Using Quantum Entangled Photons to Measure the Absolute PDE of a Multi-Pixel SiPM Array

Dr Jamie Williams

J Lapington, S Leach, C Duffy

Aims and Motivation

- Determining the photodetection efficiency is critical

- How to calculate relative PDE?
  - Comparing detector output to another detector

- How to calculate absolute PDE?
  - Calibrated laser diode and photodiode, compare responses
  - Entangled photons…

- Can we use entangled photons to calculate absolute PDE?

- Eventually….could it become the basis for a new lab-based calibration tool?

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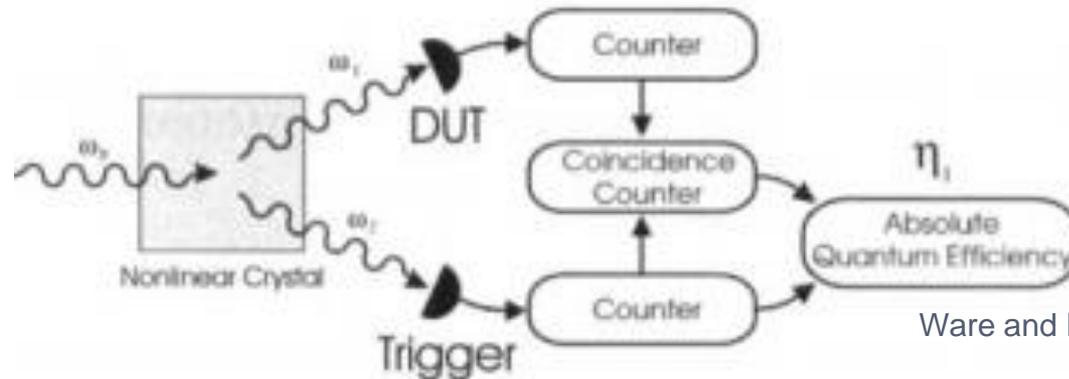
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Outline

- Quantum Entanglement and Absolute PDE

- Using a Multi Pixel Array

- The Target Module for CHEC

- Monte Carlo Simulations

- Experimental Results

- What Next?

- Conclusions

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Quantum Entangled Photons

- Incident photons can be down-converted using non-linear crystals
  - e.g. beta barium borate (BBO), potassium titanyl phosphate (KTP), $LiNbO_3$

- Photon strikes non-linear crystal, generates two lower energy photons through spontaneous parametric downconversion (SPDC)

- Photons are entangled: what happens to one happens to the other

- For BBO, SPDC photon emission rate is 4 in 10^6

- Emission at different angles depending on each photon energy

- Different types of entanglement, whether or not the emitted photons are ordinarily or extraordinarily polarised

Type I

Entangled Photons

Type II

Entangled Photons

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# Quantum Entanglement and Absolute PDE
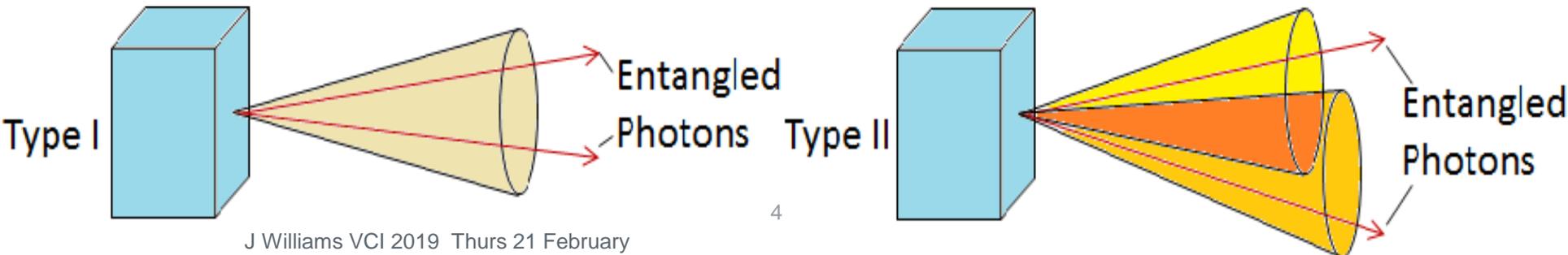
Ware and Migdall, 2004

- Proposed by Ware + Migdall (2004)

- Entangled photons, N, strikes both detectors

- Both detectors should detect the photons
  → PDE limits the response

- Ratio of the number of coincident events to trigger-only events gives the PDE

- Need individual outputs from two separate detectors

- This can be achieved with a single, multi-pixel array

$$N_{Detector} = \eta_{Detector} N$$

$$N_{Coinc} = \eta_{DUT} \eta_{Trigger} N$$

$$\eta_{DUT} = \frac{N_{Coinc}}{N_{Trigger}}$$

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Using a Multi-Pixel Array

DETECTOR ARRAY →

DUT

D

TRIGGER

C
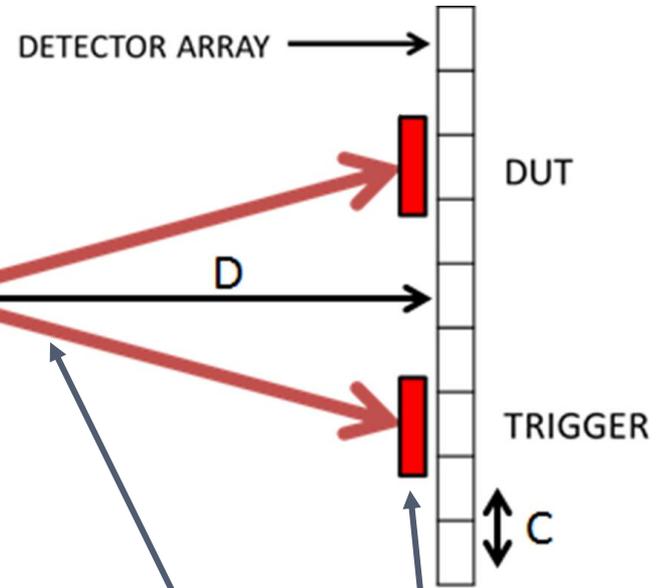
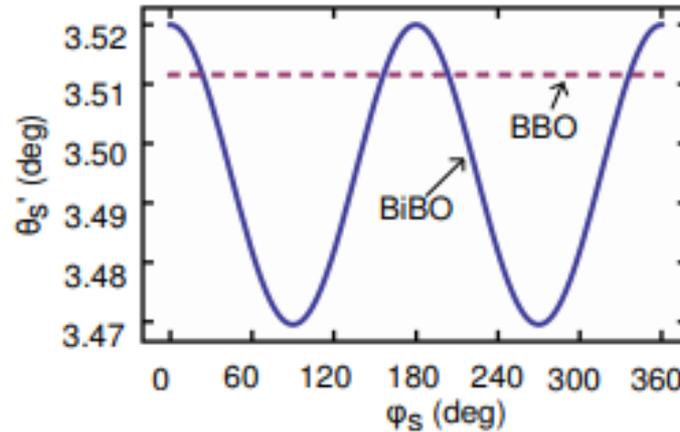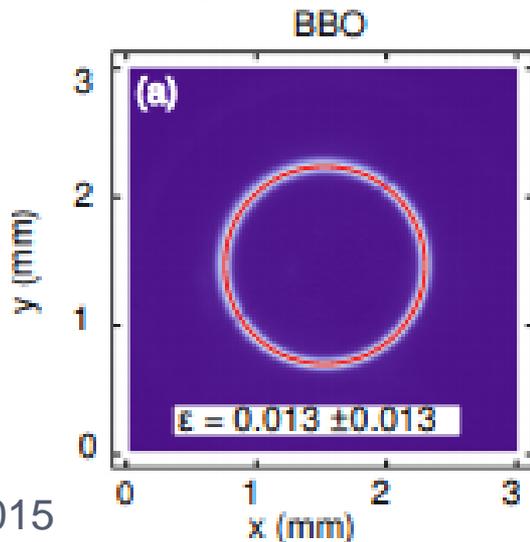| UV photon ~ 405nm from pulsed laser source	Non-linear crystal (BBO) • Downconverts photon to two photons with energy that total initial photo • Crystal operates in given frequency range	Photon pair generated at angle relative to photon energies • Symmetric position on array about a central pixel gives photon energy	Band pass filter → photon striking photon is the required energy

