



# Multi-Anode Photomultiplier Tubes

Inter-Channel Occupancy & Timing Variations in RICH MAPMTs

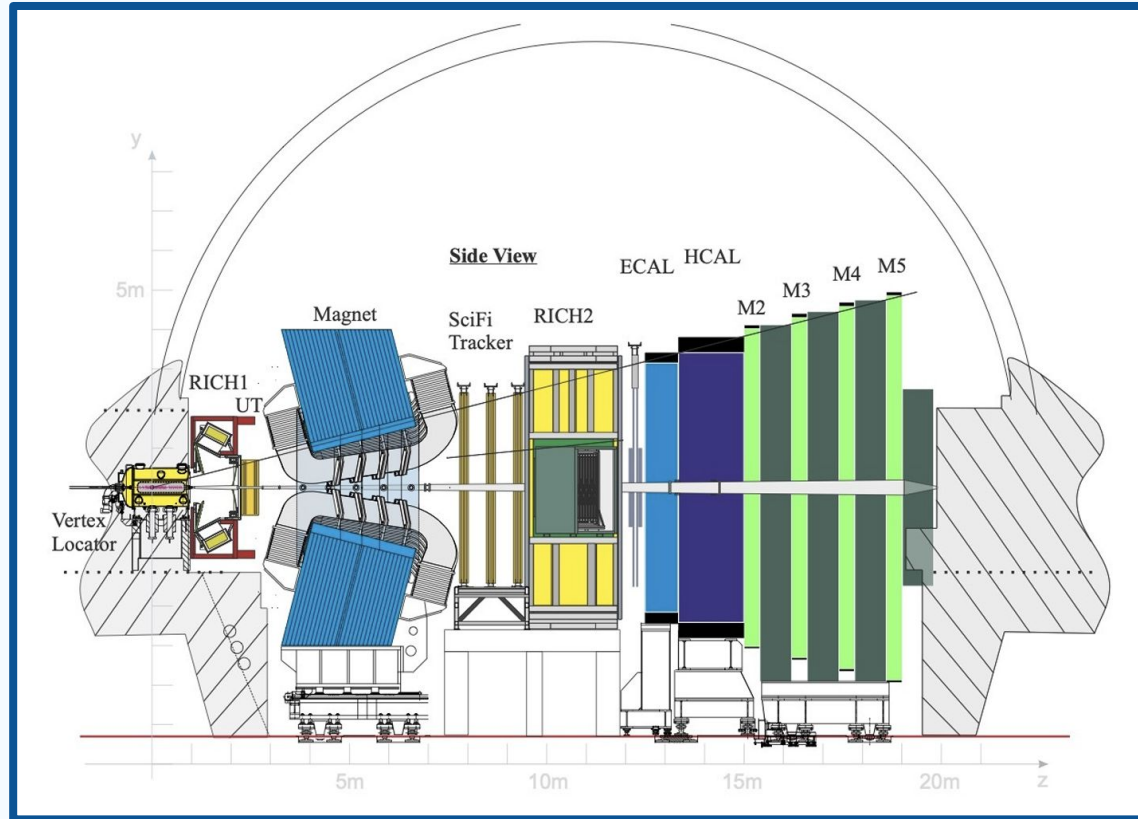
Callum White

# Motivations

LHCb, RICH & MAPMTs

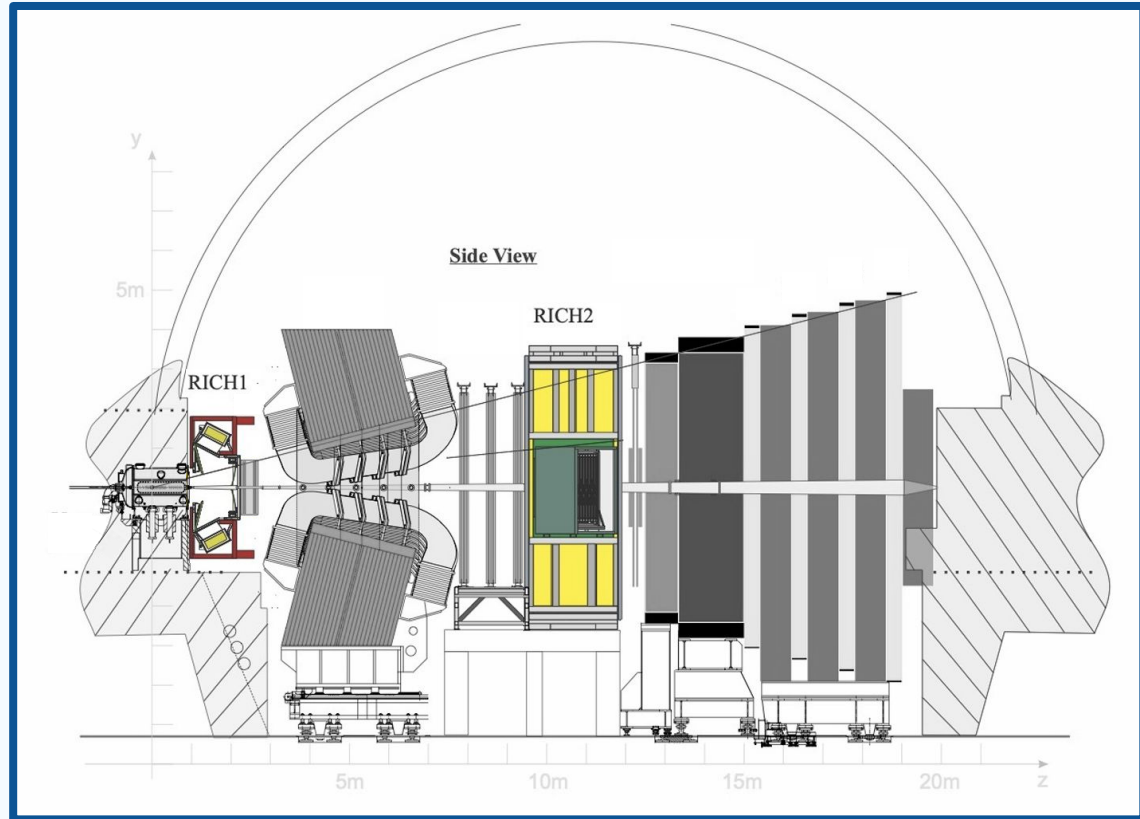
## Large Hadron Collider Beauty Experiment

- One of four experiments around the main LHC ring
- Focus on  $b$  &  $c$  quark based interactions

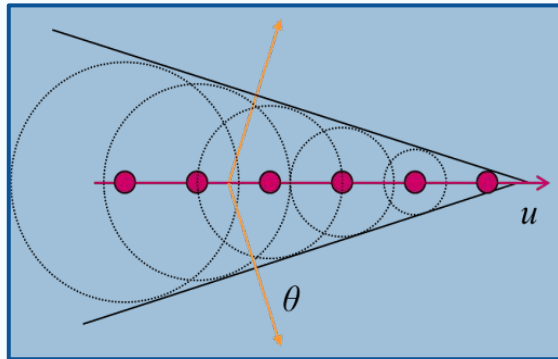


## Ring Imaging Cherenkov Detector

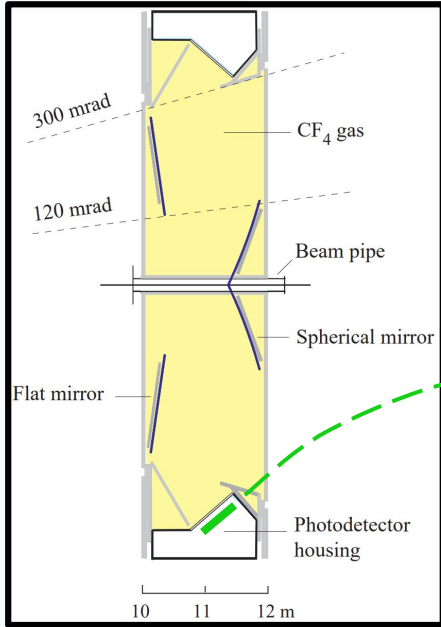
- Specialised for the identification of hadrons such as protons, pions and kaons
- Identification via rings of Cherenkov radiation



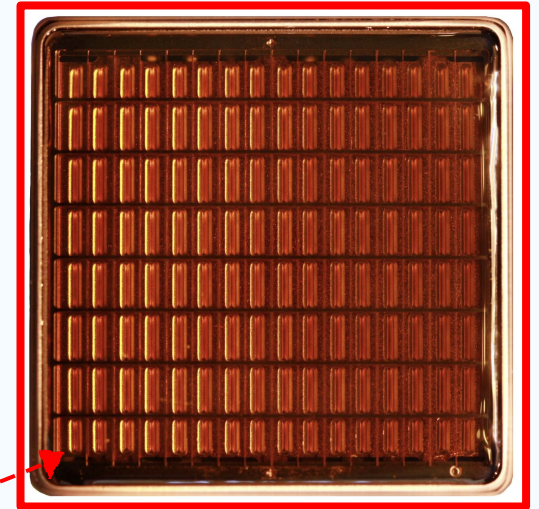
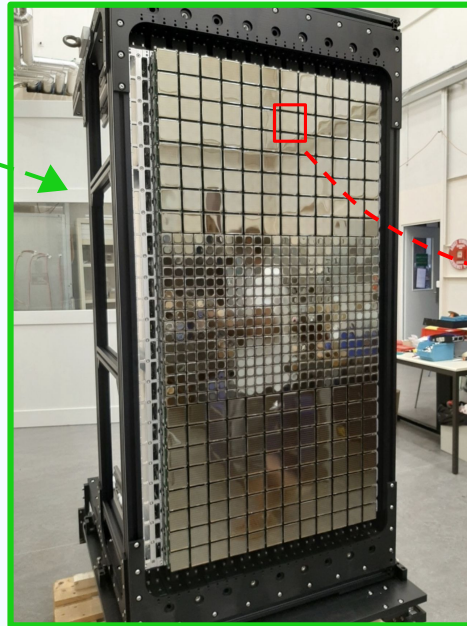
**Cherenkov Radiation** - Photonic emission when a particle travels faster than the phase velocity of light in the medium



- Analogous to a sonic boom, but in the EM field instead of air pressure
- Measure  $\theta$ , calculate velocity, using tracking momentum to work out mass



