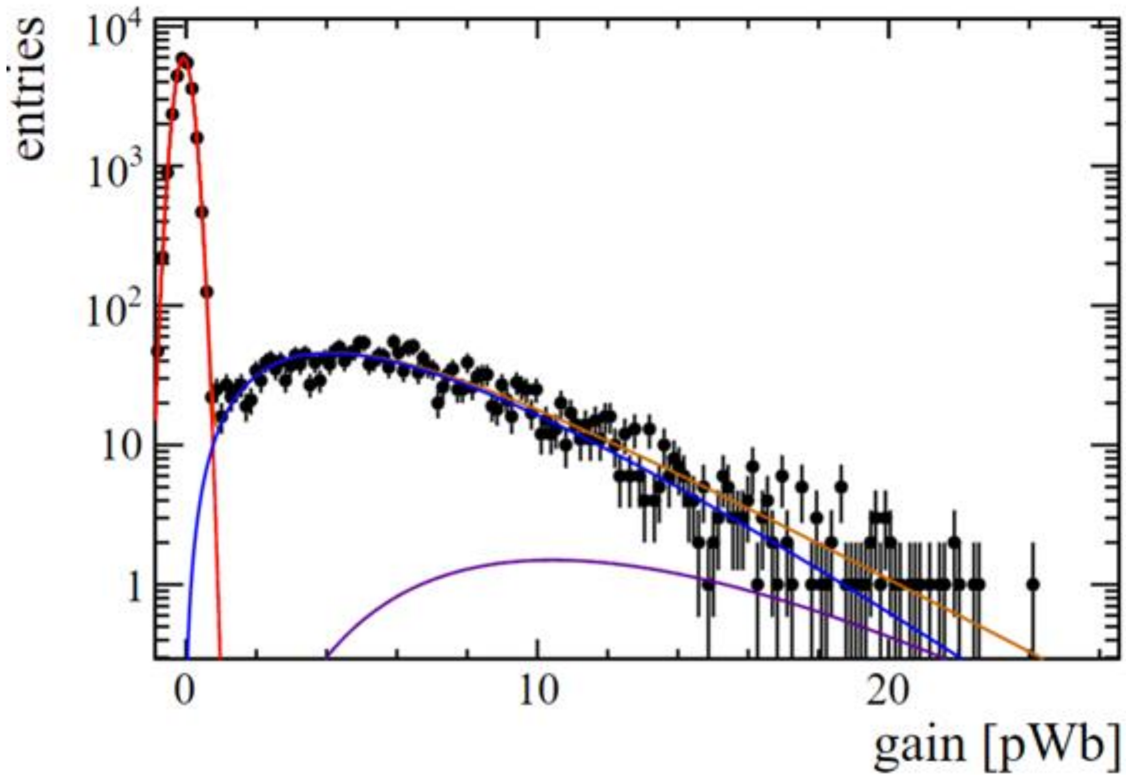
Single Pixel – Average Single Photon Pulse Shape



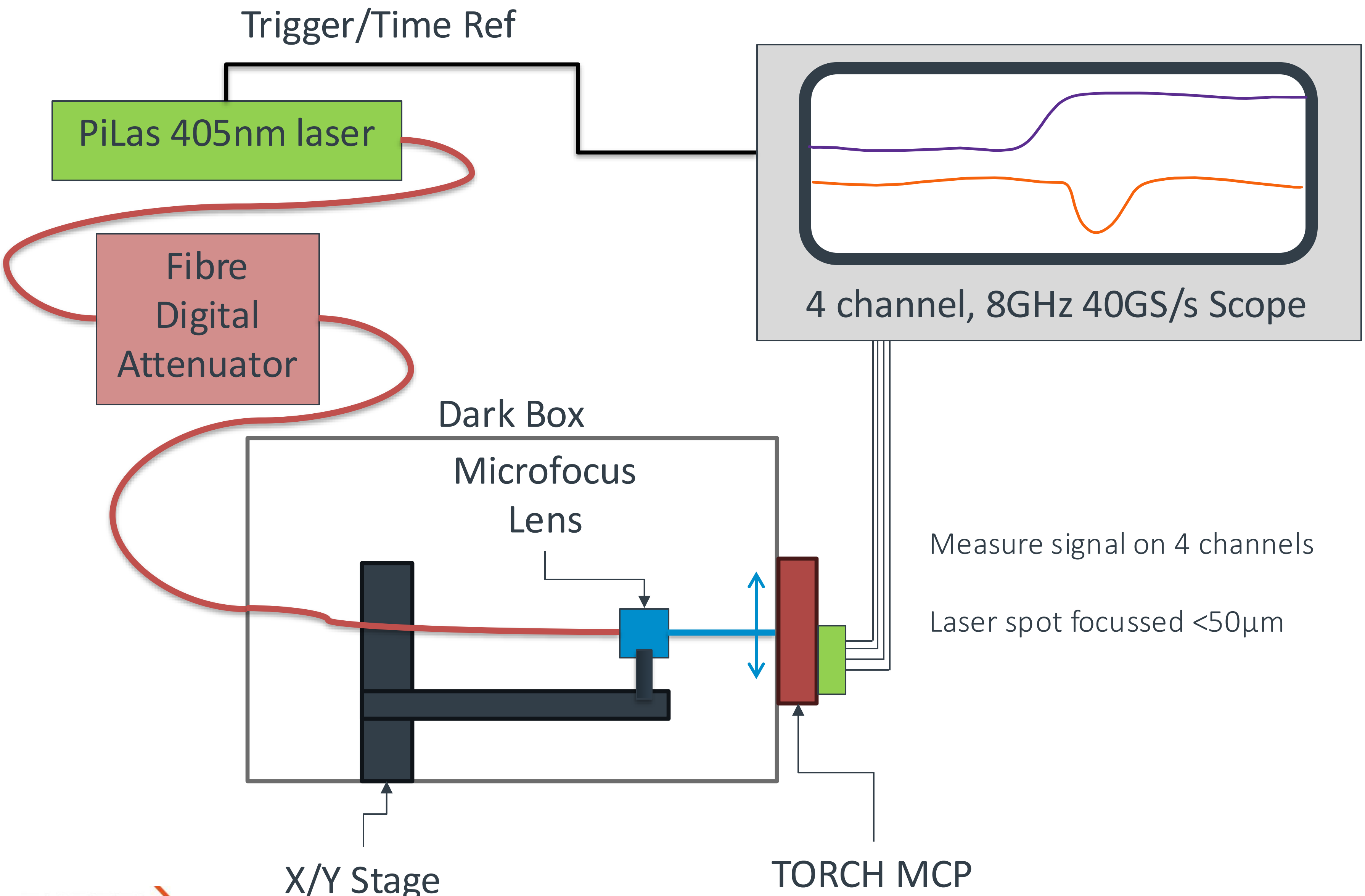
NB: Ripple due EM pickup from laser

Single Pixel Gain – Pulse Area (on oscilloscope)

- Trigger on each laser trigger
- Integrate pulse area for single photon events, on a single pixel
- Histogram to produce Pulse Height Distribution (PHD) to characterise gain
- Gaussian (noise floor) + multi-Polya fit to find gain
    - 0 photon
    - 1 photon
    - 2 photon
    - Etc….