- Count the number of events observed on both pixels simultaneously

- Count the number of events observed only on the trigger pixel

- Ratio gives the PDE → $\eta_{DUT} = \dfrac{N_{Coinc}}{N_{Trigger}}$

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Quantum Entangled Photons

- Photon strikes crystal

- Daughter photons emitted at angles θ,φ relative to incident photon

- Photon momentum related to the angle and frequency dependent refractive index, etc

- Relationship between θ and φ found via conservation of momentum
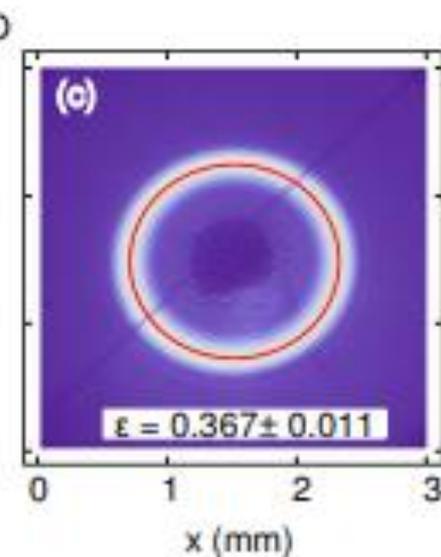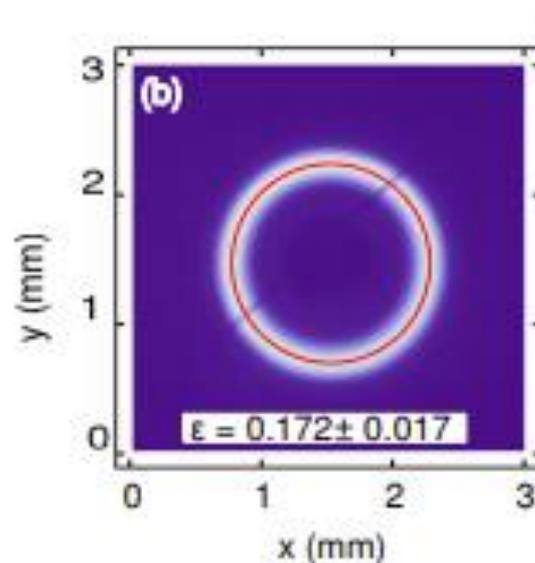

Guilbert 2015

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Quantum Entangled Photons

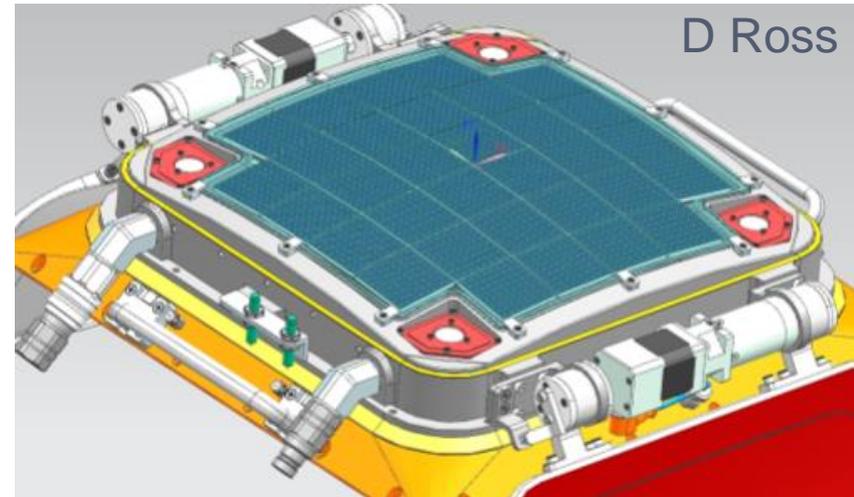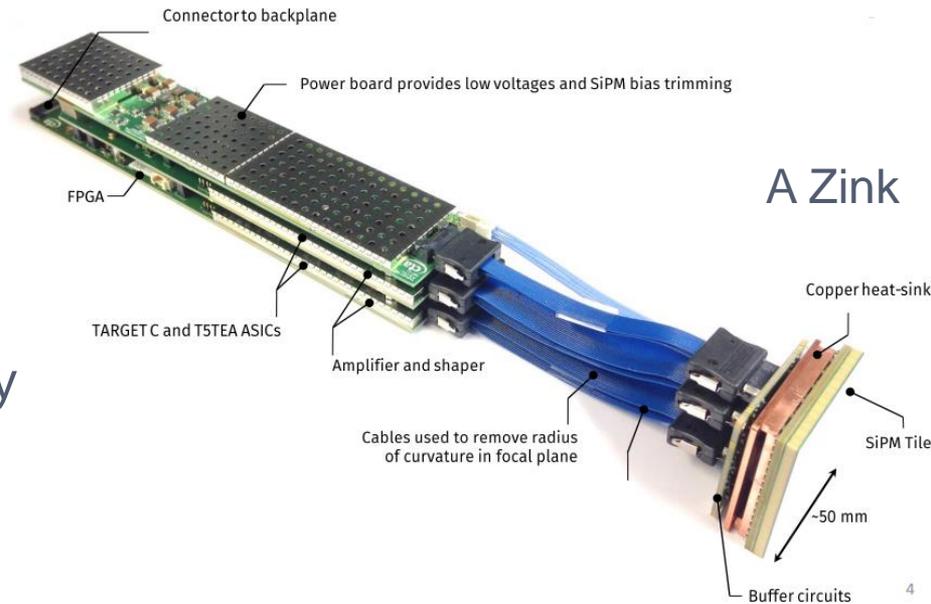- BBO generates a ring
- BiBO generates an oval

Guilbert 2015

- BBO easier to identify where a downconverted photon should be

Target Module

- Developed for the CHEC camera for the Cherenkov Telescope Array

- Silicon Photomultiplier detectors
  - Hamamatsu S12642 SiPM array
  - 64 6mm x 6mm pixels
  - Each pixel is four 3mm x 3mm pixels coupled together

- Output from SiPM arrays goes to 64 channel digitiser based on TARGET ASIC, designed for fast timing and coincidence measurements
  - GHz sampling

- For more information about TARGET module AIV and testing, please speak to J Lapington or C Duffy

A Zink

Connector to backplane
Power board provides low voltages and SiPM bias trimming
FPGA
TARGET C and T5TEA ASICs
Amplifier and shaper
Cables used to remove radius of curvature in focal plane
Copper heat-sink
SiPM Tile
~50 mm
Buffer circuits

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Monte Carlo Simulation

- Tested with a Monte Carlo simulation

- Pick a random angle θ

- Work out corresponding energy of downconverted photons

- Does it pass the band pass filter of E/2 ± σ?
  - E is energy of initial photon, σ is the width of the band pass filter

