CASST 2026

Canadian Astroparticle Physics
Student Summer Talk Symposium

Queen's University

SiPM Based Gamma-ray Detection

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Outline

The high maintenance pet

The Pet Store:

- What is a SiPM?
  - Why choose this detector?
- How does a SiPM work?
- What am I using it for?

→

Training Your SiPM:

- Get to know your SiPM
- How is it used in the experiment?
- How your SiPM communicates
- What affects your SiPM resolution?

Did it work out?

- Results of the experiment
- Why this was helpful
- Where we can go with this

Motive

What is going on?

My work this summer:

I am working on **calibrating Silicon Photomultipliers** (SiPM's) and **analyzing inorganic scintillation crystal spectrums** for an upper year engineering course at Queen's University that will be following in my footsteps.

- **SiPMs let us detect very small flashes** (single Photoelectron (PE)) **of scintillation light** from gamma-ray interactions.
- **Calibrating the SiPM** is essential because gain, noise, PDE, and bias voltage all affect how much we can trust the measured signal.
- Radiation is difficult to detect at times, so we can use **scintillators to absorb the radiation and emit a light that is easier to detect!**
- This experiment **gives students a complete detector workflow: from gamma-ray energy deposition, to light production, to SiPM signal, to resolution.**

How a SiPM Works

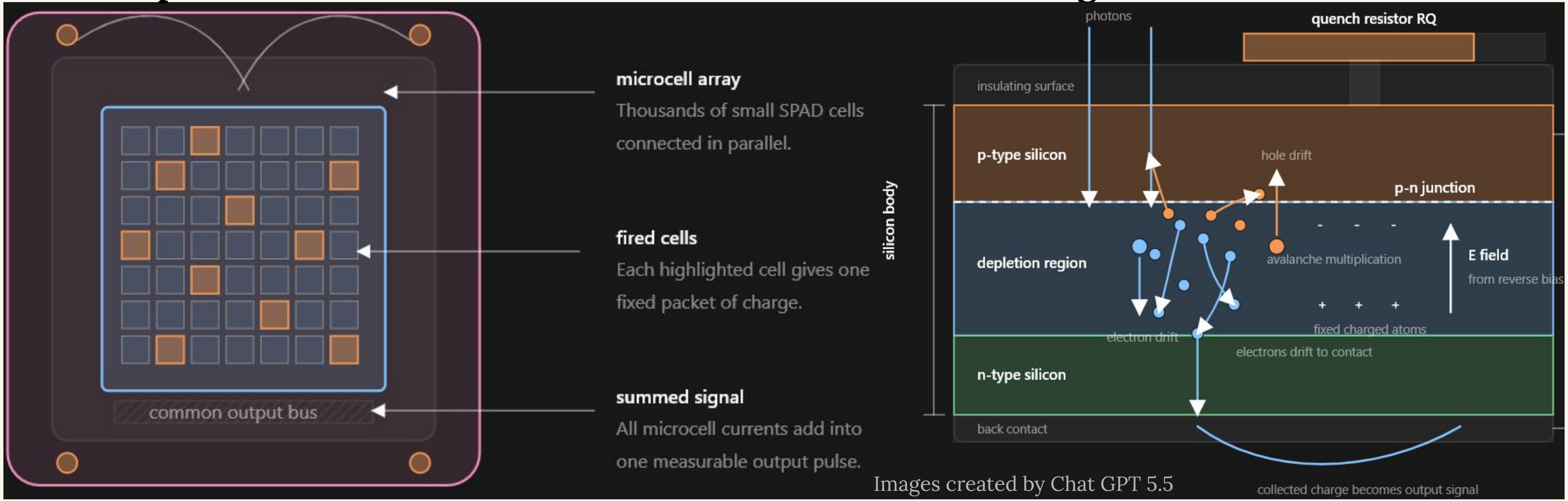
What makes this detector special?

Your SiPM's day-to-day

Photon creates electron hole pair ➔ **Avalanche current rapidly grows** ➔ Quench Resistor causes voltage drop ➔ Micro-**cell voltage falls below bias** and avalanche stops ➔ **Bias supply recharges the cell** through the resistor ➔ SiPM ready to play again!