Single Photon Scanning - Crosstalk/Timing Measurement setup



Measure signal on 4 channels

Laser spot focussed <50µm

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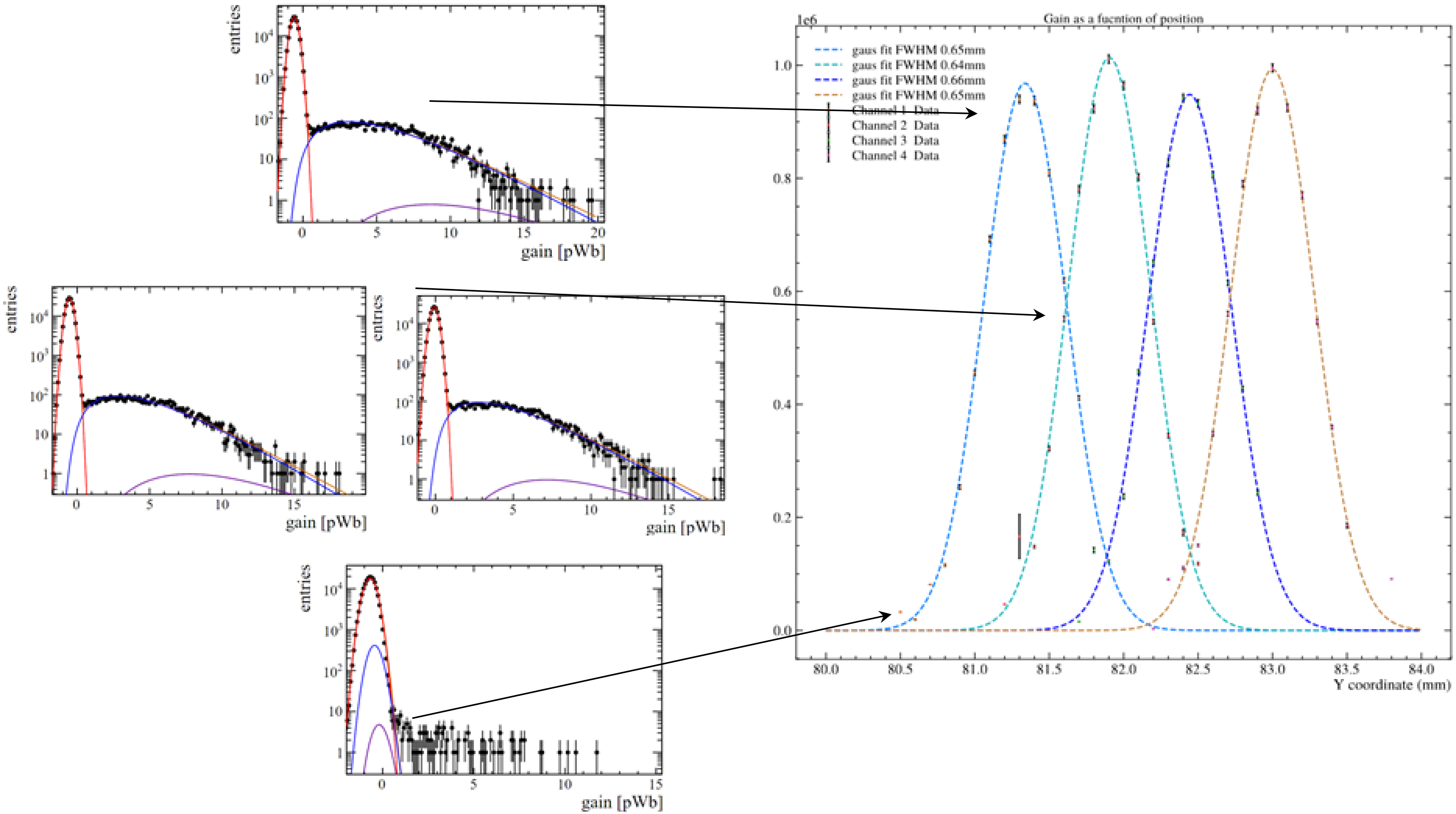
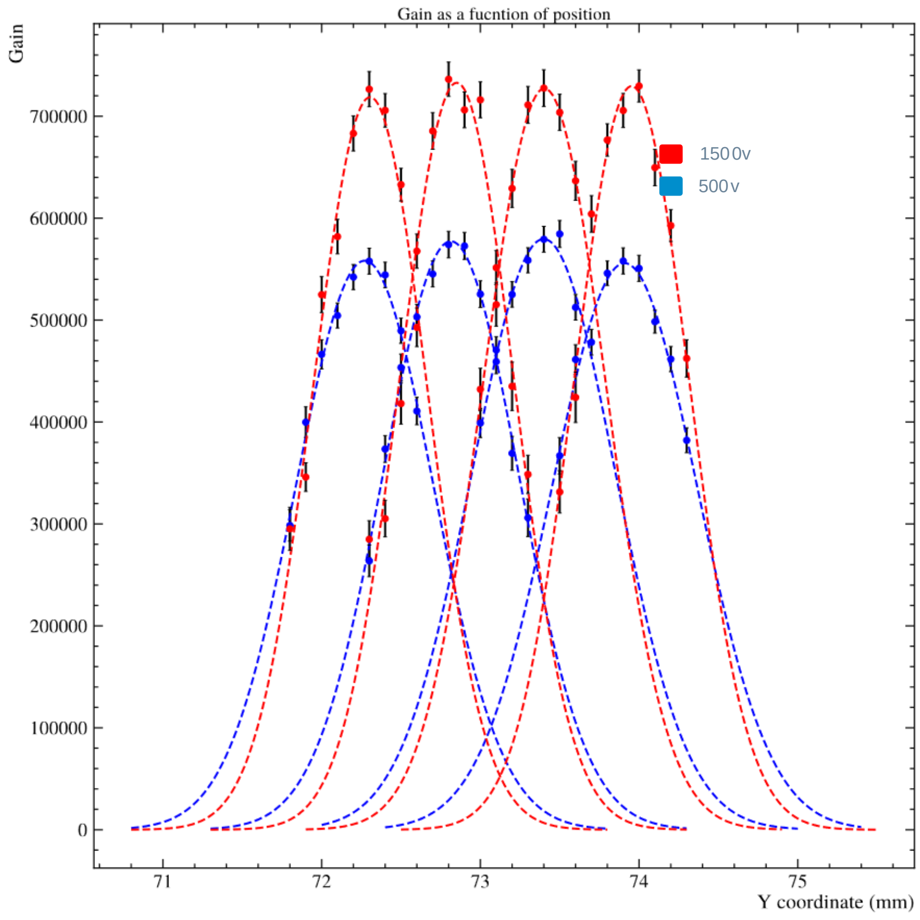
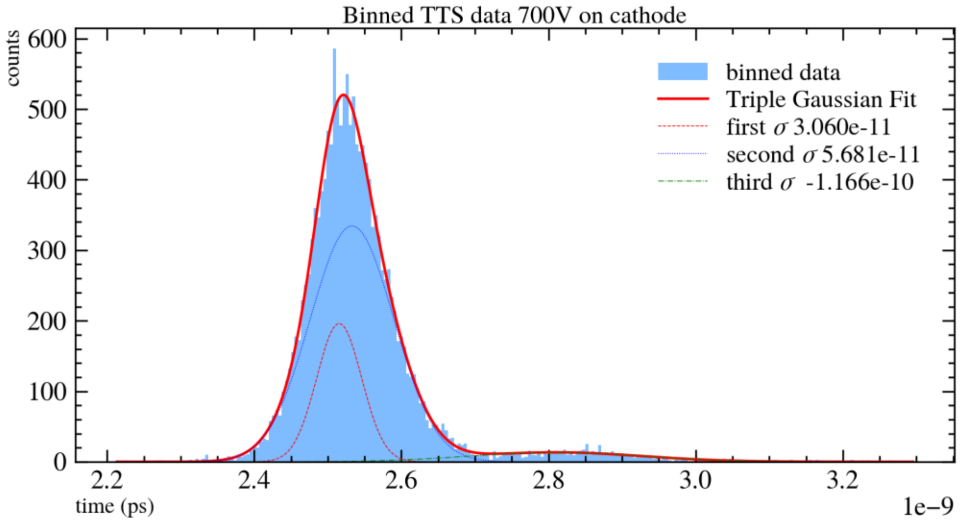
Scope Measured – Gain crosstalk

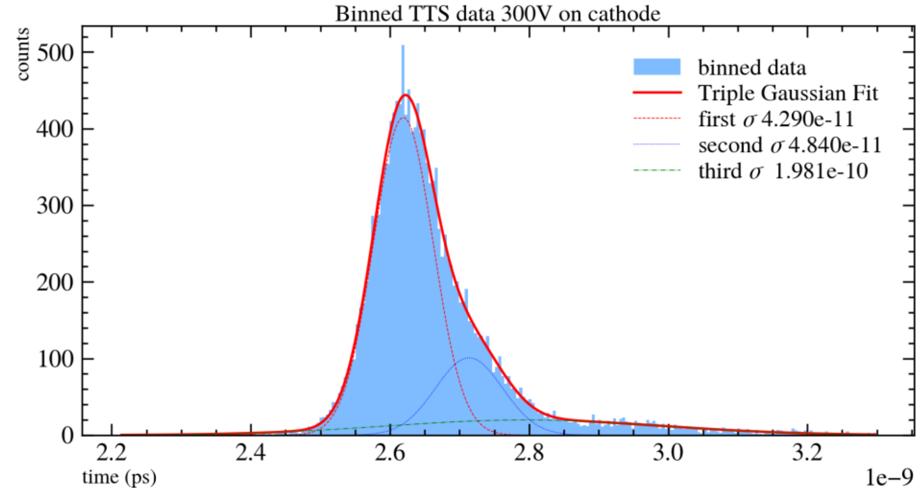


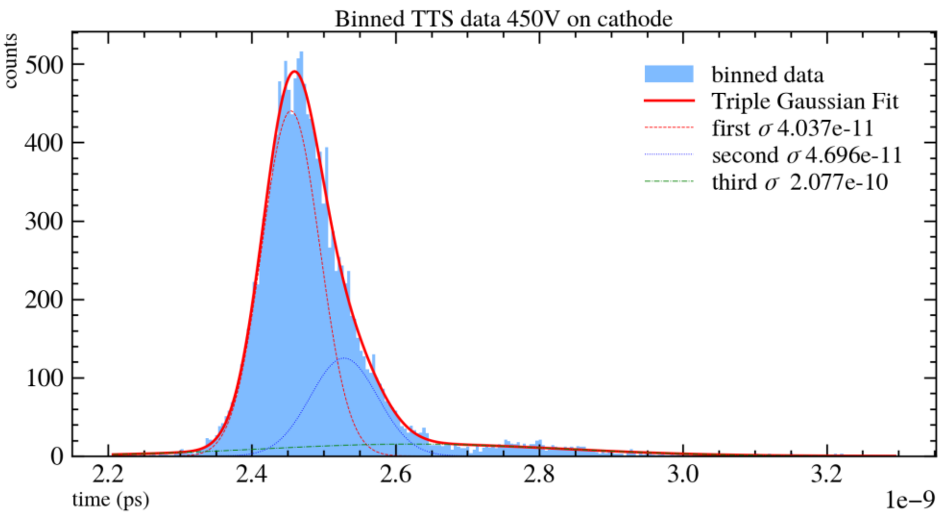
Increasing rear field – MCP output to anode