- Generates ring on multi-pixel array

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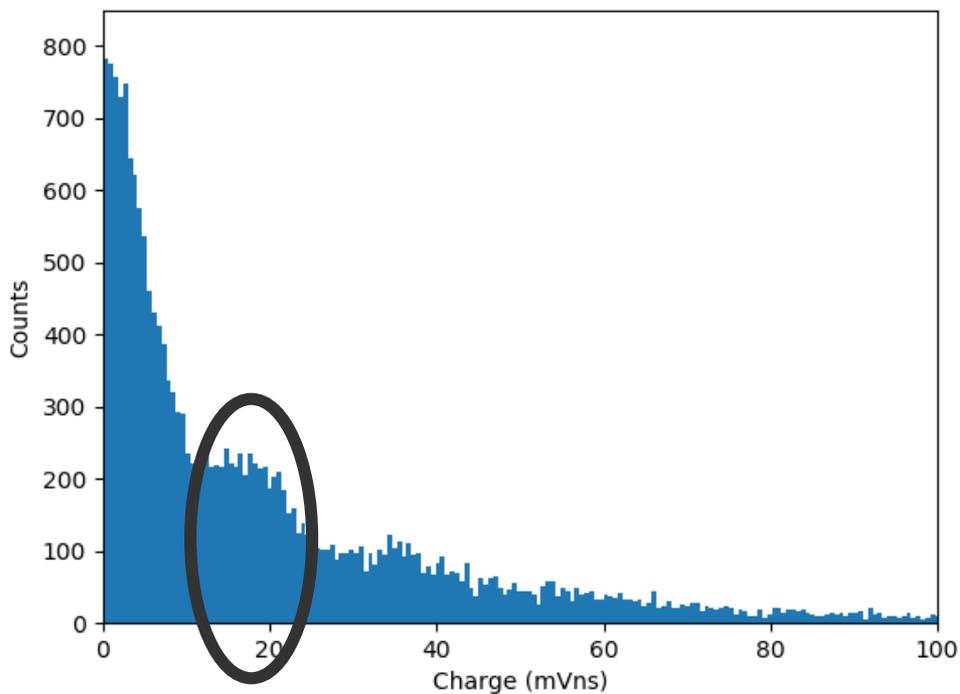
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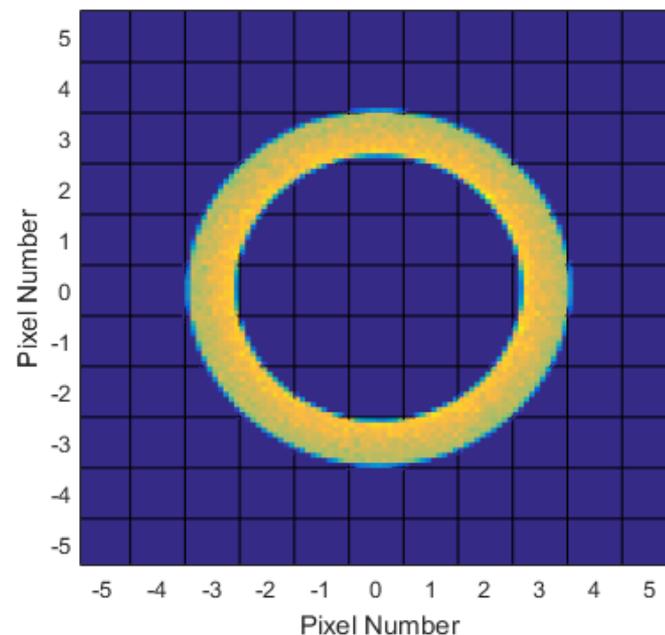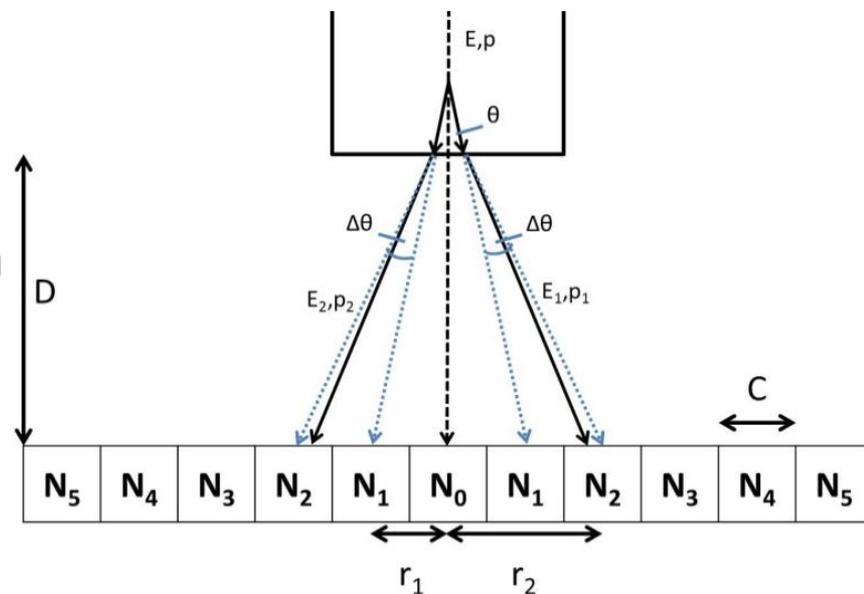
Monte Carlo Simulation

- How does distance and band pass filter width affect which pixel the photon strikes?