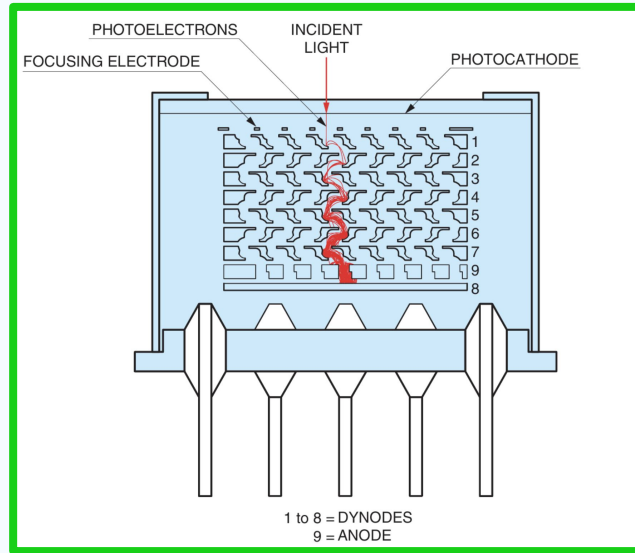
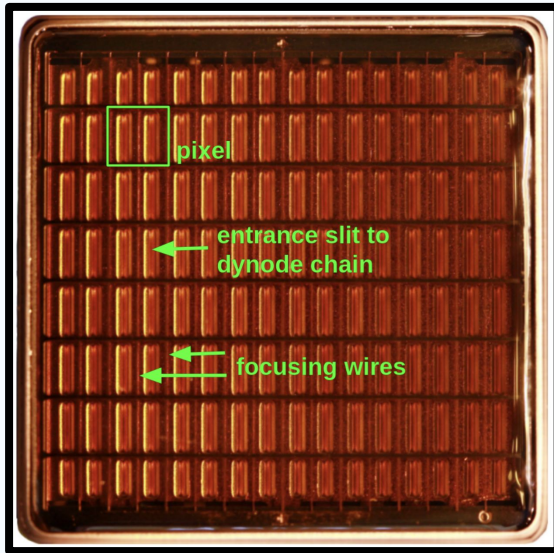
- 1 inch and 2 inch sensors for different granularity in higher occupancy regions



- Zoomed in view of the 2 inch multi-anode photomultiplier tube (MAPMT)
- 64 channels (8x8)

- RICH 2 focuses the Cherenkov emission into a ring on an array of photomultiplier tubes

- A photon hits the photocathode and emits a photoelectron via the photoelectric effect
- The photoelectron is accelerated and multiplied down the dynode chain
- A cloud of electrons is then absorbed as a signal pulse

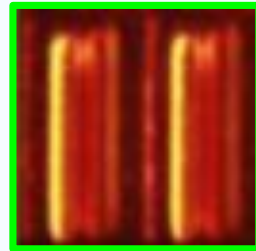
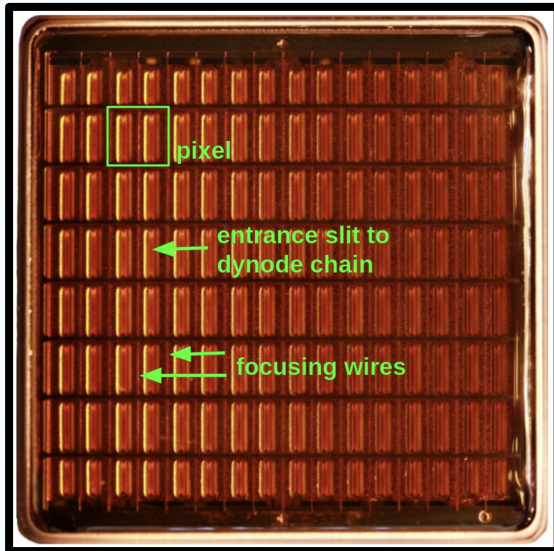


The time it take from photoelectron production to electron cloud absorption is the **transit time** of the sensor

The resolution in this timing is the key parameter in determining the sensors ability to reject out-of-time photons

# Why Did I Explain All That?

- [Previous study](#) in 2020
- Discovered significant time resolution degradation coming from the outer regions of any specific MAPMT channel
- Aim to expand from this and visually display this reported degradation

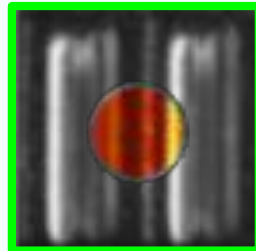


## **Full Channel Illumination**

FWHM:  $\sim 400\text{ps}$

Time Resolution:  $\sim 170\text{ps}$

\*Conversion dividing by 2.355



\* Spot size not to scale

## **1mm Diameter Hole**

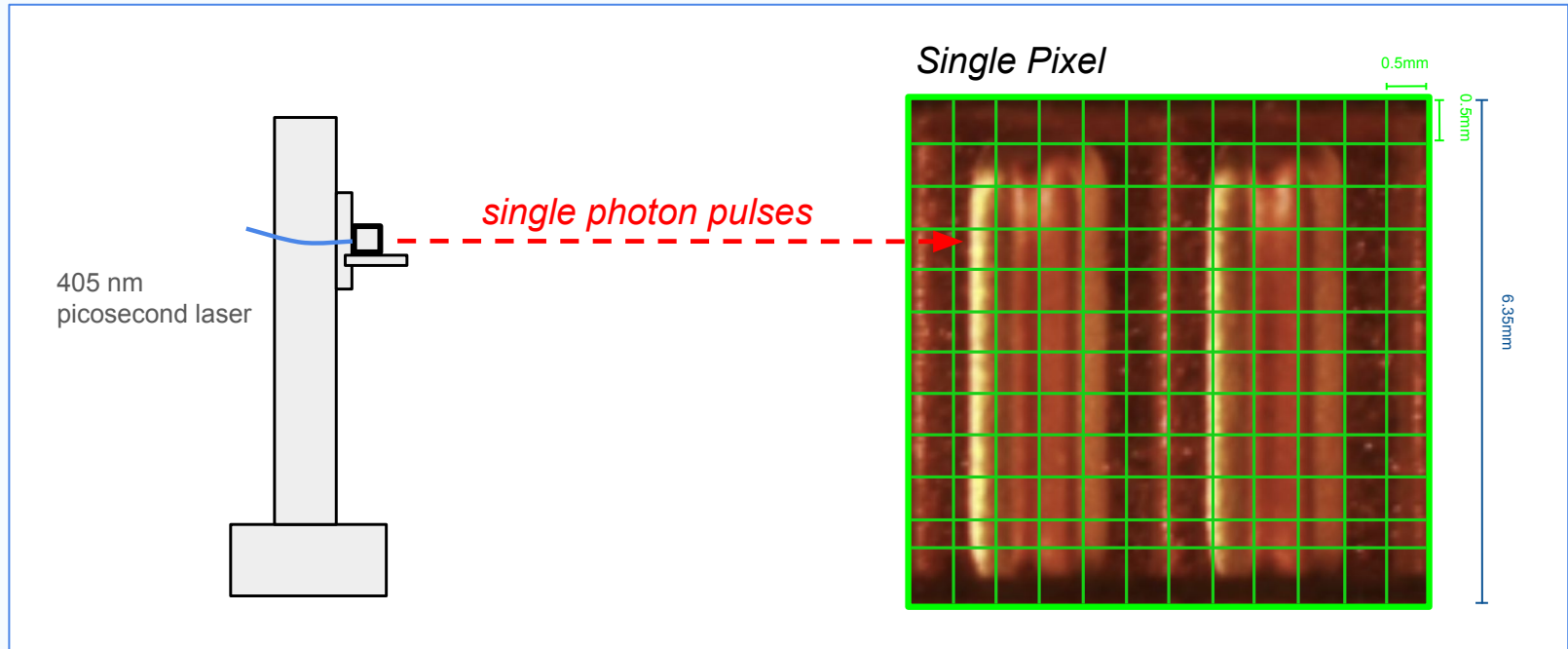
FWHM:  $\sim 250\text{ps}$

Time Resolution:  $\sim 106\text{ps}$

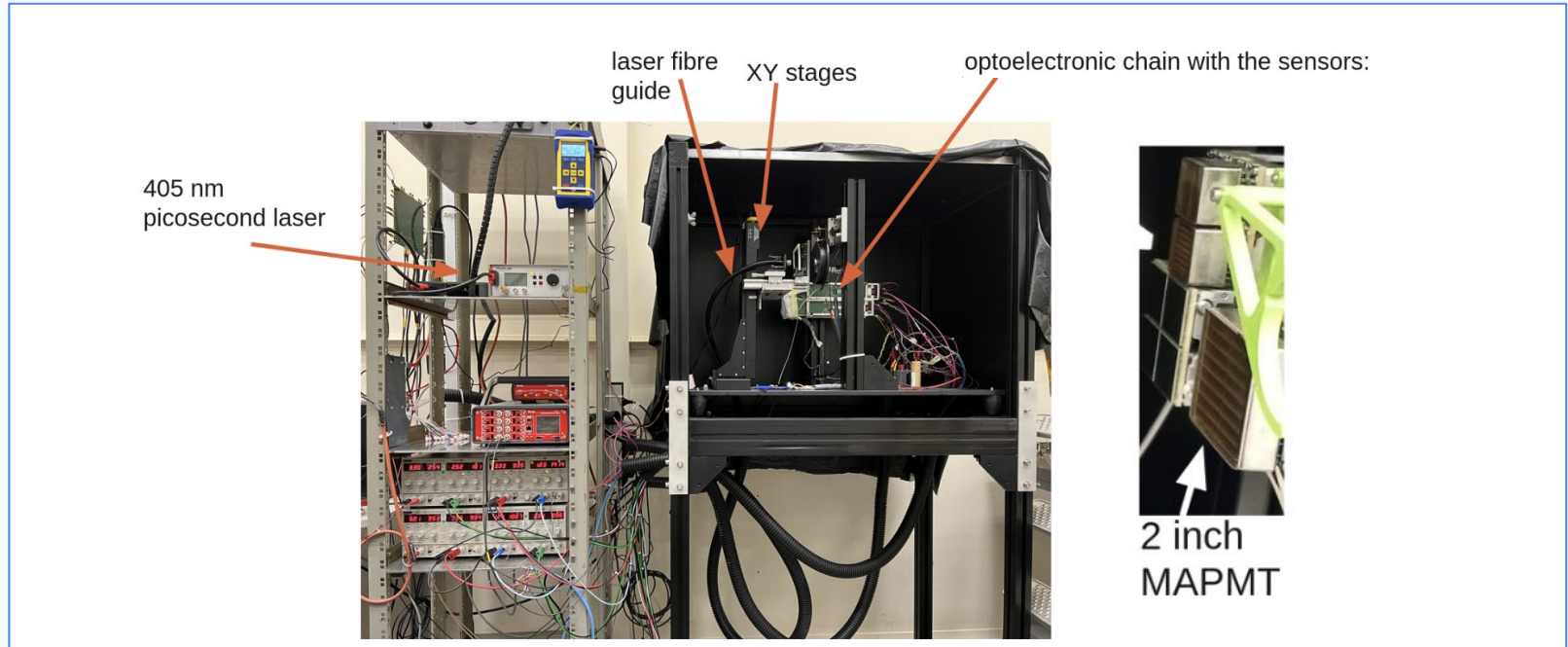
# Methodology

Lab Setup & Thresholds

- Divide half of the full 2-inch MAPMT into 0.5mm x 0.5mm squares
- For every square fire 50,000 single photon pulses
- Measure the amount and the time spread of the recorded photons