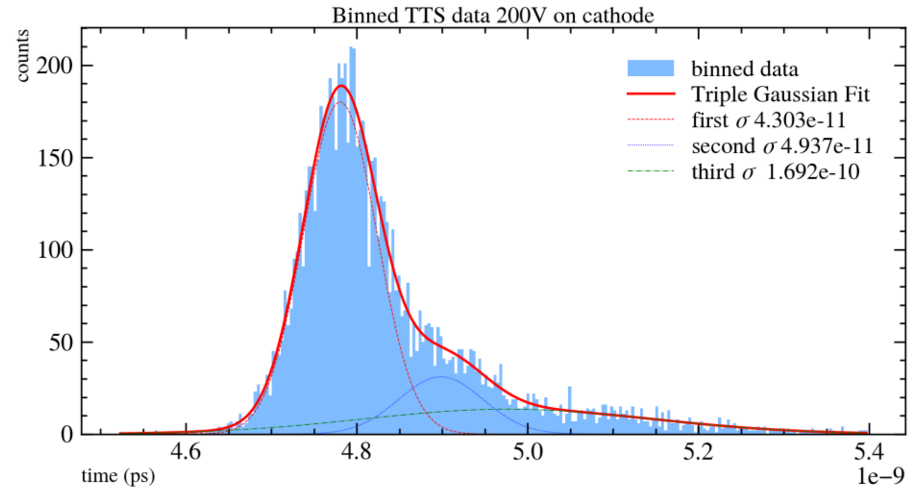


	@500V	@1500v
Channel 1	1.02 mm	0.84 mm
Channel 2	1.00 mm	0.84 mm
Channel 3	1.06 mm	0.90 mm
Channel 4	1.07 mm	0.85 mm


Binned TTS data 700V on cathode
binned data
Triple Gaussian Fit
first σ 3.060e-11
second σ 5.681e-11
third σ -1.166e-10
counts
0
100
200
300
400
500
600
2.2
2.4
2.6
2.8
3.0
3.2
time (ps)
1e−9


Binned TTS data 300V on cathode
binned data
Triple Gaussian Fit
first σ 4.290e-11
second σ 4.840e-11
third σ 1.981e-10
counts
0
100
200
300
400
500
2.2
2.4
2.6
2.8
3.0
3.2
time (ps)
1e−9


Binned TTS data 450V on cathode
binned data
Triple Gaussian Fit
first σ 4.037e-11
second σ 4.696e-11
third σ 2.077e-10
counts
0
100
200
300
400
500
2.2
2.4
2.6
2.8
3.0
3.2
time (ps)
1e−9


Binned TTS data 200V on cathode
binned data
Triple Gaussian Fit
first σ 4.303e-11
second σ 4.937e-11
third σ 1.692e-10
counts
0
50
100
150
200
4.6
4.8
5.0
5.2
5.4
time (ps)
1e−9

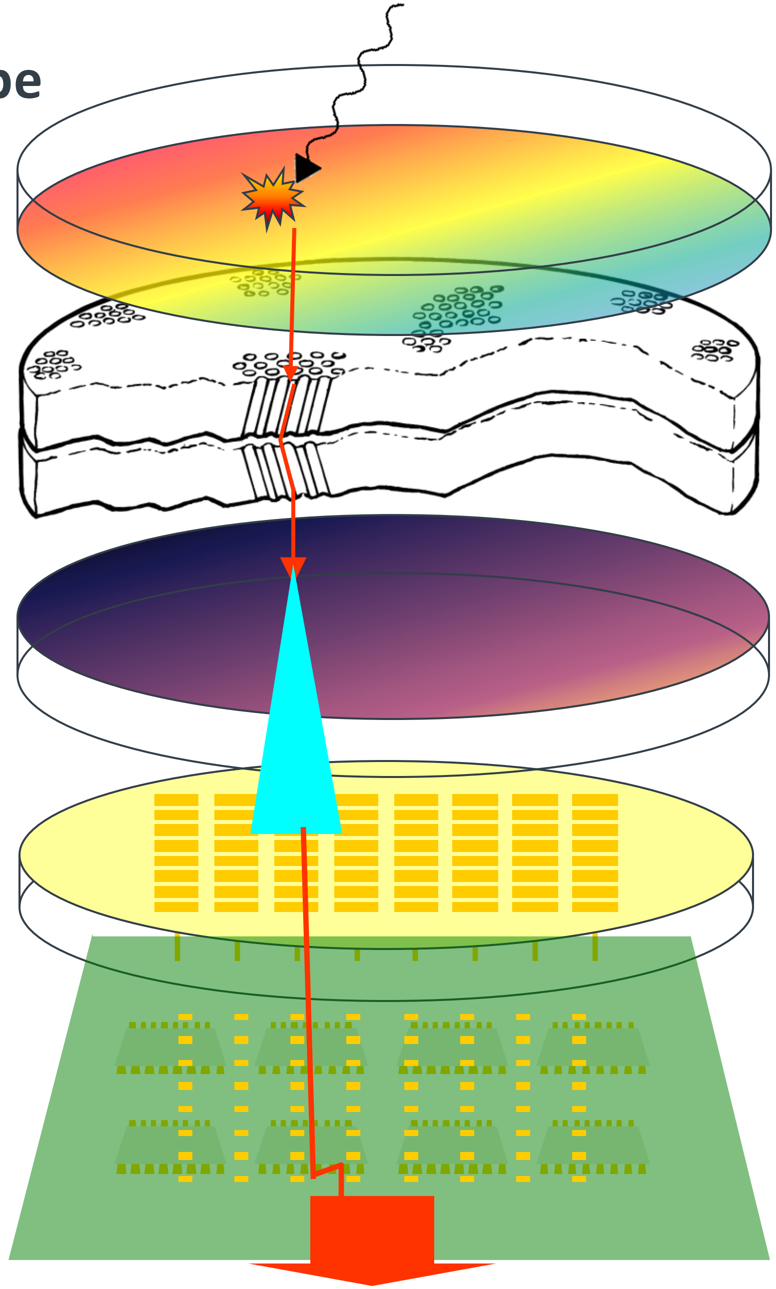
Charge Sharing Photon Timing/Imaging Detector

Neural network imaging for ToT charge measurement

Microchannel based Photo-Multiplier Tube

Multi- Anode Photon Multiplier Tube

- Photocathode to convert photon to an electron
  - Photoelectron accelerated toward micro-channel Plate (MCP)
- MCP amplifies photoelectron
  - Electron enters pore
  - Hits wall produces secondary electrons
  - Multiple "bounces" creates gain (up to a factor of 10^7)
- Collected by a readout
  - Capacitively coupled to Multi anode → Multi-channel current pulse → Tofpet2d Electronics