- Increase distance, test pixels further from central pixel

- Reduced number of counts with band pass filter
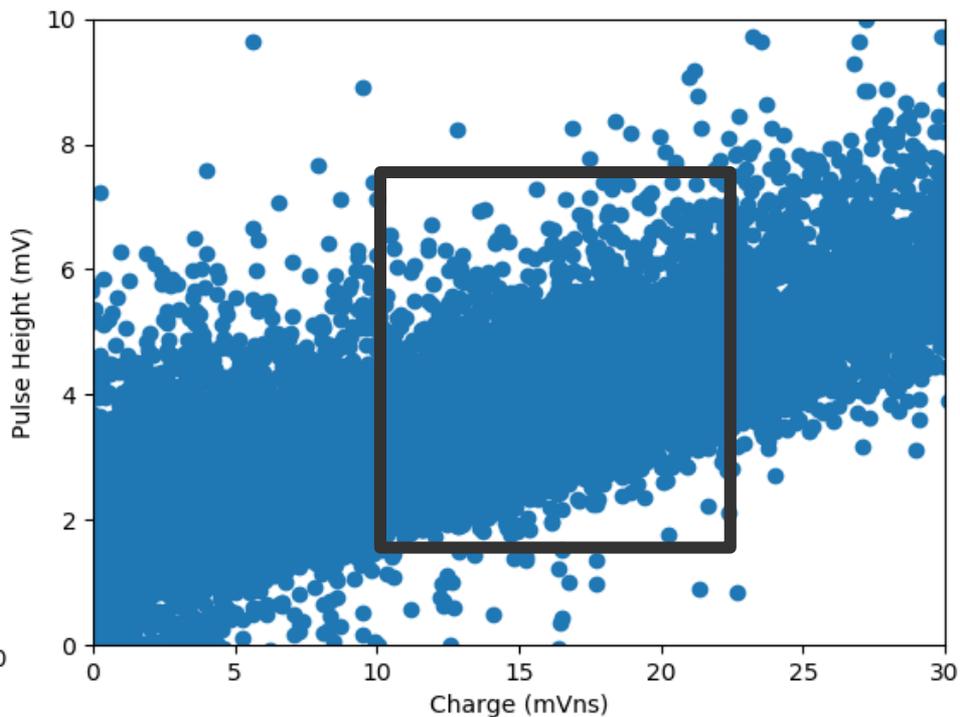
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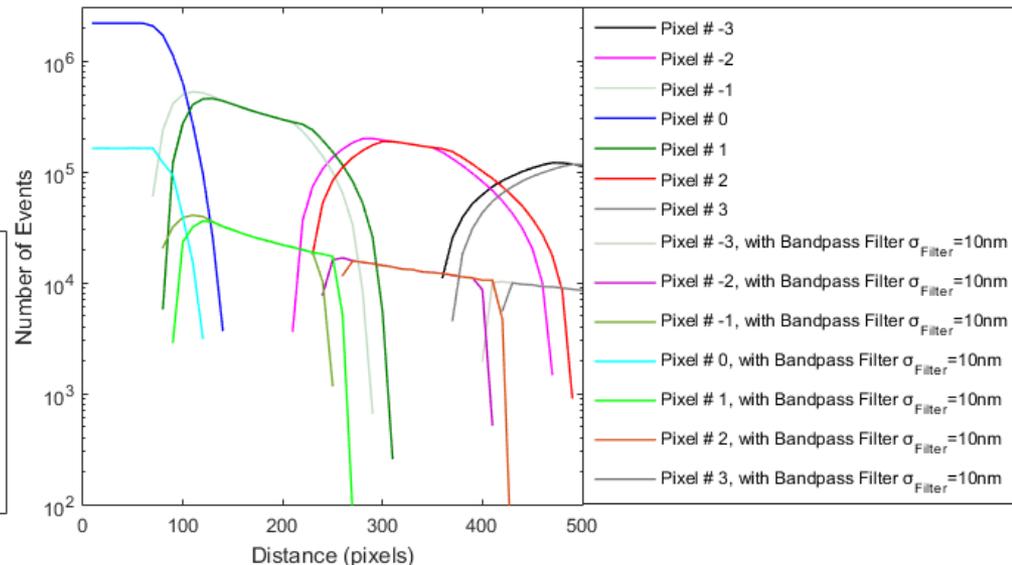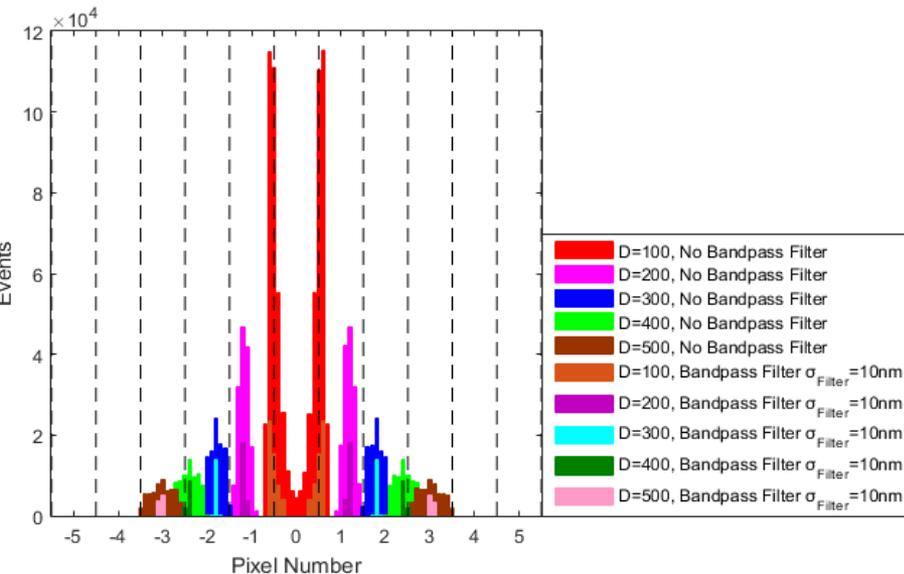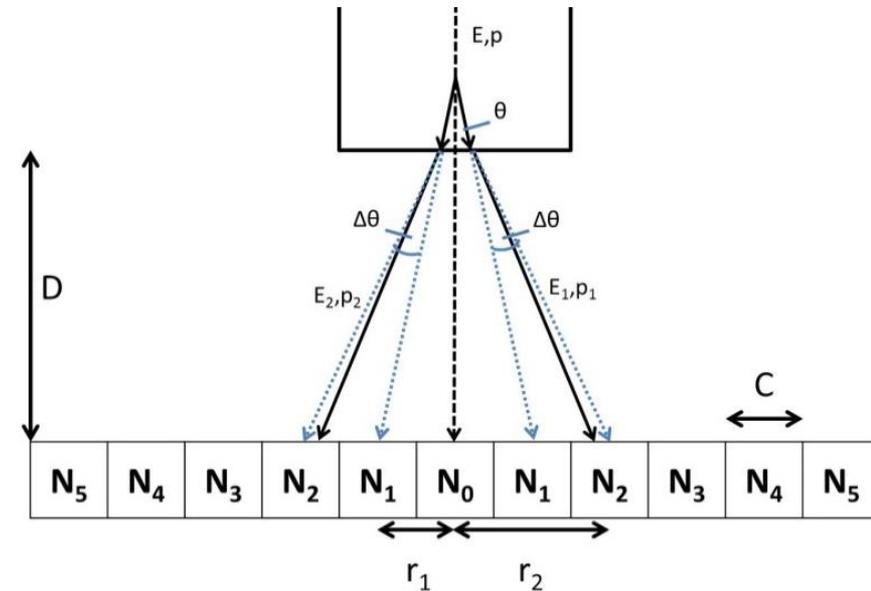
Experimental Requirements

- Single PE resolution

- Pulse Height – Charge calibration

- Choose pulse heights of 2-7mV only

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Experimental Requirements
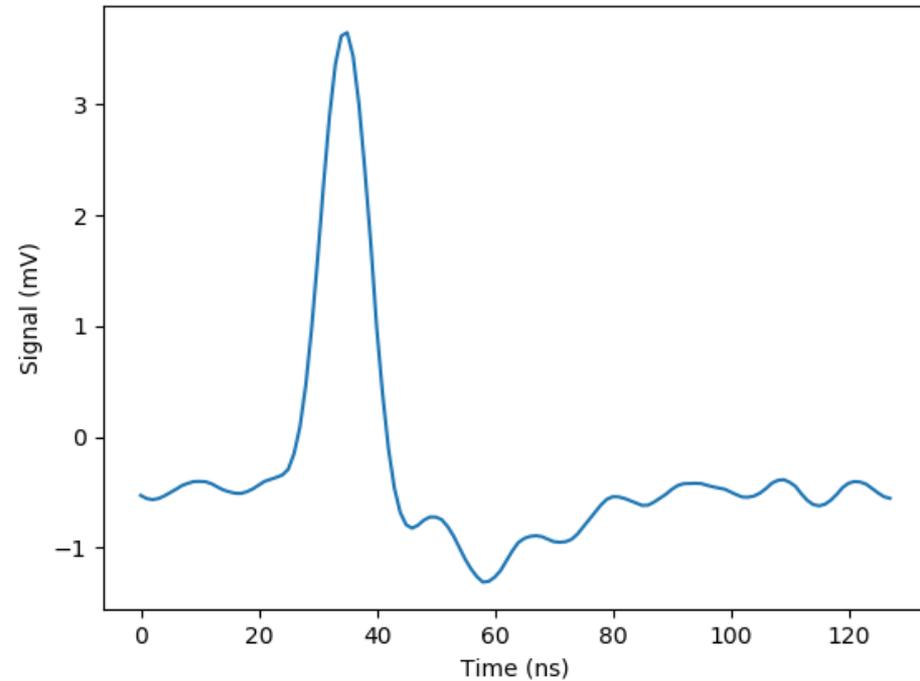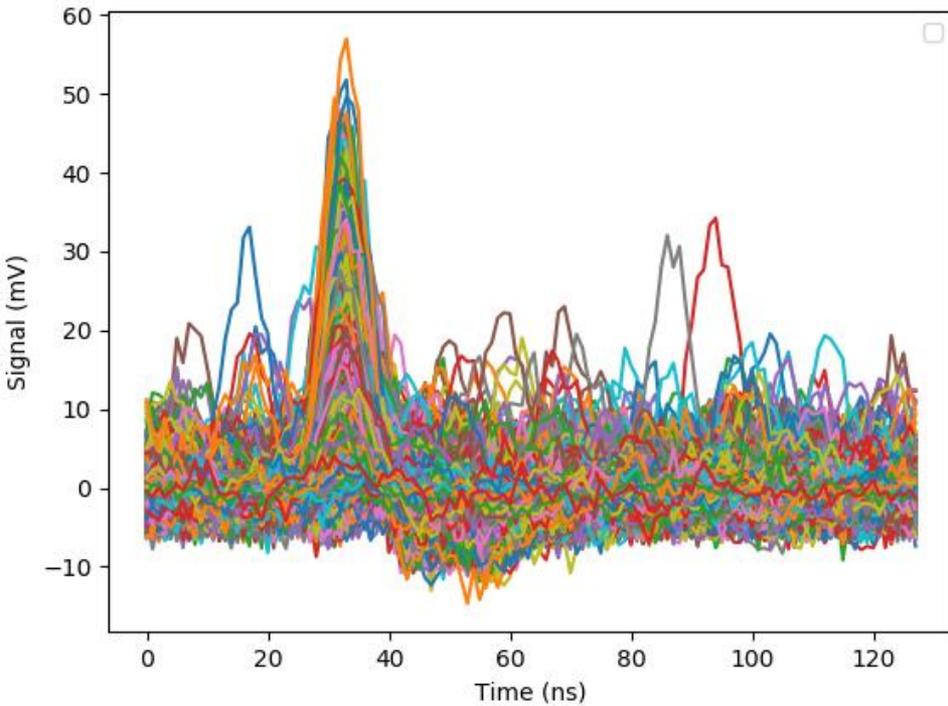
- Window the peak between ~30-40ns