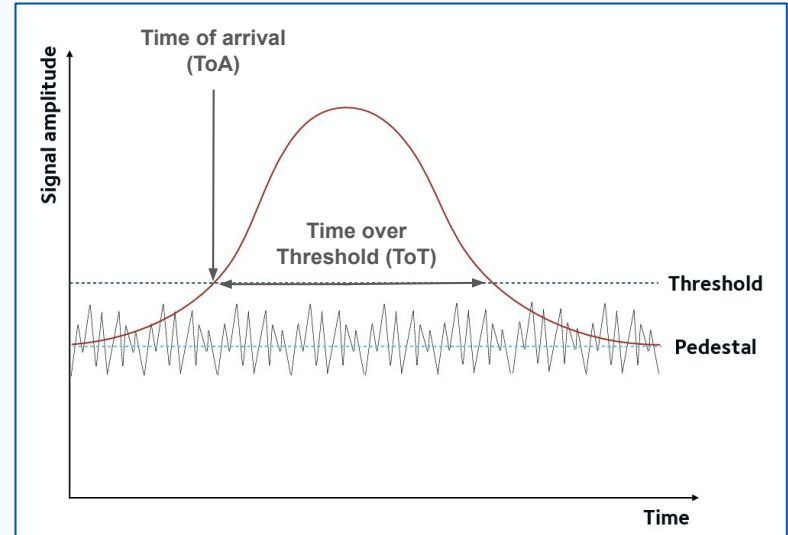


- The experiment happens inside a dark box to minimise background sources of photons
- Inside the dark box: MAPMT, optoelectronic chain and precise laser translation mechanism
- Outside the dark box: laser, attenuator, MuDAQ, fanout board and power supplies



# What Do We Actually Readout?

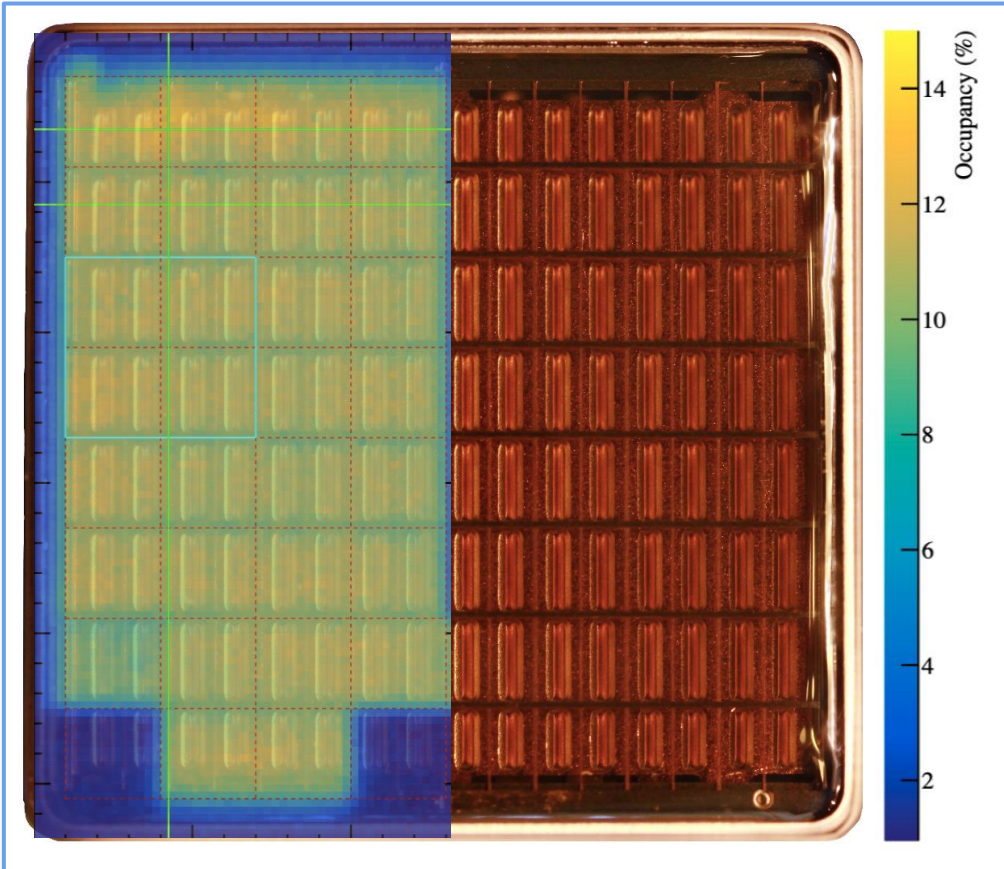
- Once the photoelectron cloud is absorbed it creates a signal pulse
- To avoid recording electrical noise, only signal amplitudes above set thresholds are recorded
- When a signal is recorded, the time at which it crosses the threshold (time of arrival, ToA) and the time it drops back below the threshold are recorded



# Occupancy Results

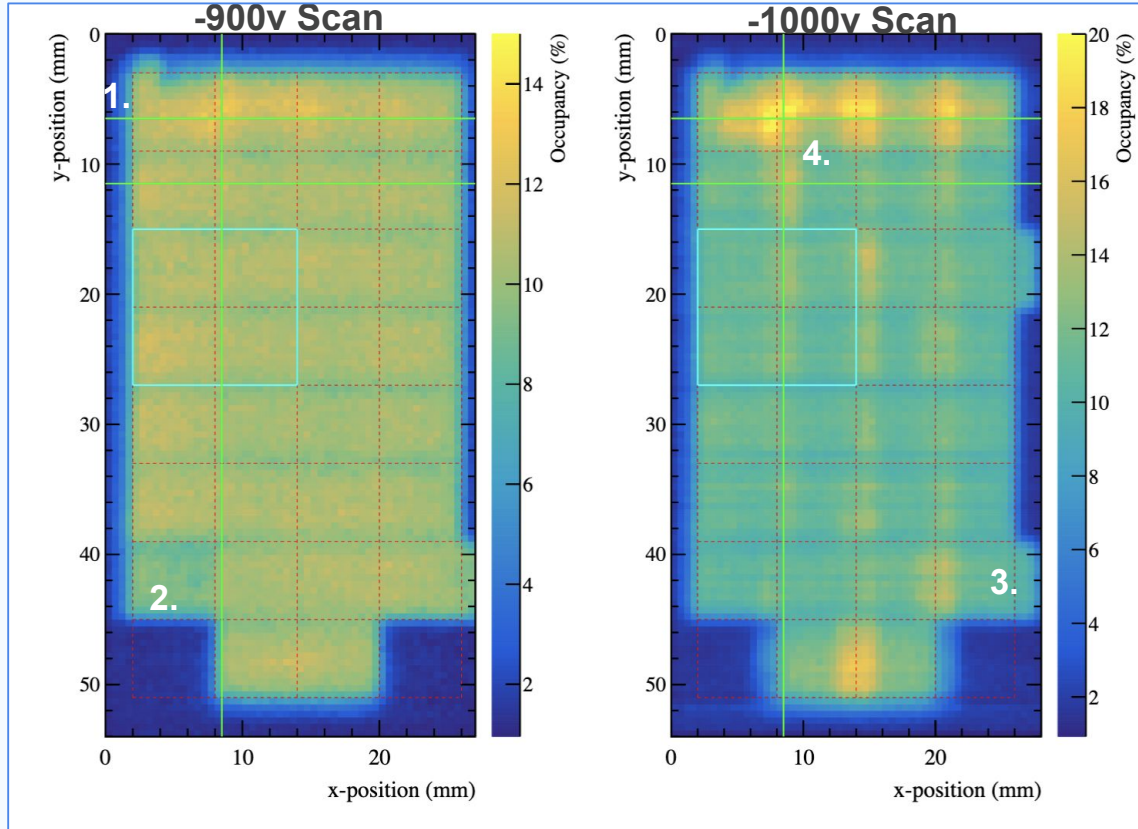
Unexpected Features

# Overlay Occupancy



$$\text{Occupancy} = \frac{\# \text{ Recorded Photons}}{50,000} \times 100$$

- The occupancy map layered onto the sensor
- Only the LHS is powered due to board limitations
- Bottom left & right channels switched off
- Aiming for 10% occupancy to be in the single photon yield



\*Only LHS of MAPMT sensor powered hence 4 x 8 channels

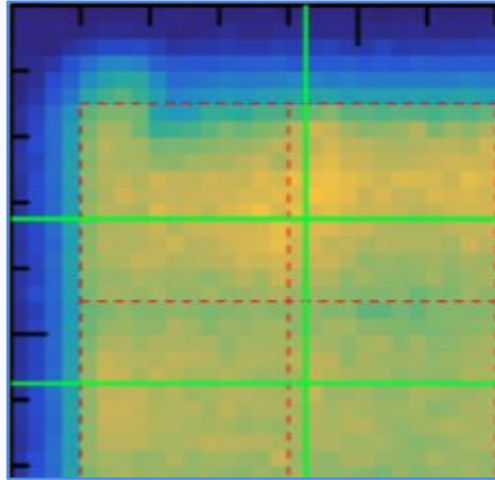
Occupancy scans are taken at -900v and -1000v:

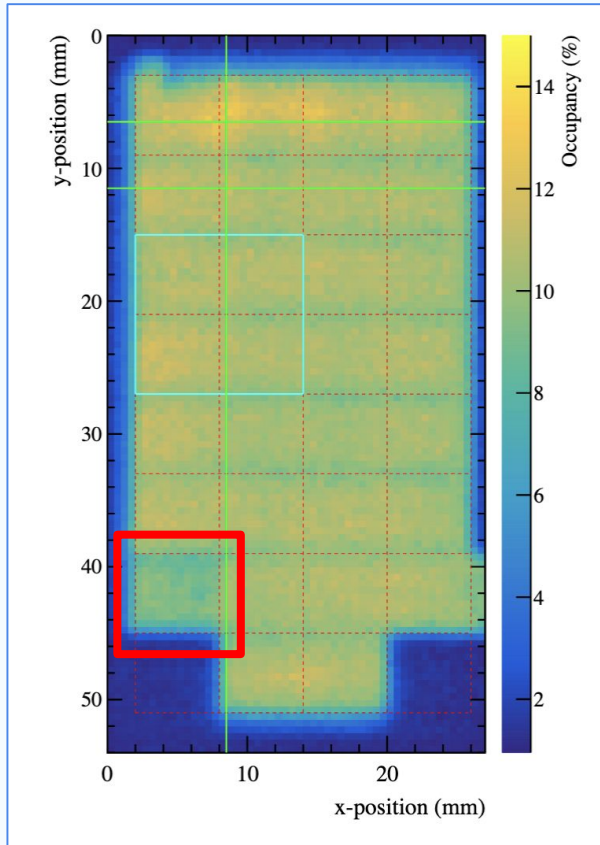
- **Red grid** highlights channel positions
- **Green lines** highlight further finer 1D scans (see later)
- **Blue box** highlights the region used in timing variation imaging (see later)

### Notable Occupancy Features:

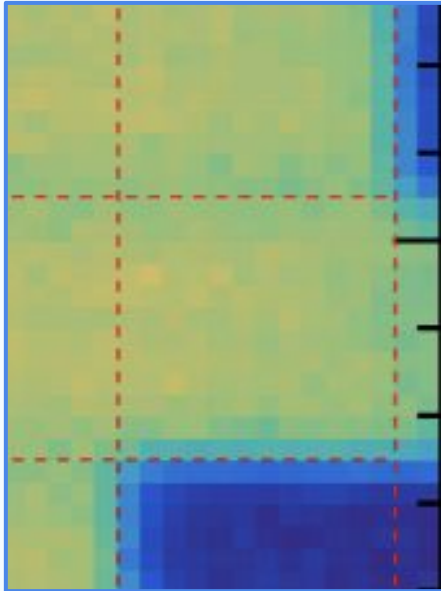
1. Top Left Hook shape
2. Low occupancy Channel
3. Outward bulging extending past the edge of the channels
4. High occupancy bumps at channel edges in the top row (especially at 1000v)

- This “hook” shaped occupancy region has been observed in previous analyses of the MAPMT
- Most likely cause being a result of double focusing wires in combination with the top rows being slightly smaller causing a potential non-uniformity in field





- The low channel occupancy in the bottom left (red) is an understood observation
- A failure to find the optimal threshold for this channel resulted in simply setting this channel's threshold away from noise
  - Non-optimised threshold resulting in slightly lower occupancy

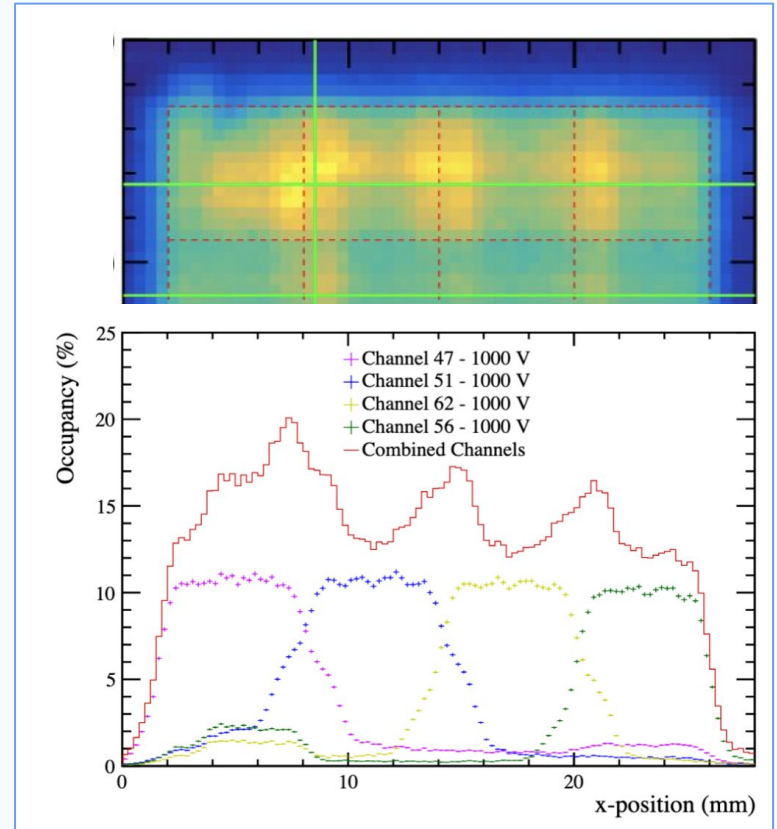
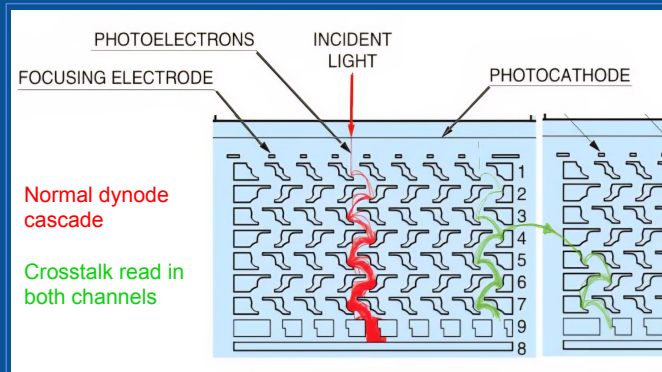


- Bulging past the channel boundary towards the centre of the MAPMT
- Cause currently unknown
  - Several smaller studies have removed the potentiality of physical scan movement effects
- Can be mitigated via ToA cuts (see later)
  - Distinct region of Time of Arrival (ToA) vs Time over Threshold (ToT) plots - existing at higher ToA and higher ToT (backup)

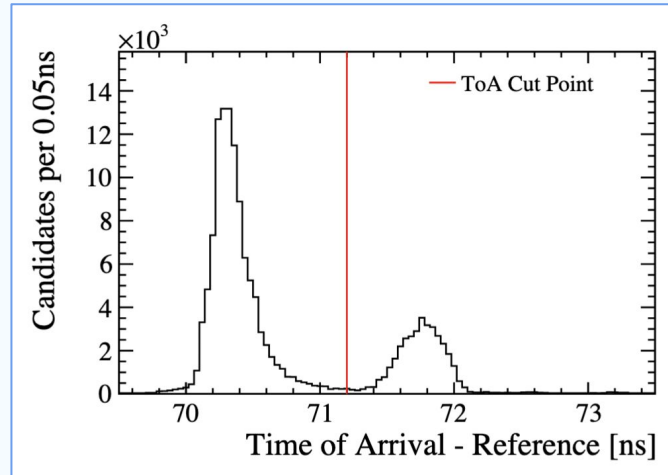
# Features - Crosstalk

- The high level of occupancy in the top row is explained with 'crosstalk'
- Further 1D studies were taken to further analyse these effects (right & backup)

**Crosstalk** - the crossover of electrons in the dynode chains resulting in multiple recorded hits from one photon

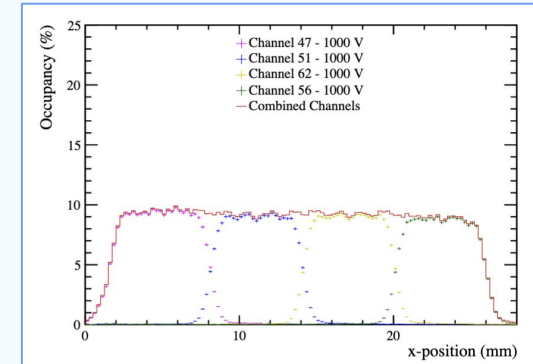


- Looking at the arrival times of the amplitude signals (ToA) for specific channel there is a clear secondary peak resulting from this crosstalk

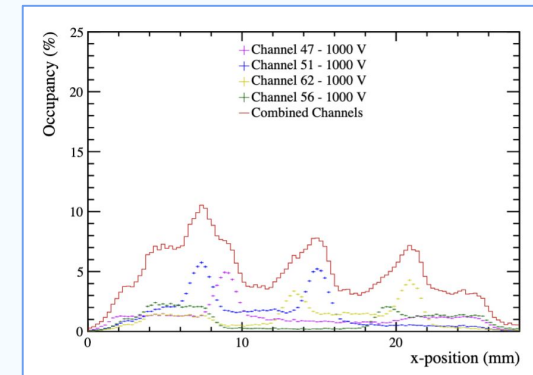


- Isolating the two regions shows full isolation of all crosstalk effects to this second peak