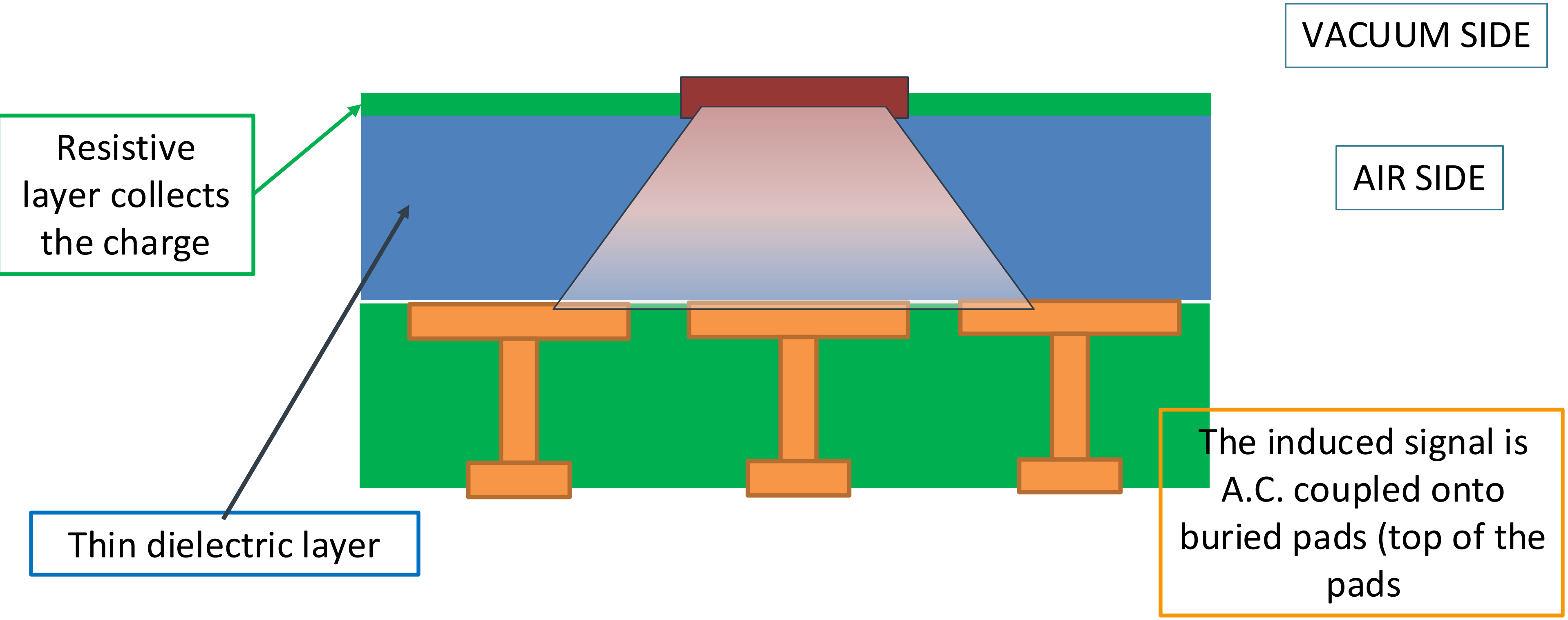
Next generation of Auratek PCS: Charge sharing

Electronic output:

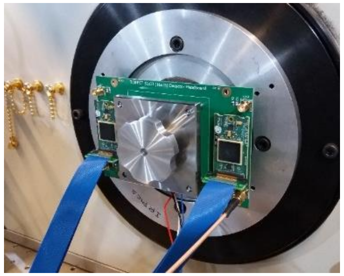
Each pixel has its own ToT discriminator

- Digitally time stamp
- Charge measurement via Time over trehosld

Capacitively Couple MCP charge cloud to multiple readout pads



Experimental data testing empirical detector data



Example of electronics set up outside the dark box

For training data perform a fine pitch scan of the detector area, using pulse laser

Photons are detected, and produce multi channel events in TOFPET2d

Further processed to cluster photon events coincident with laser

A single charge distribution:

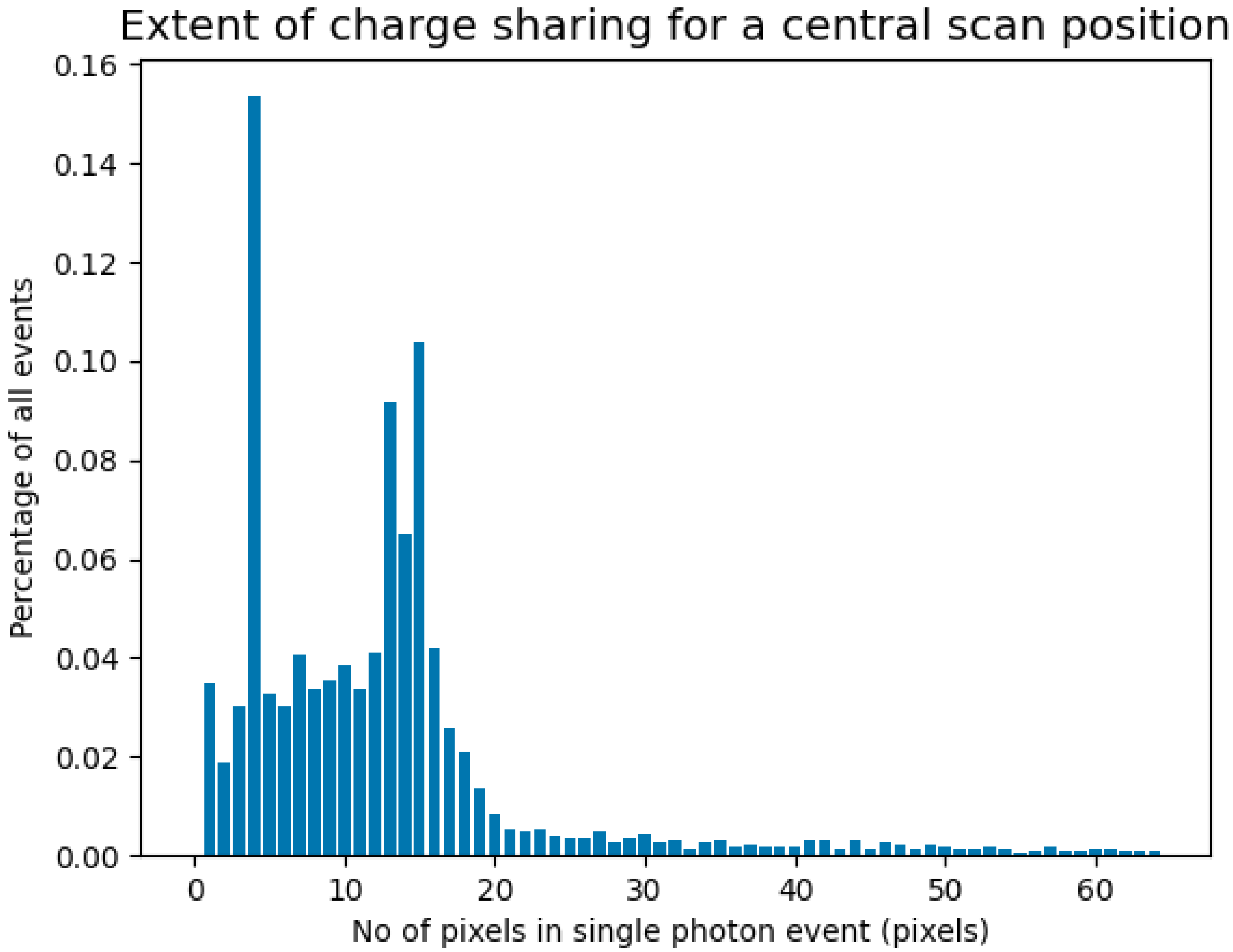
What the neural network sees as input:

X (in pixels)	Y (in pixels)	TOT (charge)	Time 2 (in ps)	Time 1 (in ps)
X_1	Y_1	TOT_1	T_1	T_{laser}
X_2	Y_2	TOT_2	T_2	T_{laser}
X_3	Y_3	TOT_3	T_3	T_{laser}
X_4	Y_4	TOT_4	T_4	T_{laser}
X_5	Y_5	TOT_5	T_5	T_{laser}
X_6	Y_6	TOT_6	T_6	T_{laser}

x 10,000 for a scan position

Expected output: X_{laser} (mm), Y_{laser} (mm), T_{laser}

Charge Sharing – Number of TOFPET2d channels over threshold



Analytically spatial reconstruction of empirical detector data

- The Convolutional neural network is trained a single sample representing a charge distribution giving information:
  - $64 \times (X_p, Y_p, Q_p)$
- to give outputs of:
  - X_γ and Y_γ.

Each (X_p, Y_p, Q_p) represents a packet of data from a single anode pad.

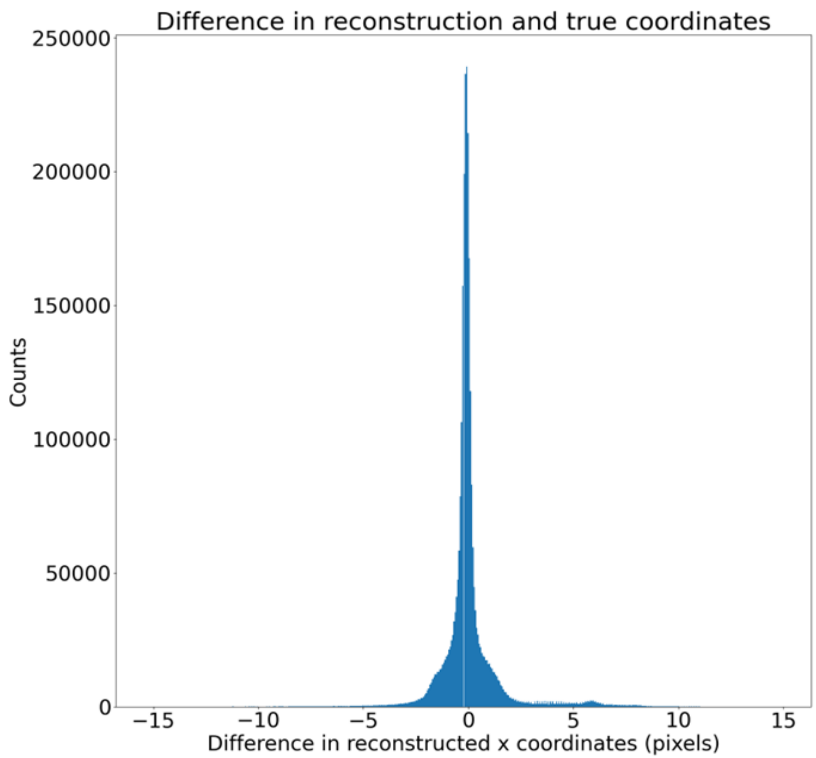
Each $(X_\gamma$ and $Y_\gamma)$ represents the spatial photon coordinates for each charge distribution