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Experimental Setup
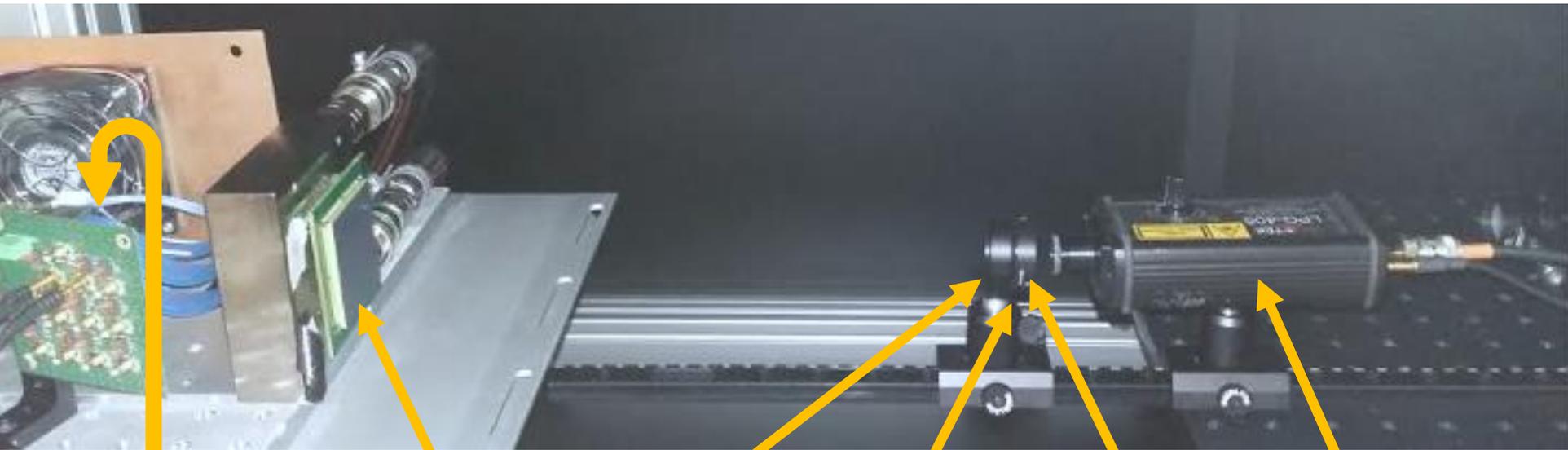
TARGET module

SiPM array in cooled holder. Operating at 14.5degrees C
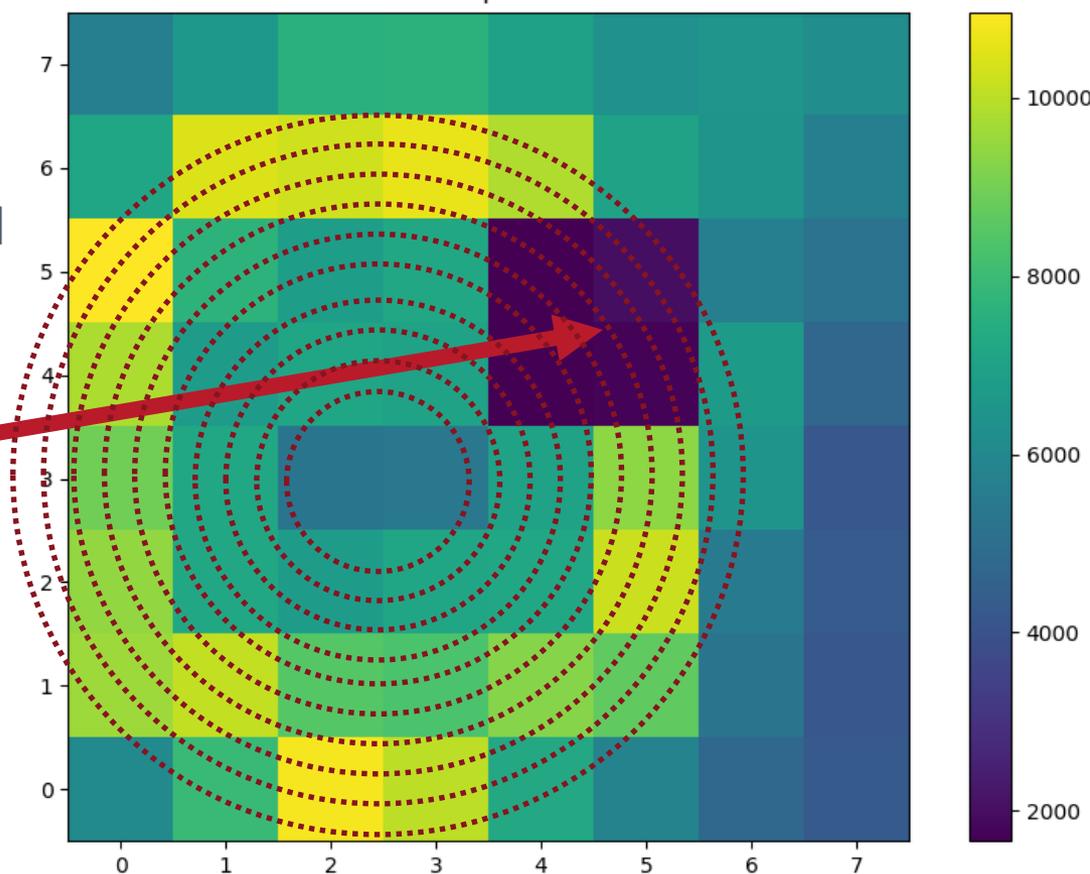
810nm bandpass filter

5mm diameter SPDC BBO crystal

Optical Iris

Photek LPG-1 405nm Pulsed Laser

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Experimental Results

- Run of ~30000 events

- Count the number of events with a peak between 30 and 40ns and 2-8mV

- Dead pixel due to damaged silicon
  - output turned off

- Central pixel: residual blue photons that pass through bandpass filter

- Visible ring

- CHALLENGE: the BBO crystal we purchased had an opening angle of 3°. It also has an SPDC cut at 10°, which is what our results suggest