ToA < 71.2ns



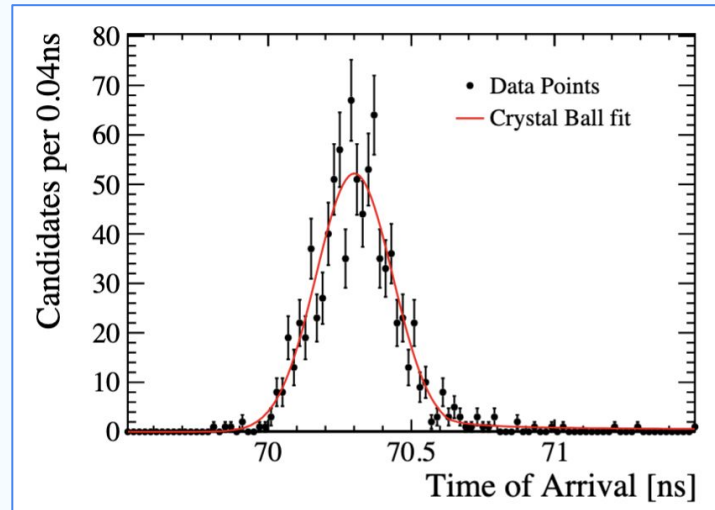
ToA > 71.2ns



# Time Resolution Results

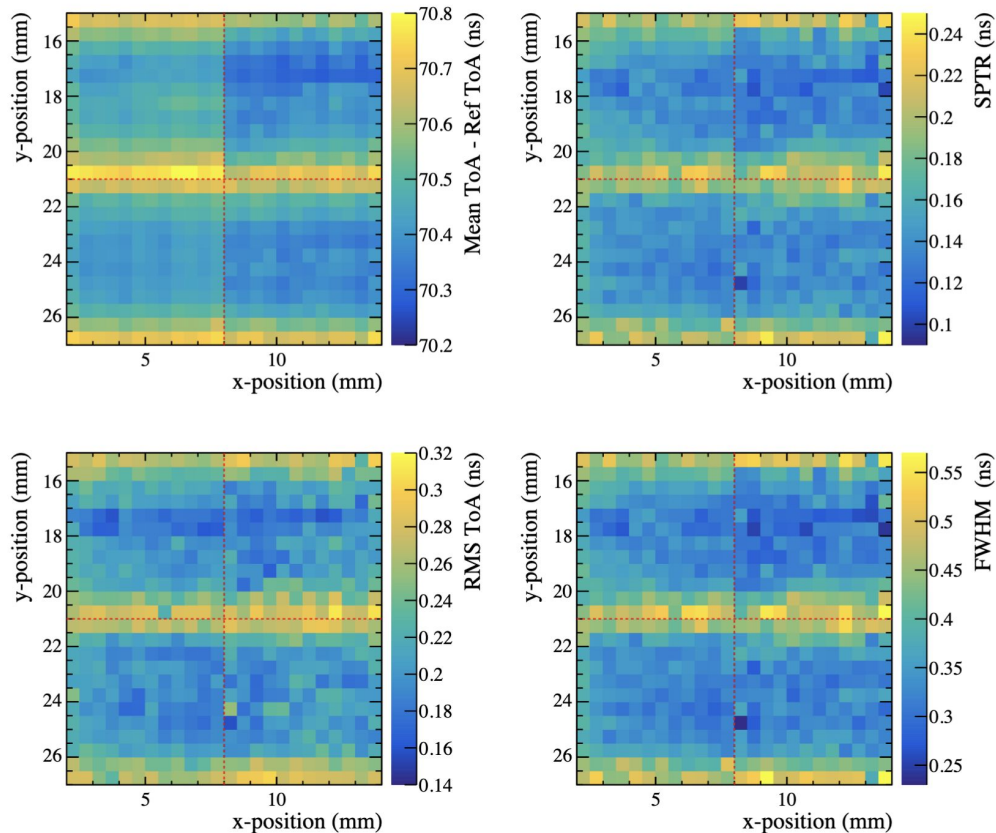
Variation imaging

- To study the time resolution a crystal ball fit is made to the times of arrival (minus the reference time) of all recorded photons in each 0.5mm x 0.5mm bin



- From the CB fit, the mean, FWHM and RMS are extracted
- This procedure is completed for every 0.5mm x 0.5mm square in a four channel region (see before)

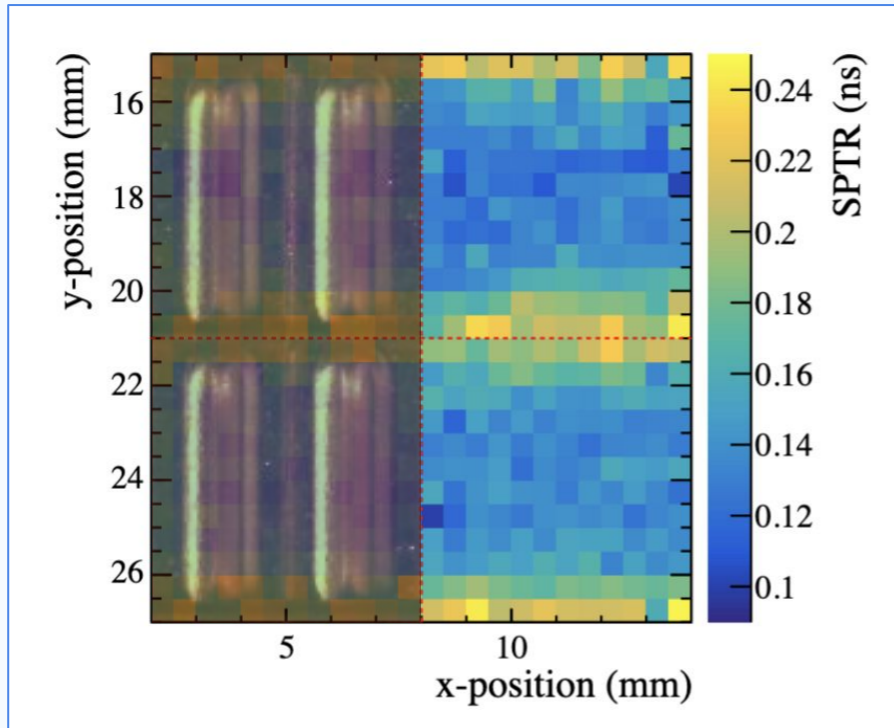
# Time Resolution Variation



- -1000v results
- Uniform in the central region
- Degradation at vertical boundaries
- Rough combination: Institute of Physics

Region	Average FWHM	Average Time Res
Central Illumination	320ps	136ps
Full Illumination	370ps	157ps

- Note: Results currently based on averaging of small 3x3 pixel regions
- Consistent with previous analysis



- Degradation between vertically adjacent channels is presumed to be a result of dynode chain orientation and field focusing
- Photoelectron falling into these regions between channels may need more significant focusing for detection resulting in a longer transit time spread
- This matches the fact that lower occupancies are observed in these same regions highlighting potential difficulties in detection

# Conclusion

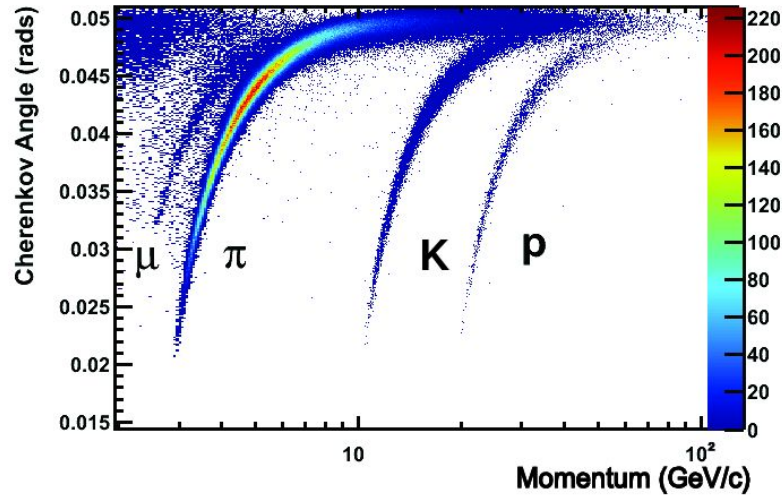
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- Very quick overview of the MAPMT sensor in the LHCb RICH detectors
- A mixture of understood and unknown occupancy features are presented
  - Some of these features can be mitigated via ToA cuts
- Time resolution has significant degradation at vertical boundaries of channels
  
- Paper in the works!

*Thank You For Listening!*

Any Questions?

Back Up



Muons - Use the muon dedicated detectors

Electrons - Light, hit very high beta, large Cherenkov angle, saturated

$$\cos(\theta) = 1 / (n \beta) \quad \text{where } n = \text{Refractive Index} = c/C_M = n(E_{ph})$$

$$\beta = v/c = p/E = p / (p^2 + m^2)^{0.5} = 1 / (1 + (m/p)^2)^{0.5}$$

$\beta$  = velocity of the charged particle in units of speed of light (c) vacuum

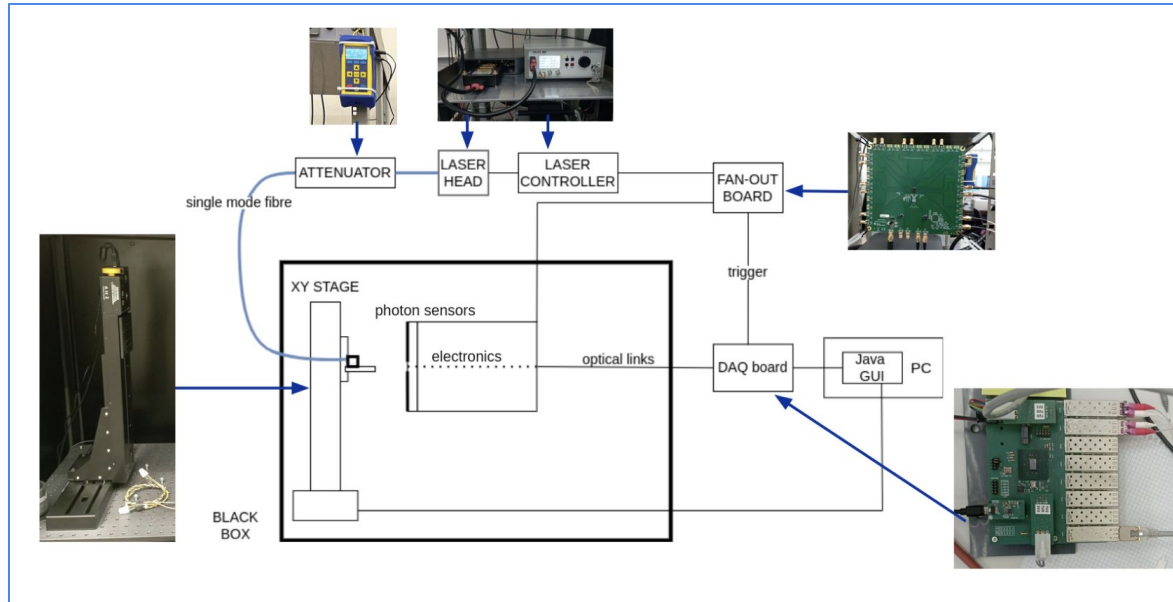
p, E, m = momentum, Energy, mass of the charged particle.