CENTROIDING ALGORITHMIC METHOD

$$X_\gamma = \sum \frac{x_p q_p}{\sum q_p} ,$$

$$Y_\gamma = \sum \frac{y_i q_p}{\sum q_p} ,$$

$$T_\gamma = \overline{t_i}$$



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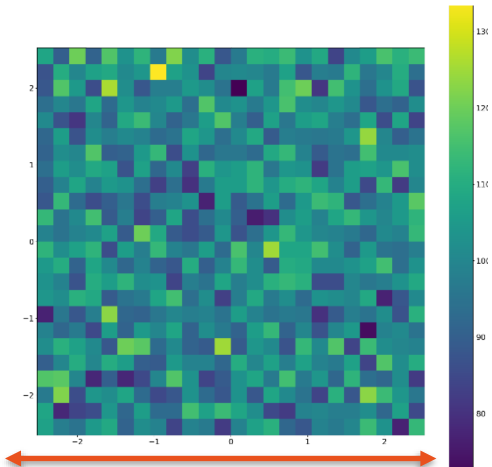
Reconstructing X and Y, convolutional NN

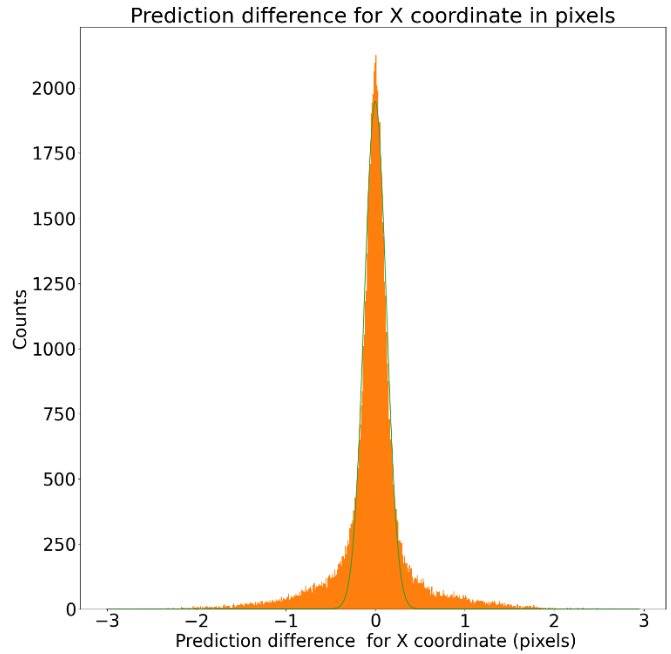
Central data scan:

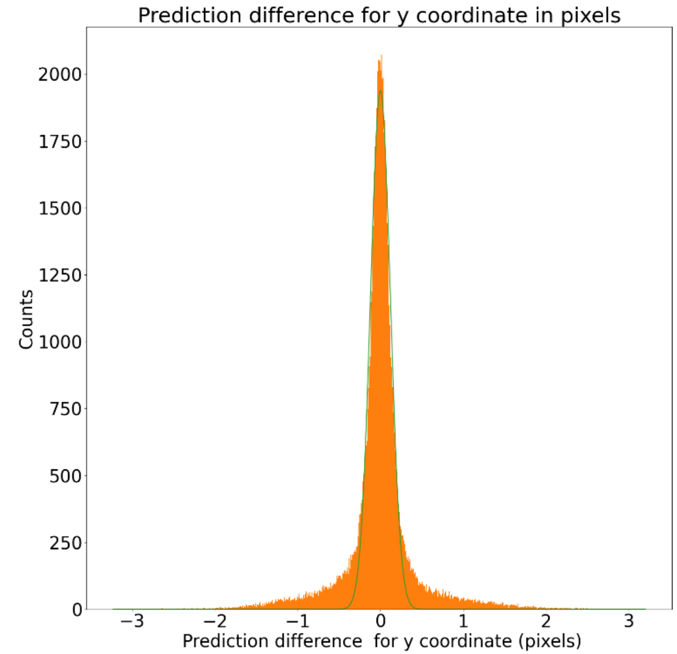
Active area: -2.5mm to 2.5mm

Counts of samples per position in test data



5 mm





Difference in reconstruction and empirical coordinates

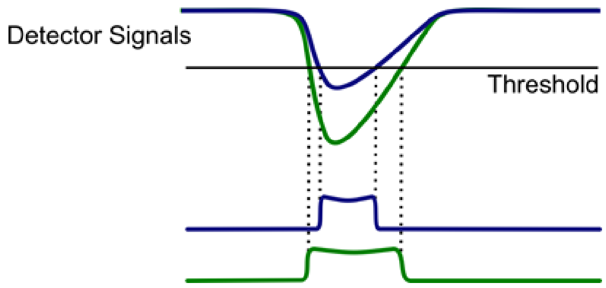
	Reconstruction error (Pixels)	
	Full Width Half Maximum	Root Mean Squared Error
X/Y error in reconstruction (CNN)	0.26	0.11
X/Y error in reconstruction analytical	3.42	1.46

RMS of a top hat distribution:

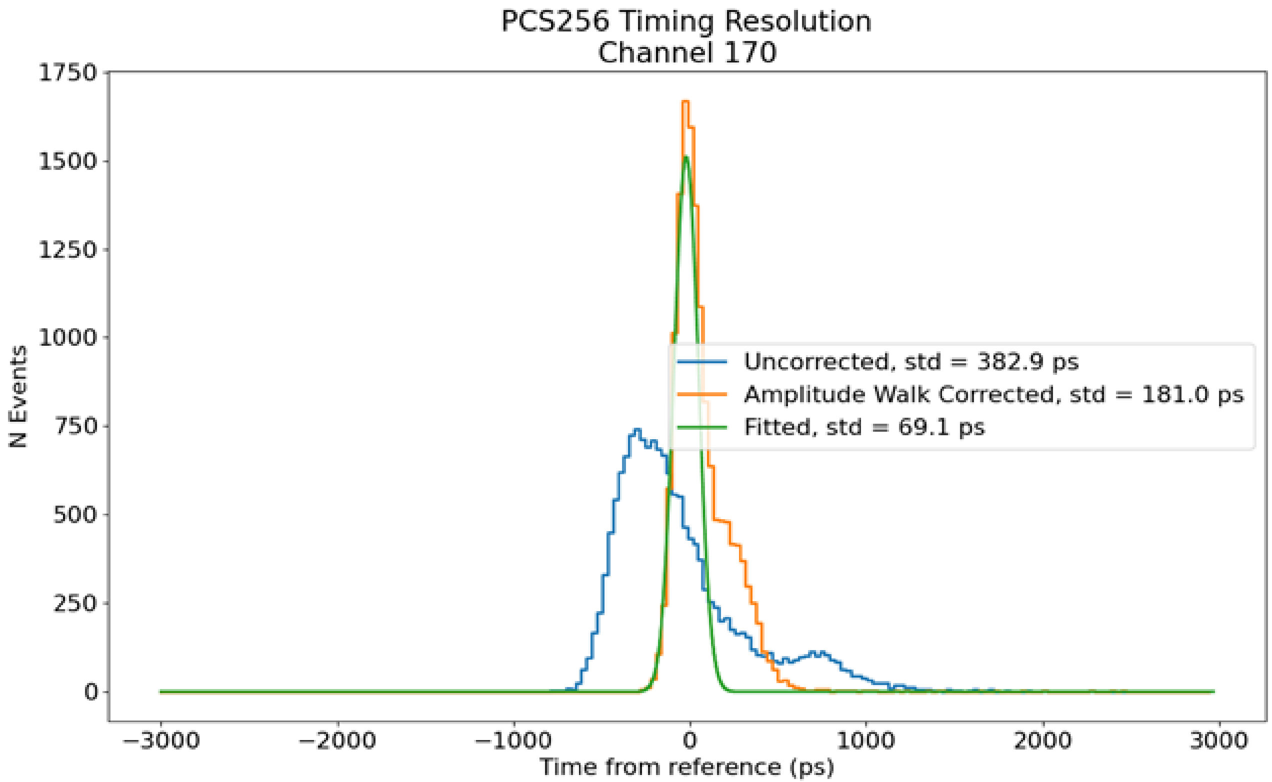
$$\mathrm{Rms} = \frac{1}{\sqrt{12}} Pixel_{width},$$