Top down view

Single micro-cell: side view



Images created by Chat GPT 5.5

What I Am Detecting

Detection Chain

- **Using gamma sources** such as Am-241, Ba-133 **to scintillate a variety of inorganic crystals** such as BGO and CsI(Tl)

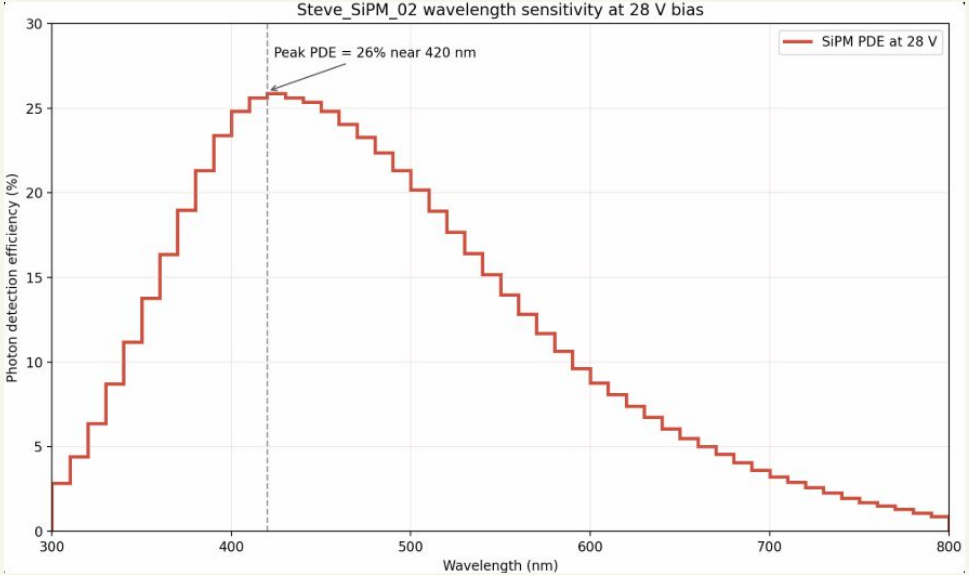
- Use a **SiPM to detect this scintillation light**

- **Analyze the data** and **compare to theoretical predictions** to determine if the experiment is successful/ **replicable**

Get to know your SiPM

Want a SiPM that can roll over?

Your SiPM's Talent:



My SiPM was best at looking for wavelengths of 420 nm, but isn't very efficient

Get to know your SiPM

Not sure what SiPM? Pick the right breed!

So many different kinds of SiPMs!

SiPM Breed:

SiPM detail	Value / estimate	Why it matters
Breakdown voltage	$\sim 24.7\,\mathrm{V}$	Voltage where a microcell can begin avalanche multiplication.
Bias voltage	28 V	Operating voltage used for the SiPM measurement.
Overvoltage	$\sim 3.3\,\mathrm{V}$	Difference between bias and breakdown voltage; affects gain and PDE.
Gain	$(2.7666 \pm 0.0043) \times 10^5$ electrons/photoelectron	Charge produced by one fired microcell.
Photon detection efficiency	$\sim 26\%$	Fraction of incoming photons that trigger avalanches.
Peak sensitivity	$\sim 420\,\mathrm{nm}$	Wavelength where the SiPM is most sensitive.

High breakdown voltage + Low efficiency

Low breakdown Voltage + High efficiency

Low breakdown Voltage + Low efficiency

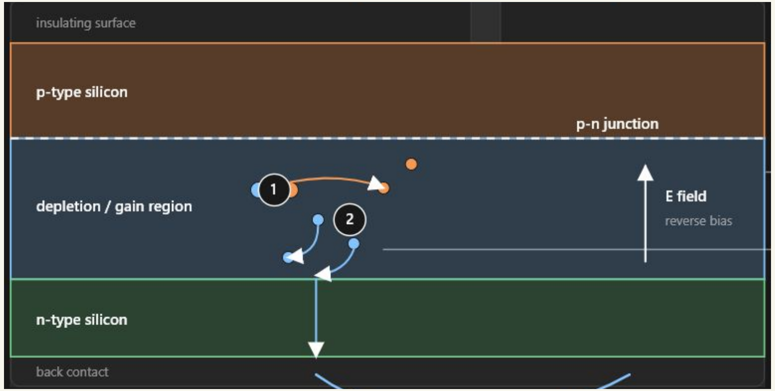
High breakdown Voltage + High efficiency