Run 62. Number of events with peak between 30-40ns of 2-8mV

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Estimating the Absolute PDE

- Calculate coincident events in opposite pixels

- Treat one as DUT, one as trigger

- Count number events coincident in DUT and trigger

Run 62. Number of events with peak between 30-40ns greater than 2mV

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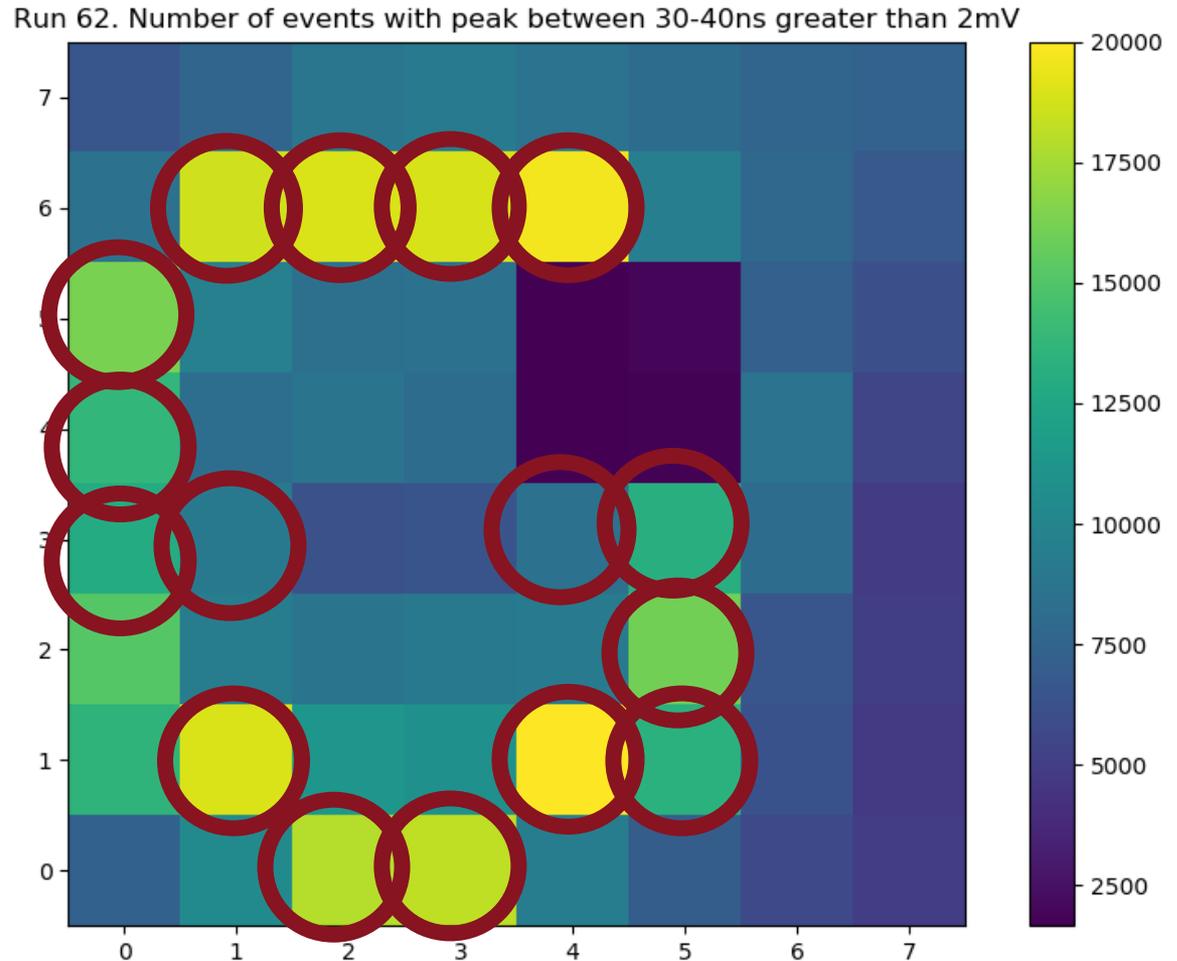
Experimental Results
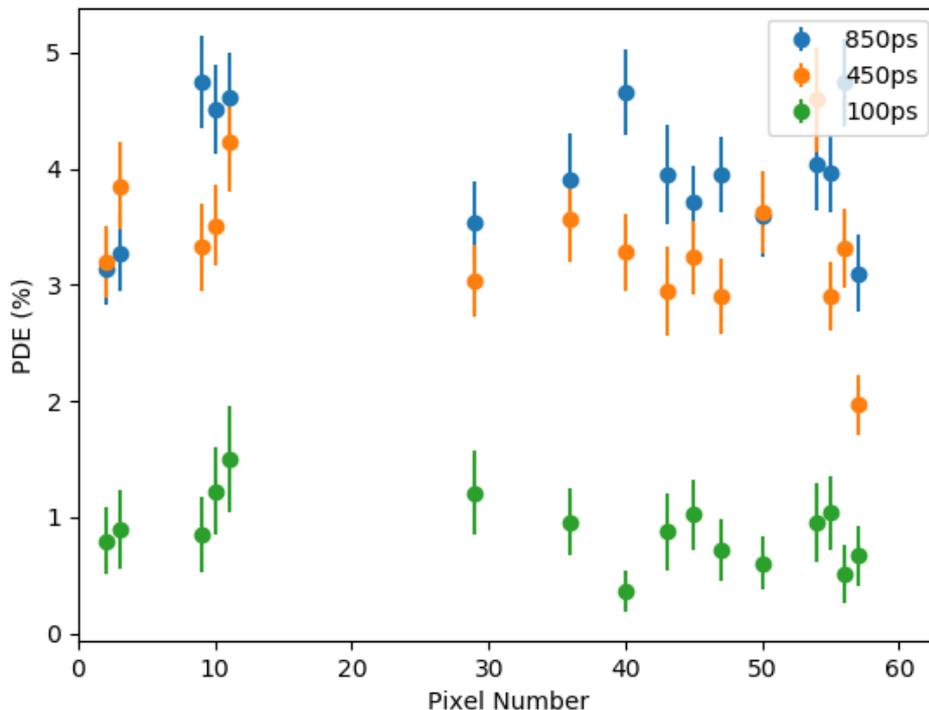
- Count number of instances where events are coincident

- Take the ratio of number of coincident events to DUT-only events

- Tested for different pulse width
    - ~1% for 100ps pw
    - ~3% for 450ps pw
    - ~4% for 850ps pw

- CHALLENGE: What causes the apparently difference in absolute PDE regarding the pulse width?

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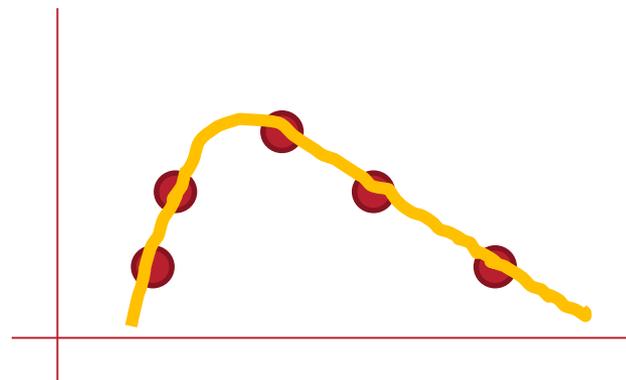
Experimental Results

- *Why do we see PDE variation with laser pulse width?*

1ns	1ns	1ns	1ns	1ns	1ns	1ns	1ns

- Each bin is a nanosecond wide
  - Currently: Looking for synchronicity within 1ns
  - Need to: interpolate timing → improved synchronicity

- Lack of timing synchronisation between TARGET electronics and pulsed laser trigger
  - Need to : determine and correct for skew
    → removes effect of electronics → incident time on detector