$$\mathrm{Rms} = \frac{1}{\sqrt{12}}\ x\ 1.656 = 0.478$$

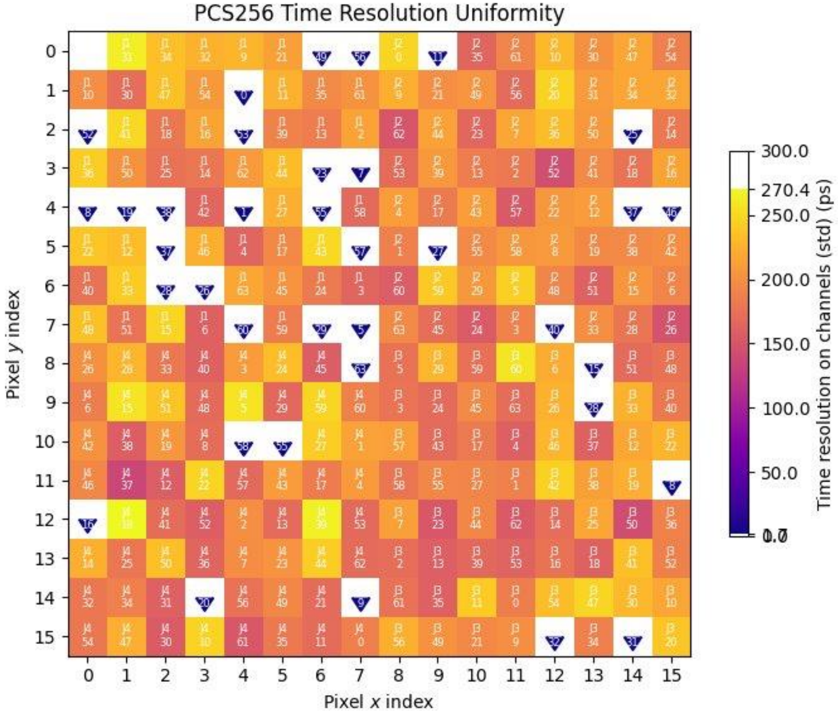
Characterisation of Resistive Sea PMT



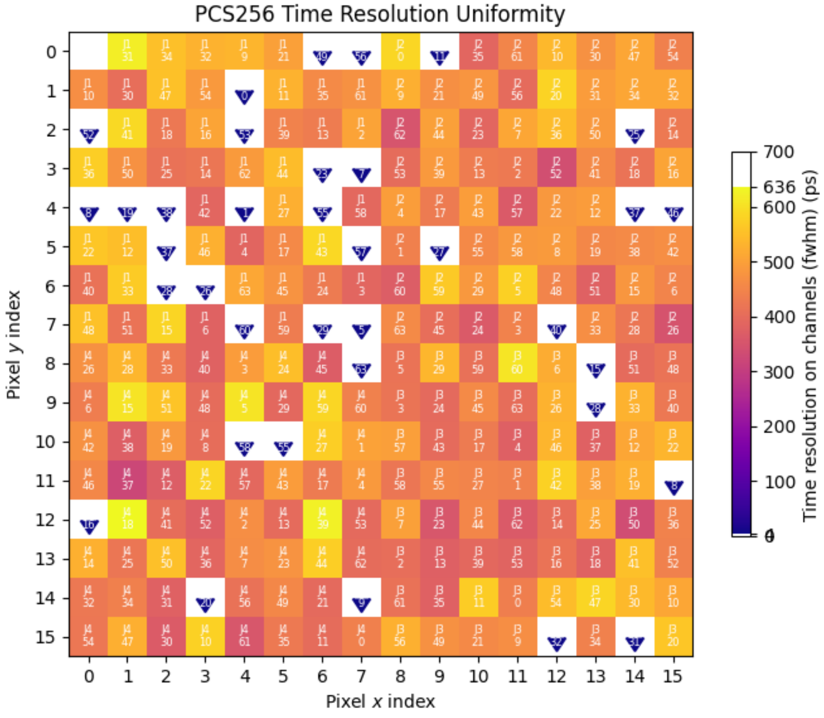
Amplitude walk calibration:



Total RMS Uniformity



Data resolution = 170.1 ps (± 74.1 ps)



Data resolution = 399.6 ps (± 174.1 ps)

To Conclude

- First prototype of TORCH 16x95 MAPMT built, characterisation ongoing
- Promising cross talk and timing performance

- Proof of principle Neural Network developed for charge sharing ToT imaging photon detector showing potential
- Need to demonstrate with real world images/timing data

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With Thanks:
University of Warwick & TORCH Collaboration
University of Leicester, Maths & Physics Departments

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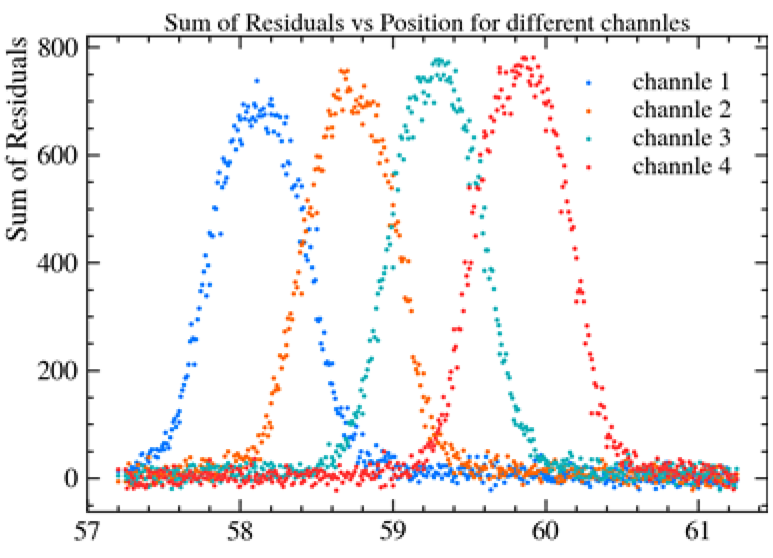
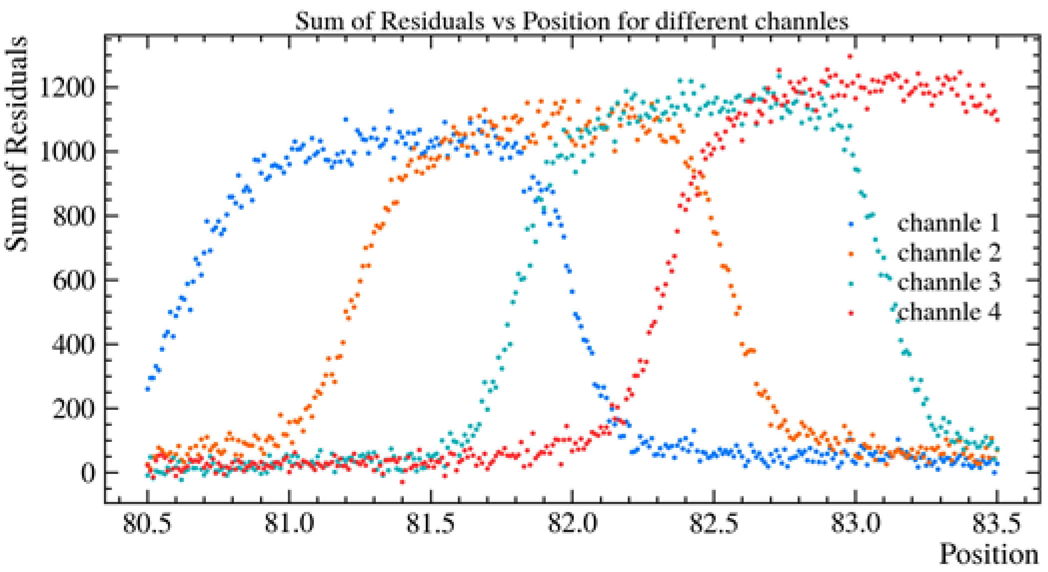
Backup Slides

Crosstalk Using residuals

- Measure crosstalk using residuals of PHD fit, i.e. number of events outside noise pedestal (e.g. 5σ and 10σ)





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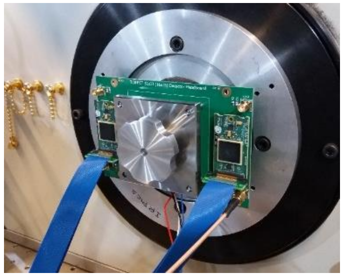
Experimental data testing empirical detector data



Example of electronics set up outside the dark box

Preliminary reconstruction of *X, Y* and *T* values of photon position

A pulsed 0.2 mm laser with a wavelength of 638 nm was triggered at a rate of 300 kHz completing a coarse 0.25 mm step 28 mm^2 **circular scan of the detector's active anode area**.