$C_M$  = Speed of light in the Medium (Phase velocity),

$E_{ph}$  = Photon Energy,  $\lambda$  = Photon Wavelength.

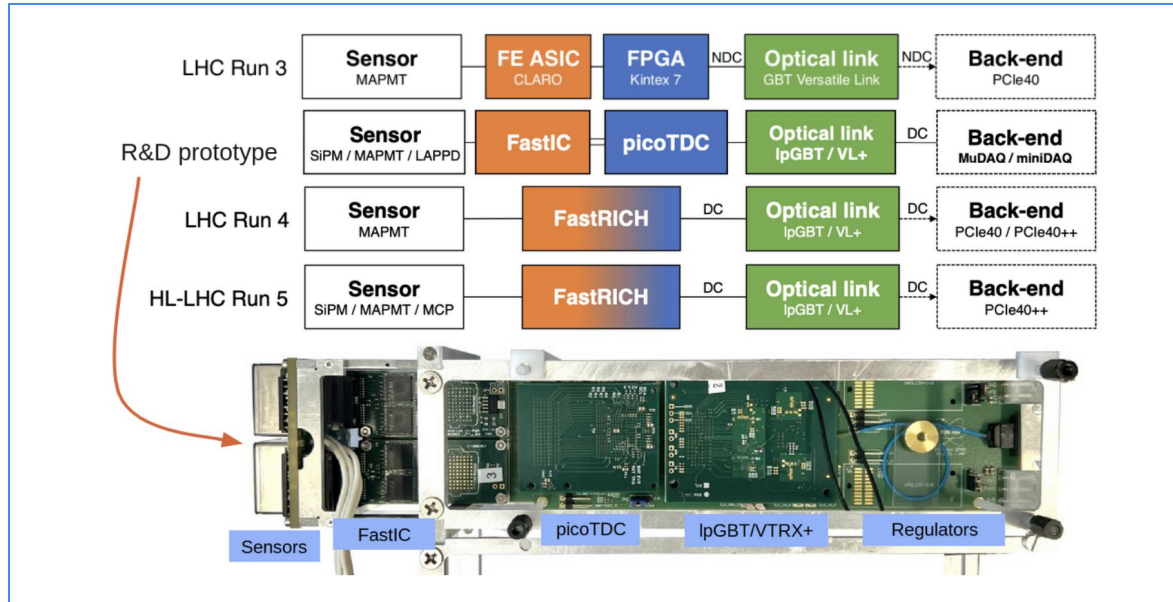
# Diagrammatic Setup

- Triggers controlled by MuDAQ
- Fan out connects directly to the electronics for reference timing
  - Bottom left and right channel readout removed from analysis
- Before scans all electronics given 15 minutes to reach operating temperature



# Optoelectronic Chain

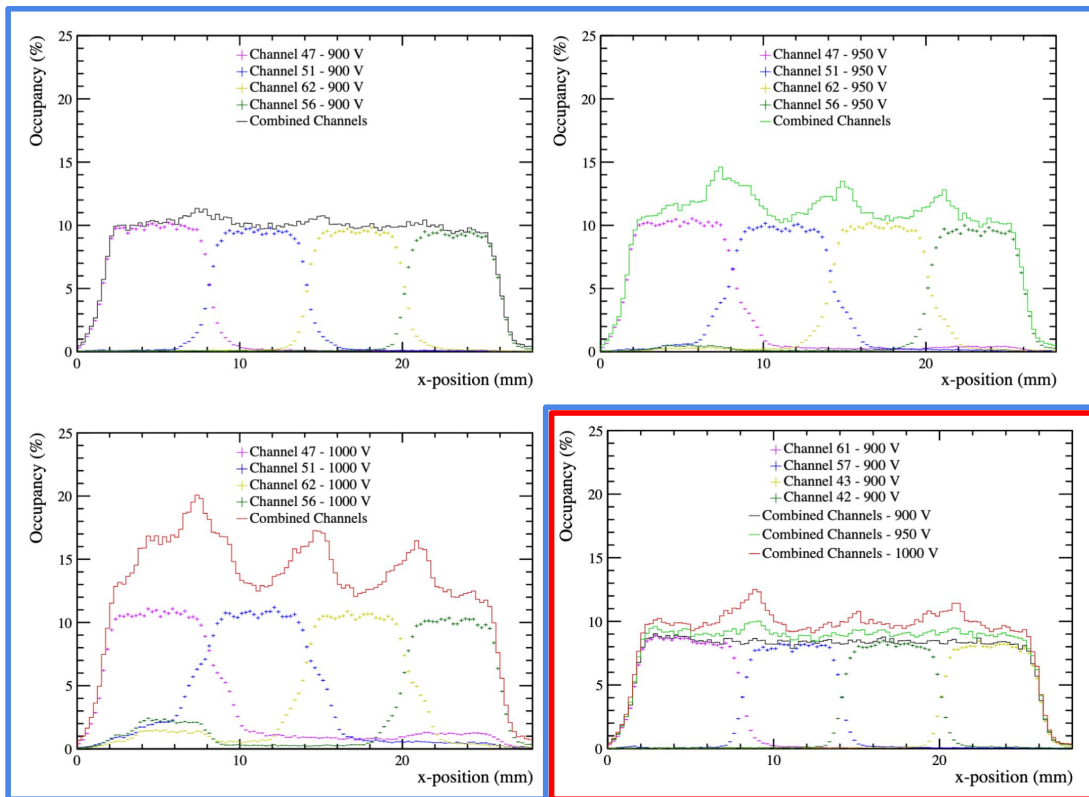
- Experiment completed using the R&D prototype optoelectronic chain
- This optoelectronic chain has been used in several prior testbeams



# Horizontal Scans

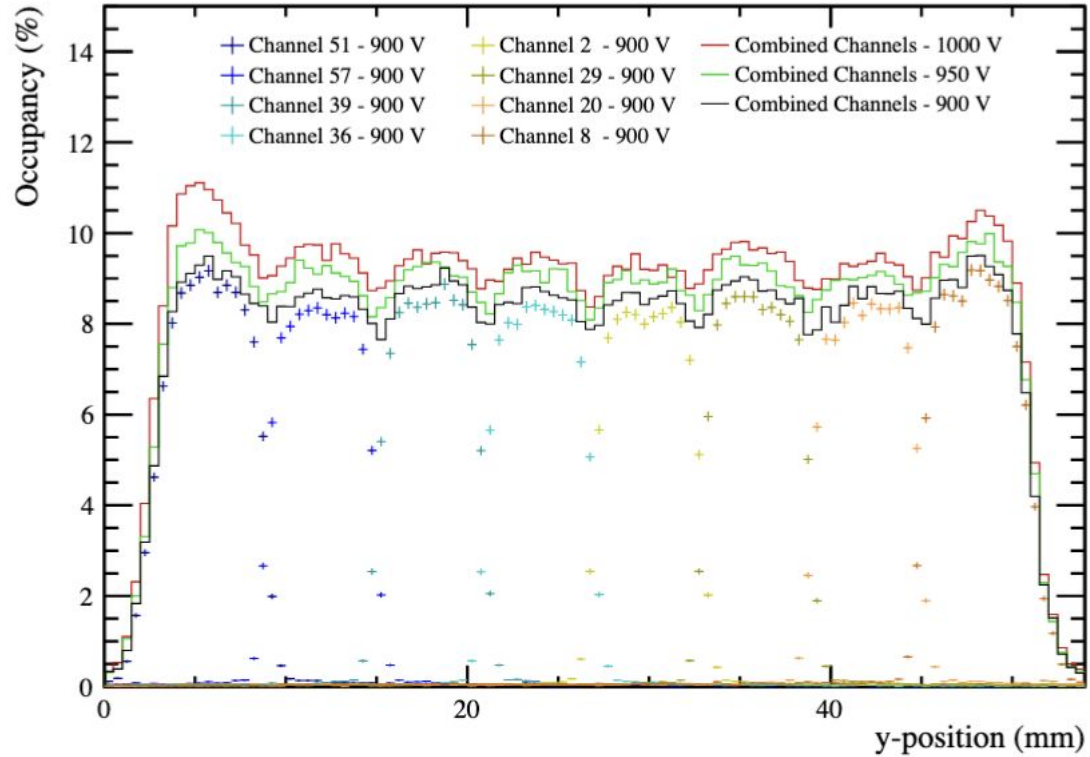
## Occupancy Scans

- Detailed 0.25mm step 1D scans are taken across the previously highlighted regions
  - All four channel readouts are overlaid at each x-position as a result from the 50,000 photon pulses sent at that position
- **Row 1** (separated into three figures) shows clear bias dependent crosstalk
- **Row 2** shows a significantly smaller, but non-zero, bias dependence in crosstalk



# Vertical Scan

BACKUP



# Crosstalk - What is it?

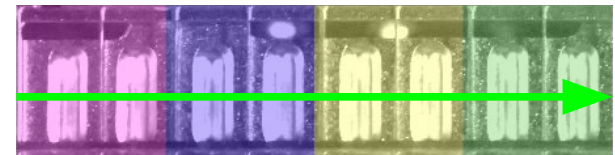
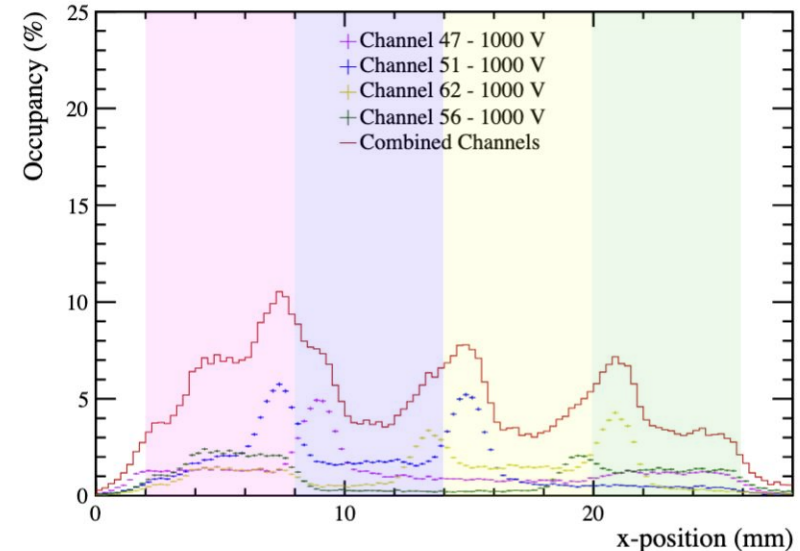
It is concluded that there are in fact **two** distinct effects here:

## Adjacent Channel Crosstalk

- Clear peaking structures recorded by directly adjacent channels
- Due to the electron sharing in the dynode chains

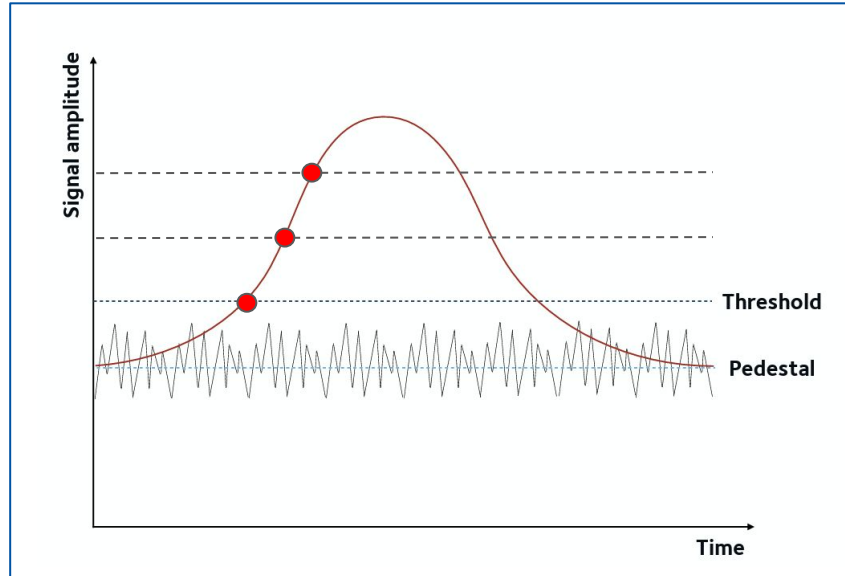
## Long range crosstalk

- Large plateaus are observed for channels at opposite sides of the sensor
  - Example channel 56 (green) positioned on the far right has recorded measurements when the laser position is scanned across channel 47 (pink) (x-positions [2mm, 8mm])
  - Not the same electron sharing crosstalk
- Unknown cause - perhaps an electrical effect?



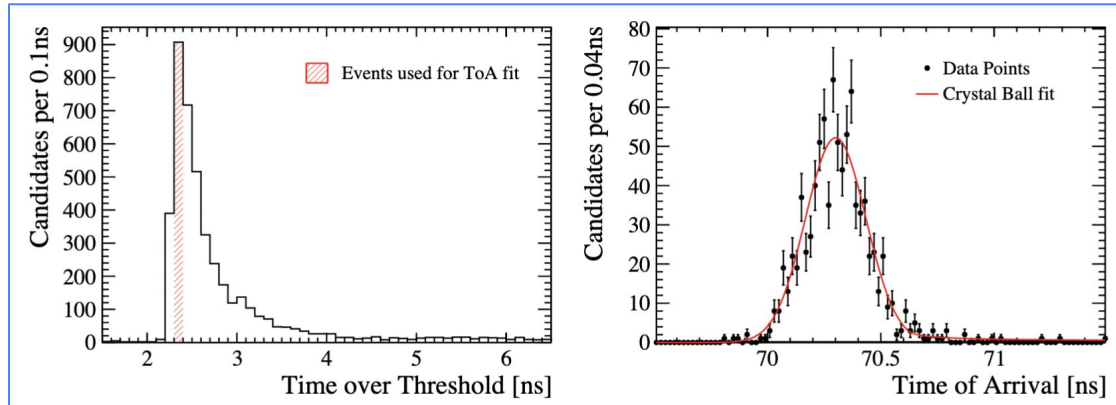
Coloured bars overlaid here to represent the relative positions of the channels

- Time walk is the movement of the ToA due to the threshold set e.g.



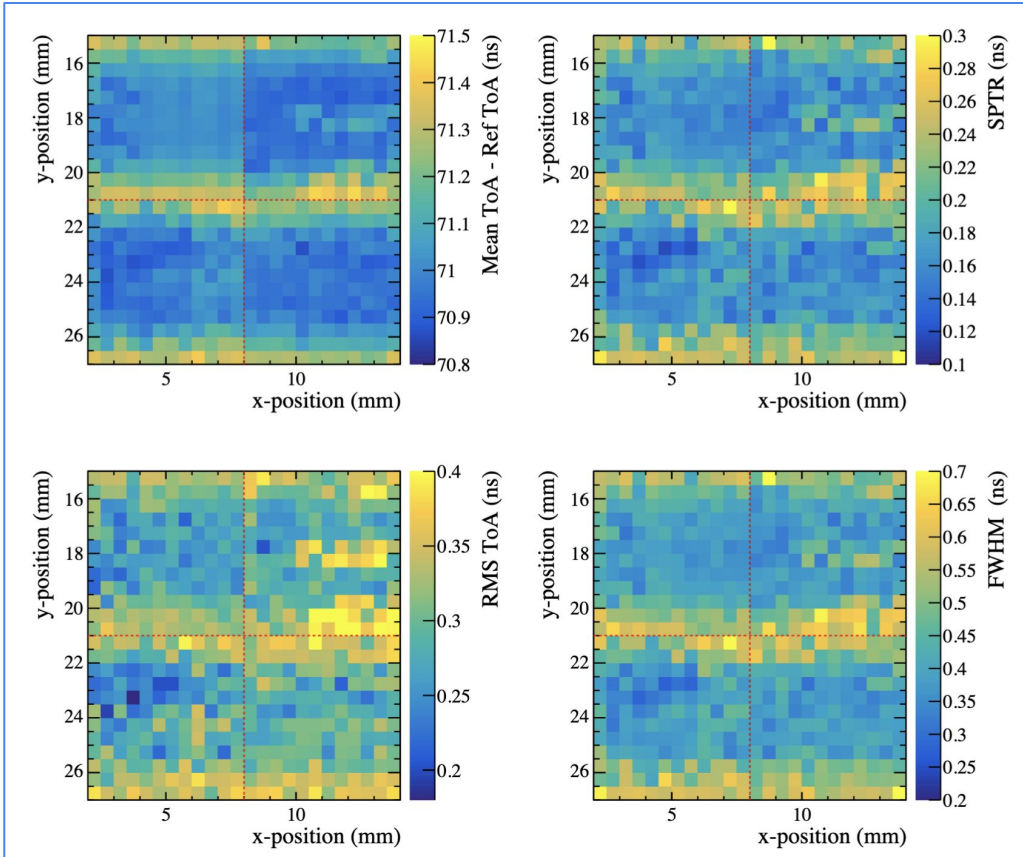
- Fixed by taken the highest occupancy bin of ToT (see next)

- To study the time resolution a crystal ball fit is made to the time of arrival (minus the reference time) in every 0.5mm x 0.5mm bin
- Setting thresholds, however, introduces a 'time walk' effect, to correct for this only events in the most populate time over threshold bin are taken for modelling



- From the CB fit, the mean, FWHM and RMS are extracted
- This procedure is completed for every 0.5mm x 0.5mm square in a four channel region (see before)

# -900v Results



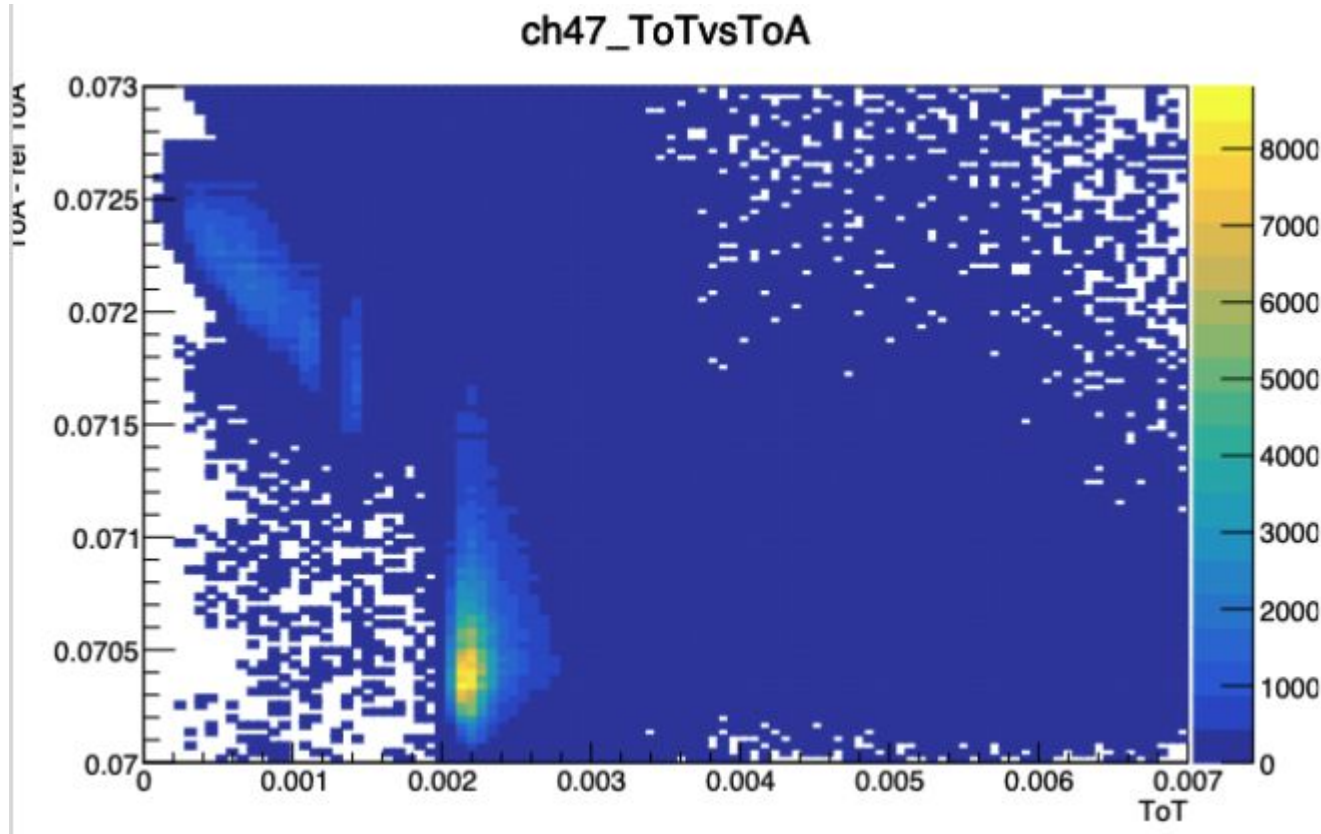
- Clear degradation between vertically adjacent channels
- Currently rough averaging results:

Region	Average FWHM
Central Illumination	390ps
Full Illumination	445ps

- Note: Results currently based on averaging of small 3x3 pixel regions
- Central illumination increased due to fluctuation in top right channel

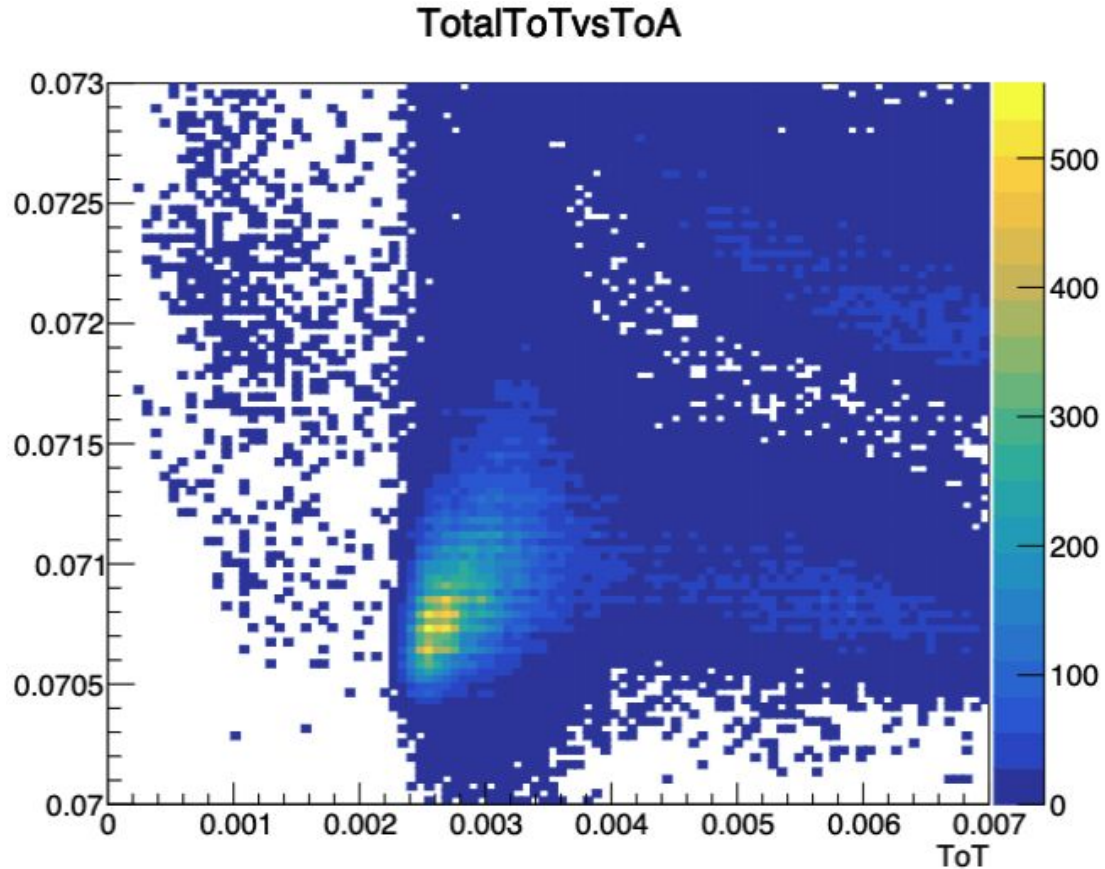
# Crosstalk - ToA vs ToT

BACKUP



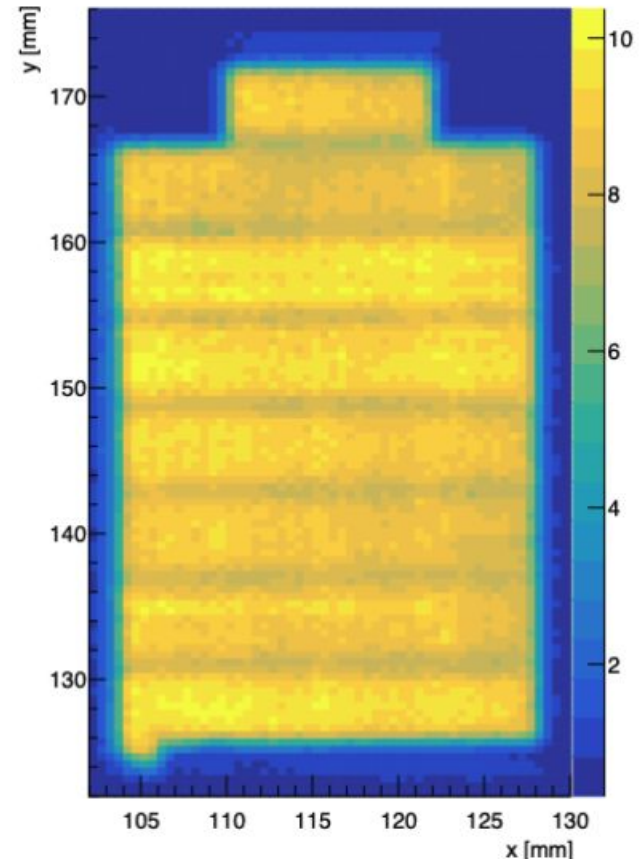
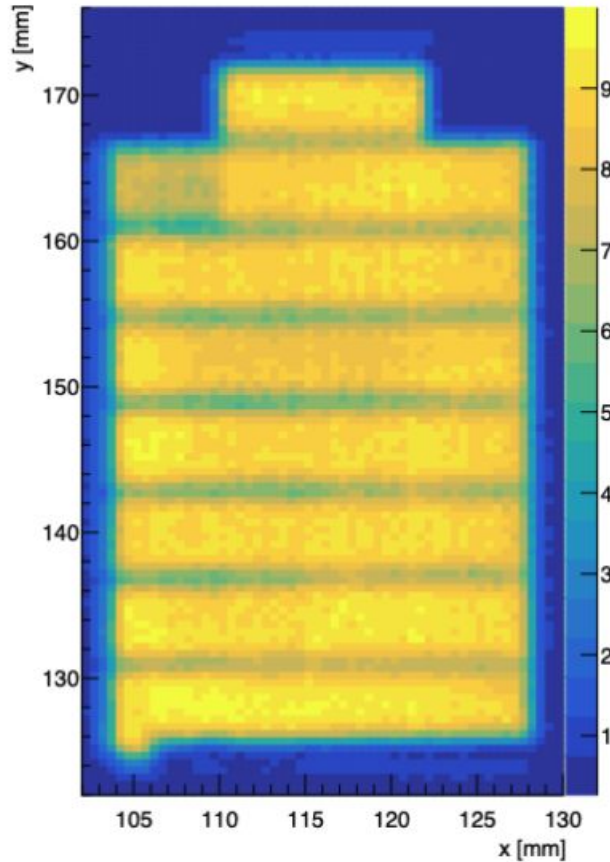
# Bulge - ToA vs ToT

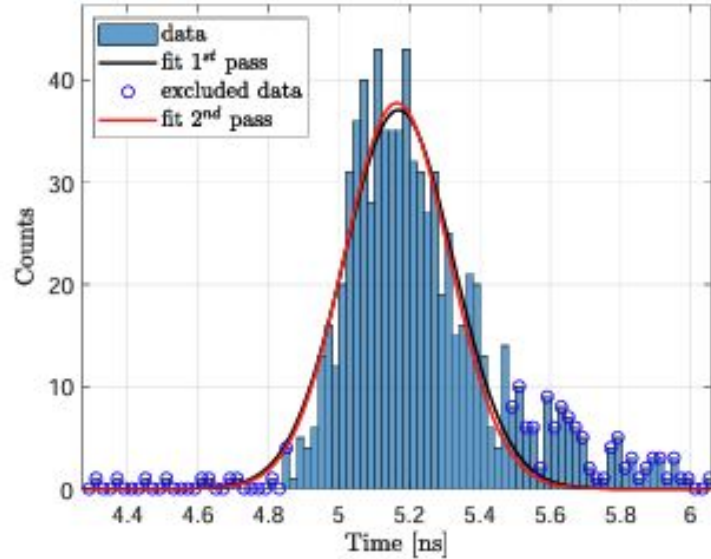
BACKUP



# Occupancy plots with ToA cut

BACKUP





**Figure 3.** Typical distribution of threshold crossing times, fitted with a Gaussian curve in two steps. The blue markers indicate data excluded from the second fit. The difference between the two fitting curves is small, indicating that the right tail gives in any case a negligible contribution.

# Why 10% Occupancy?

BACKUP

Short answer: **because the number of detected photons per channel per event follows a Poisson distribution**, and at 10% occupancy the mean is small enough that **multi-photon hits are rare**.

## 1. Define occupancy properly

For a given pixel/channel:

$$\text{occupancy} = P(N \geq 1)$$

If the number of detected photons  $N$  per event is Poisson with mean  $\mu$ :

$$P(N \geq 1) = 1 - e^{-\mu}$$

So:

$$1 - e^{-\mu} = 0.1$$

Solving:

$$\mu \approx 0.105$$

## 2. What does that imply physically?

Now check probabilities:

- $P(0) = e^{-\mu} \approx 0.90$
- $P(1) = \mu e^{-\mu} \approx 0.095$
- $P(2) = \frac{\mu^2}{2} e^{-\mu} \approx 0.005$

So:

- ~90% of events  $\rightarrow$  **no photon**
- ~9.5%  $\rightarrow$  **exactly one photon**
- ~0.5%  $\rightarrow$  **two photons**

## 3. Why this is called "single photon regime"

Because:

$$P(N \geq 2) \ll P(N = 1)$$

Numerically:

- Multi-photon contamination  $\approx 0.5\%$
- Single-photon signal  $\approx 9.5\%$

So **>95% of your occupied events are single-photon**:

$$\frac{P(1)}{P(N \geq 1)} \approx \frac{0.095}{0.10} \approx 95\%$$