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Experimental Results

- Skew correction for peak:
  - Average waveform for each pixel over 10000 events, relative to average waveform from entire array
    - -2.5 to +1ns skew, subtracted from timing

- Quintic interpolation of waveform peak
  - Peak found of initial waveform
  - Signal maximum and ±2ns around nanosecond (5 bins) used
  - Interpolate 500 points within this sector
  - Find the new peak

- Window of peak ±200ps used

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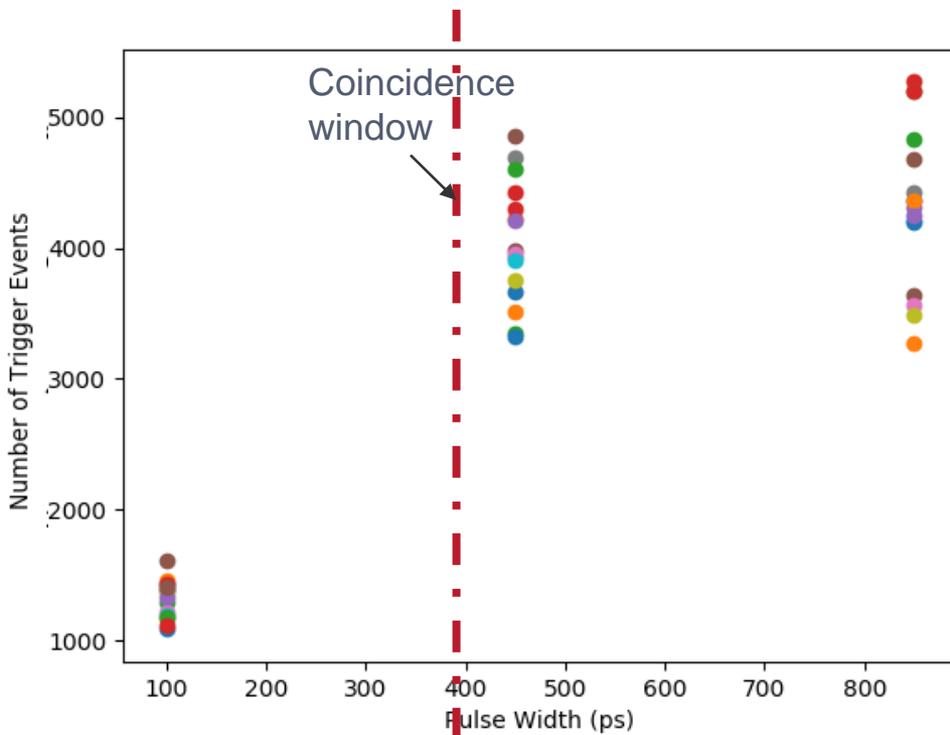# Experimental Results

- With updated data analysis…

- Absolute PDE drops ~ factor 2
  - Removing false positive coincident events

- 450ps and 850ps measurements in better agreement
  - Removes discrepancy seen earlier

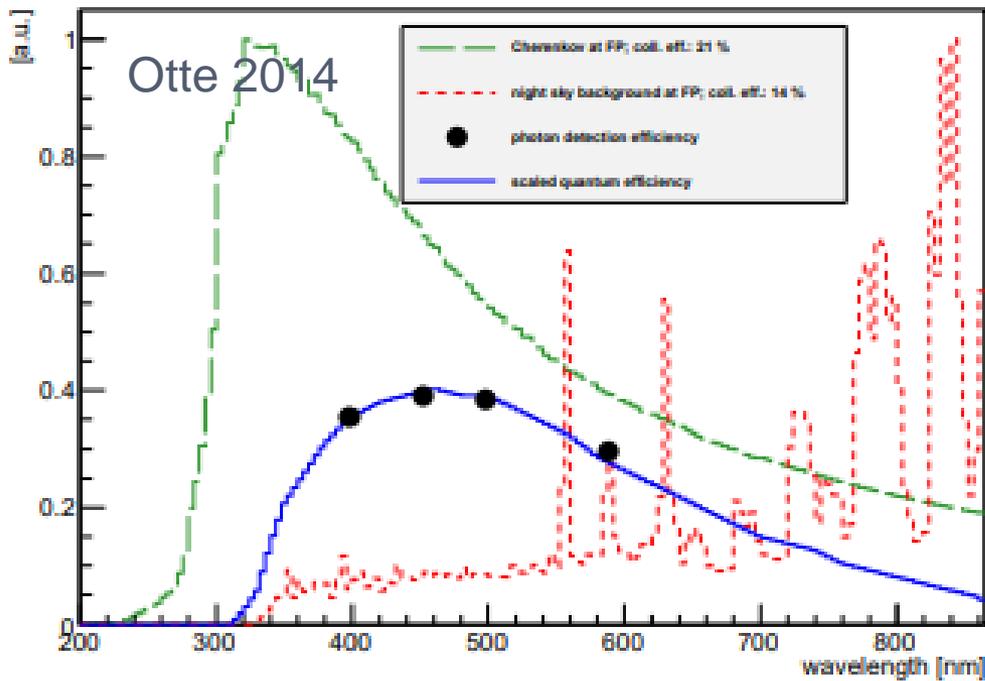- 100ps pulse width estimate still significantly lower
  - Why?

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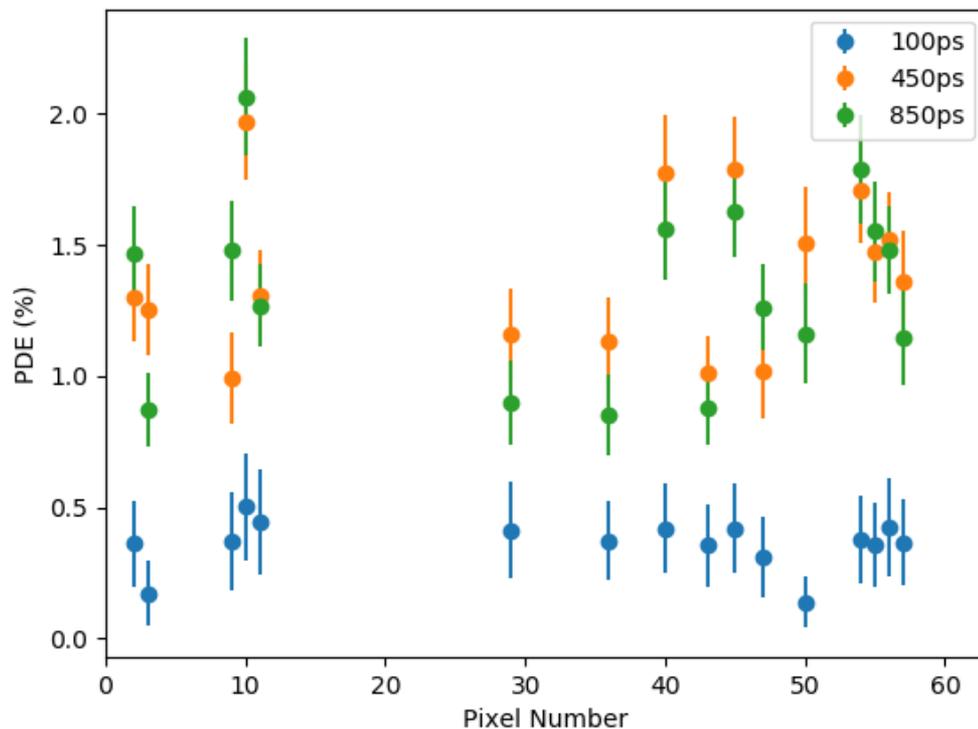
Experimental Results
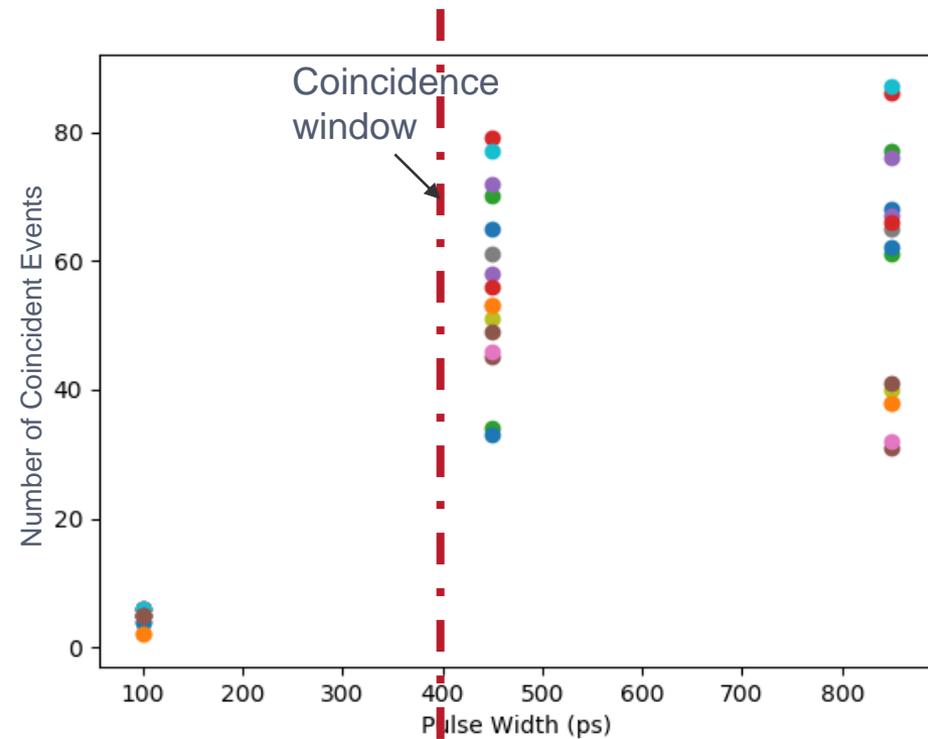
How do we compare?