A single charge distribution:

What the neural network sees as input:

Values of order 10^{13}

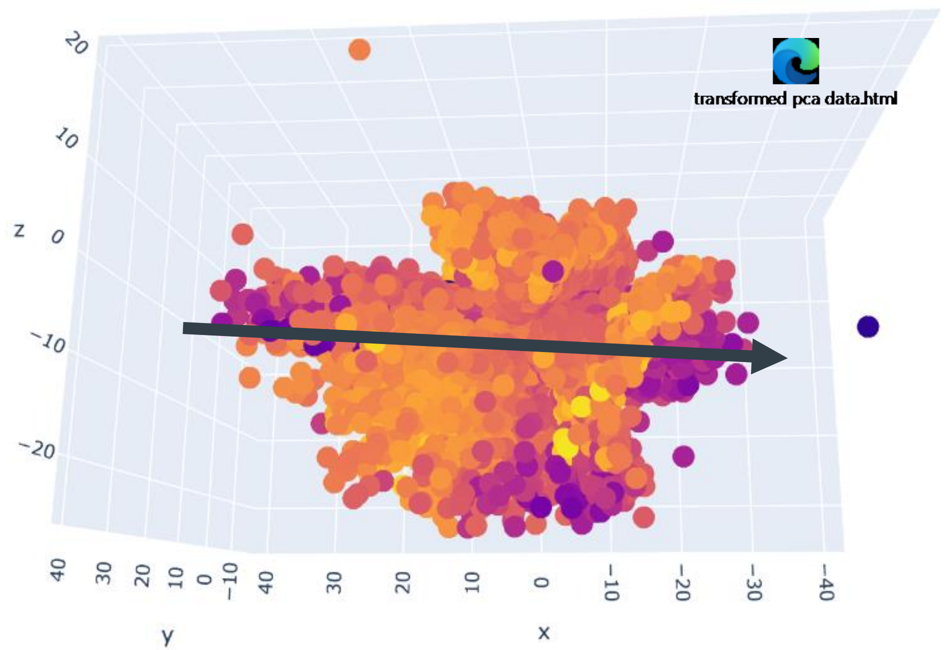
X (in pixels)	Y (in pixels)	TOT (charge)	Time 2 (in ps)	Time 1 (in ps)
X_1	Y_1	TOT_1	T_1	T_{laser}
X_2	Y_2	TOT_2	T_2	T_{laser}
X_3	Y_3	TOT_3	T_3	T_{laser}
X_4	Y_4	TOT_4	T_4	T_{laser}
X_5	Y_5	TOT_5	T_5	T_{laser}
X_6	Y_6	TOT_6	T_6	T_{laser}

x 10,000 for a scan position

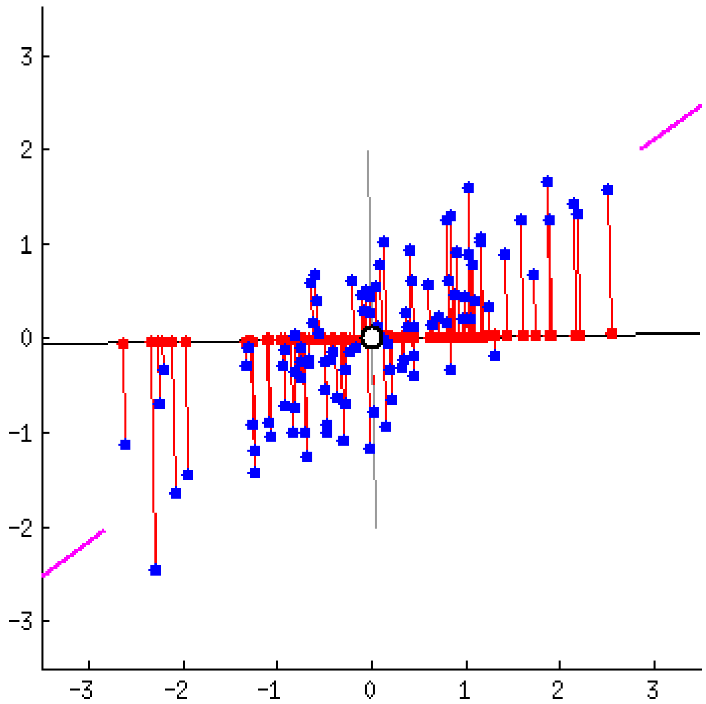
Expected output: X_{photon} (mm), Y_{photon} (mm), T_{laser}

Traversing the latent space

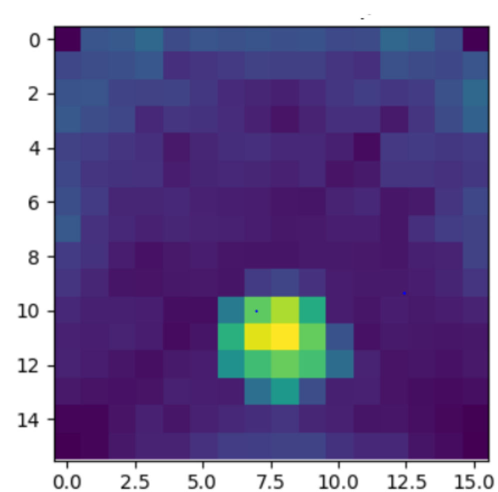
What does the latent space look like in my work?



PCA analysis



Expected result/current work:



Reconstructing the photon position using a Python Monte Carlo trained NN

Convolutional Neural Network to reconstruct photon spatial coordinates *X* and *Y*

- The CNN is trained a single sample representing a charge distribution giving information:
  - **16 × (*X_p, Y_p, Q*)**
- to give outputs of:
  - ***X_γ and Y_γ.***

Each ***(X_p, Y_p, Q)*** represents a packet of data from a single anode pad.

Each ***(X_γ and Y_γ)*** represents the spatial photon coordinates for each charge distribution

CENTROIDING ALGORITHMIC METHOD

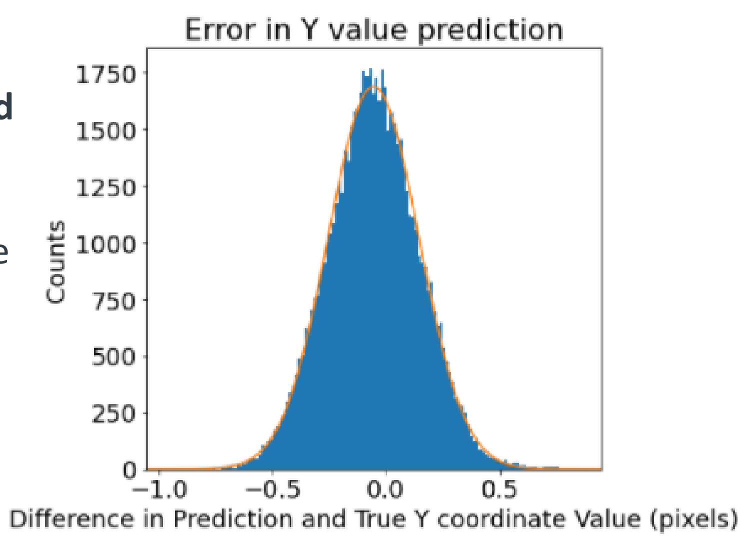
$$X_\gamma = \sum \frac{x_i q_i}{\sum q_i} ,$$

$$Y_\gamma = \sum \frac{y_i q_i}{\sum q_i} ,$$

$$T_\gamma = \overline{t_i}$$

RESULTS

Reconstruct *X* and *Y* to an RMS of 0.202 pixels, demonstrating we can increase the spatial resolution by just over 4 times!