- Bias V = 67.5V ~ 1-1.5V overvoltage

Hamamatsu S12642 silicon array:
scaled QE<10% @3V overvolts

Otte 2014

- Initial estimate ~ 1-2% @810nm
  @ 1-1.5V overvolts

Characteristics Vover dependence

PDE : measured at λ=408nm
(not including cross-talk and after-pulse)

Vover = 2.4V

measurement example
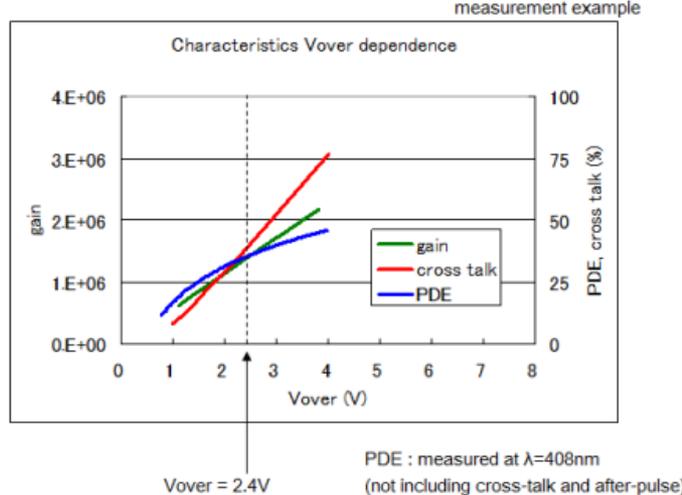
Hamamatsu S13360:
PDE ~7% @ 810nm @ 4V overvolts

Pixel pitch: 50 μm

@ 4V overvolts

(Typ. Ta=25 °C)

PDE increases
with overvoltage
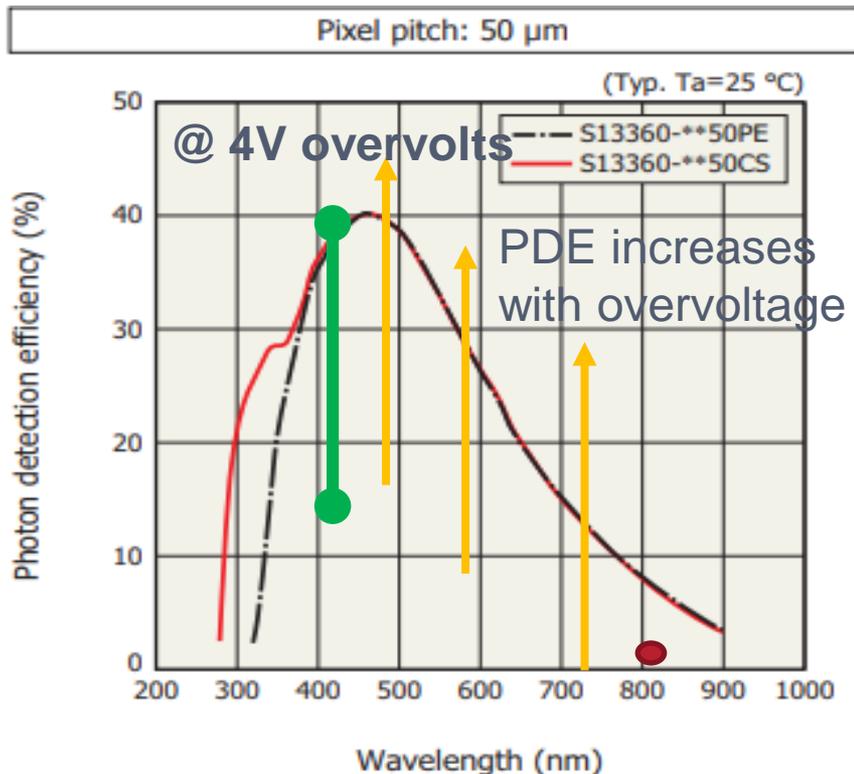
Requirements for this technique

- Individual pixel outputs
  - Achieved using TARGET ASIC

- Fast timing
  - 1GHz sampling via TARGET
  - Interpolated quintic binning used ±200ps

- Discrimination between 810nm and 405nm photons
  - Needed to prevent false positive correlation
  - Use narrowband 810nm band pass filters (10^{-4} 405nm pass through)

- Count and test each pixel

- Can be achieved with current TARGET electronics + SiPM detector array

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Verification, Issues and Possible Resolution

- Verification
  - Imaging ring with SLR camera on a long integration time
  - → Nothing spotted with 30s integration → near IR filter causing a problem?

- Possible Issues/Challenges
  - Timing and Apparent pulse width variation
    - Resolution: Improved skew characterisation of electronics
    - Resolution: optimisation of coincidence windows
  - Observed ring appears wider than expected
    - Resolution: test on bigger camera, further out to ensure this is the only ring seen
  - Achieving other wavelengths
    - Currently limited to narrowband SPDC (e.g. 405→810)

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Summary

- PDE needs to be characterised for different detectors

- Absolute PDE calibration using a calibrated photodiode

- Technique from ~2004 used to calibrate a pixel PDE using quantum entangled photons

- Applying this technique to a SiPM array used for CHEC camera module being developed for the Cherenkov Telescope Array

- Ring observed from individual pixel outputs due to BBO crystal

- Absolute PDE estimated ~1-2% at 810nm for 1-1.5V overvoltage

  – Correct order of magnitude for the silicon

- Some issues with timing, sizing, pulse width variation that need rectifying

  – Routes identified to achieve this

- Arrangement could lead to a small, cheap, versatile method of testing absolute PDE

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Thanks for listening. Any questions?

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