→ **SIMULATION OF REALISTIC INPUTS AND OUTPUTS**

Training samples used by the CNN are of the following format:

$$16 \times (X_p, Y_p, ToT(Q \pm N(ToT, \sigma ToT)), T_{measured})$$

to give outputs of:

$$X_\gamma, Y_\gamma \text{ and } T_\gamma\ (T_{measured} - AWC(ToT)).$$

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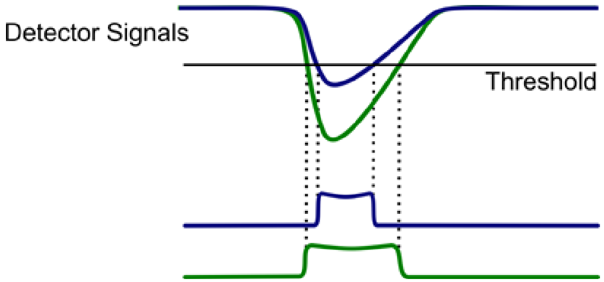
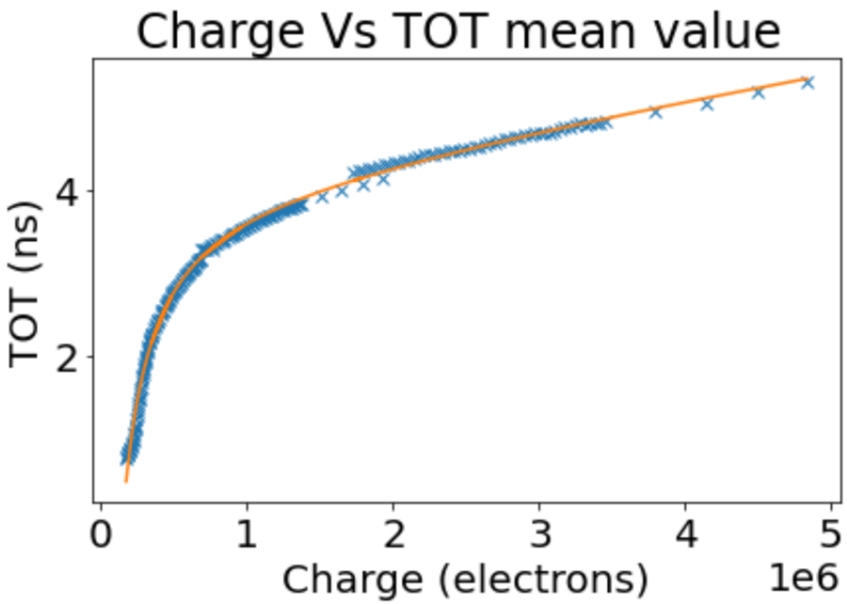
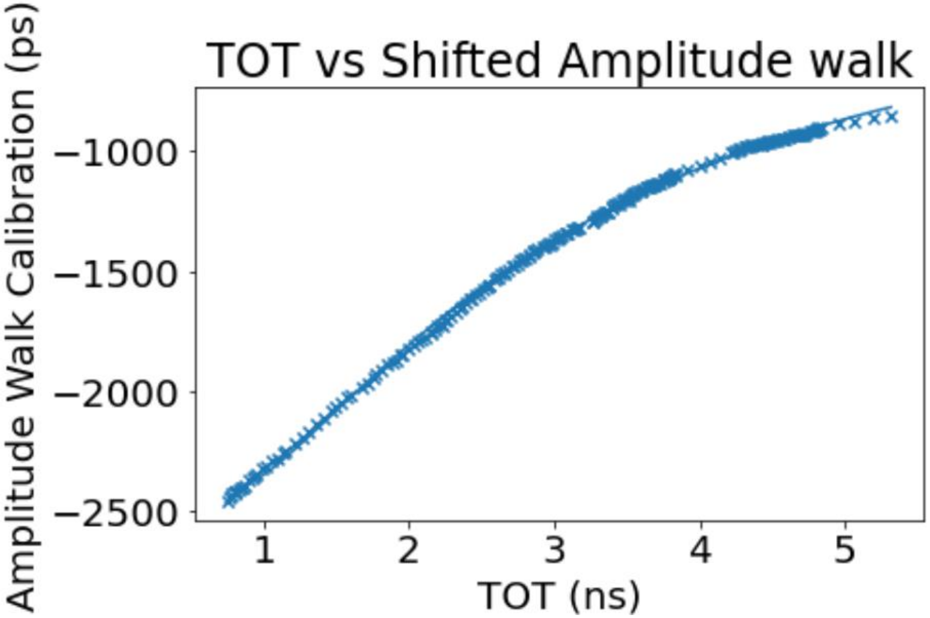
Experimental method for calibrations



Methodology

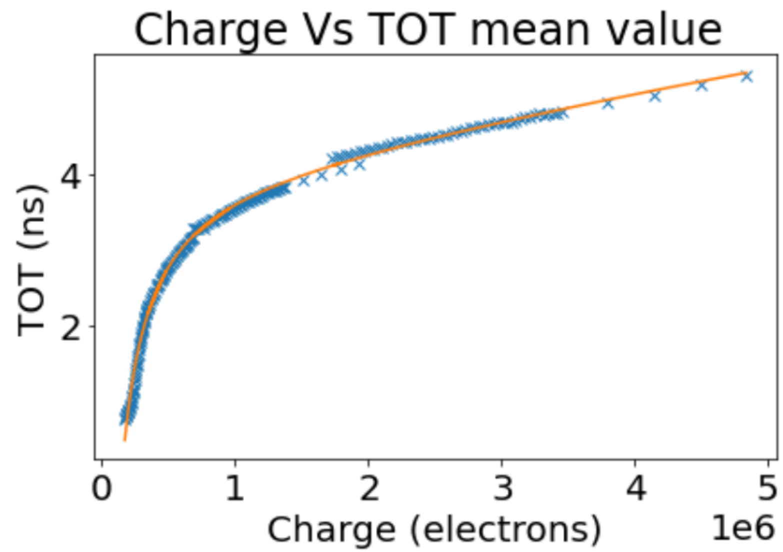
- To calibrate for **charge**, **ToT** and T_γ :
- TOFPET2d electronics do not give a direct measure of charge, instead it **measures Time-over-threshold (ToT) using a time discriminator technique**, this is related to charge collected on the anode
- a fast voltage step (1 ns rise time) produces a charge injection to each TOFPET2d channel through a 2.2 pF capacitor, emulating the MAPMT (Multi-anode Photo Multiplier Tube) output current pulse.

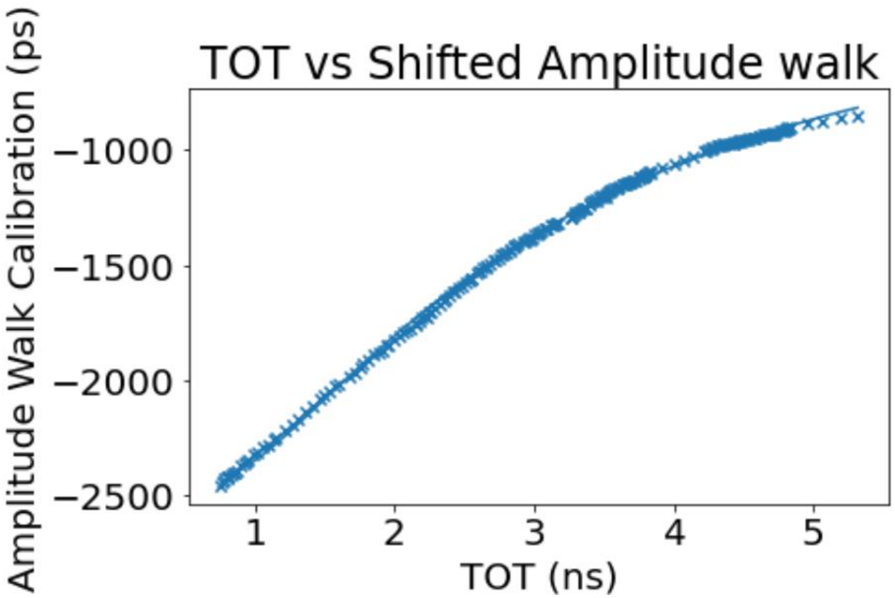




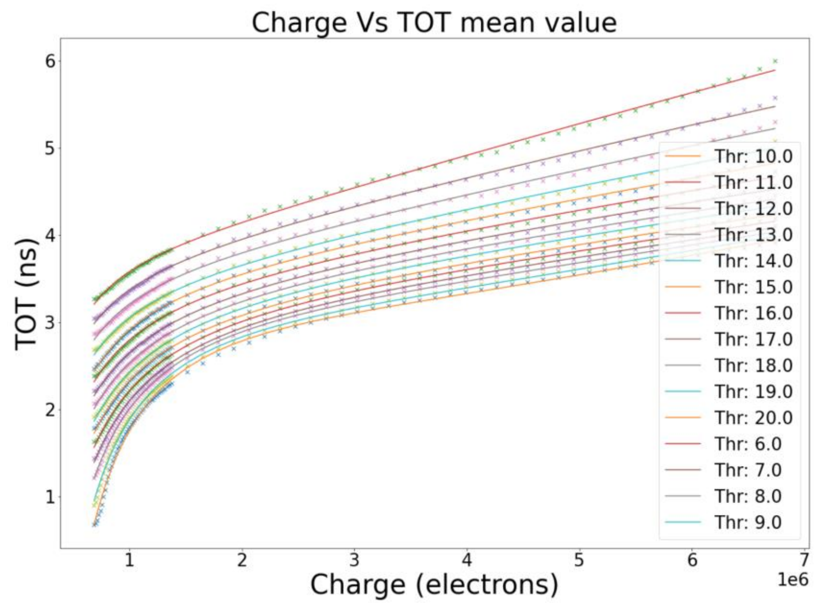
Calibration results

Charge, Time-over-Threshold and time of event calibrations





Future work…



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Training the VAEGan

Training cycle

VAE (300 epochs)

Real: Training data
Fake: Generated data

Discriminator (100 epochs)

decoder (50 epochs)

Real: Training data
Fake: Generated data

Discriminator (train on batch)