Get to know your SiPM

Your SiPM is talking to itself

Dark Counts

No photon - caused by heat

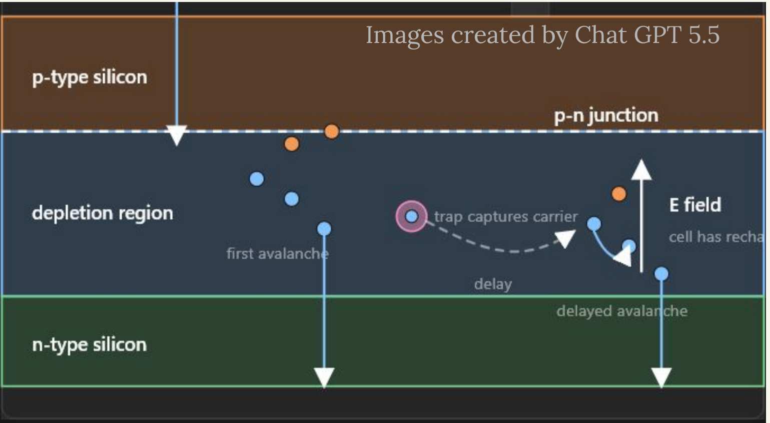


Your SiPM can be loud because:

- High temperature (causes dark counts)
- High bias voltage (**giving your SiPM a microphone**)

After pulsing

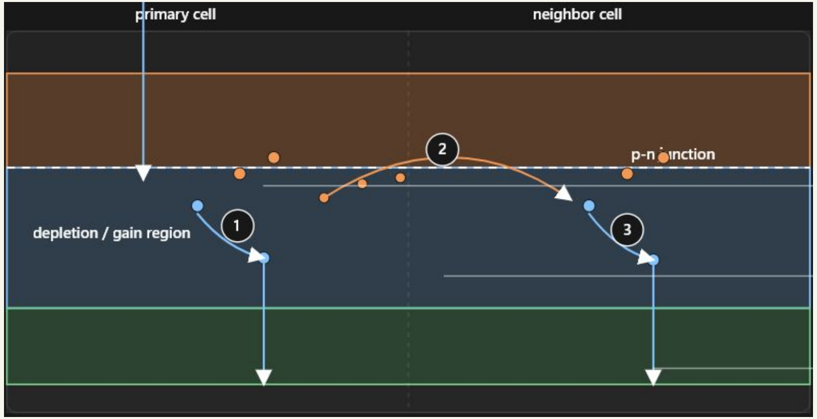
Impurities in the Silicon cause intermediate level band gaps where electrons sit after being hit



Images created by Chat GPT 5.5

Cross talk

Photon emitted from avalanche and travels into the neighbouring cell



Get to know your SiPM

Your SiPM is talking to itself

Dark Counts

Your dog will **bark at nothing all the time**

After pulsing

You will throw a toy and your dog will **take its sweet time retrieving it**

Cross talk

Your dog will **bark at all the neighbour dogs**

How to talk to your SiPM

SiPM's need help to communicate

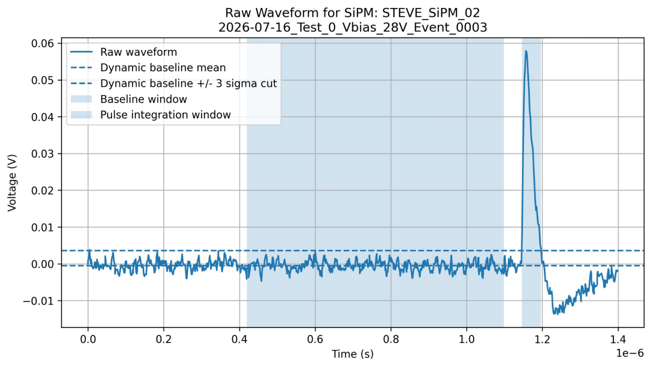
- **SiPM signal** output is **connected to a DRS4** which is 14 bit ADC

- The **DRS4 takes in the data**, saves as an **XML or Binary file**

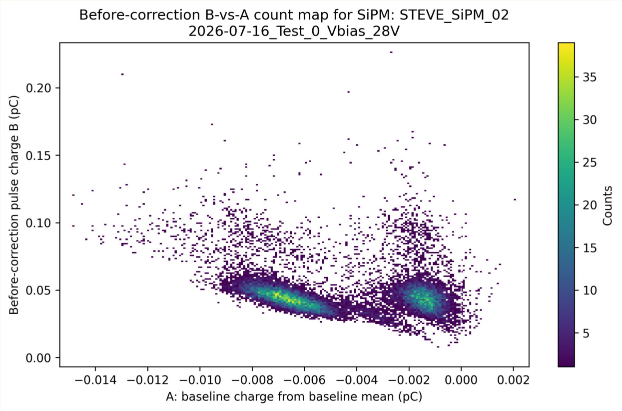
- **Use saved data** file in a script to output:
  a. **R**aw **w**ave**f**orms (**RWF**)
  b. **S**ignal **C**harge **v**ersus **P**edestal **C**harge (**SC v PC**)
  c. Final output: **C**ounts **v**ersus **Ch**arge histogram (**C v Ch**)

What My SiPM Tells Me

What it talks about

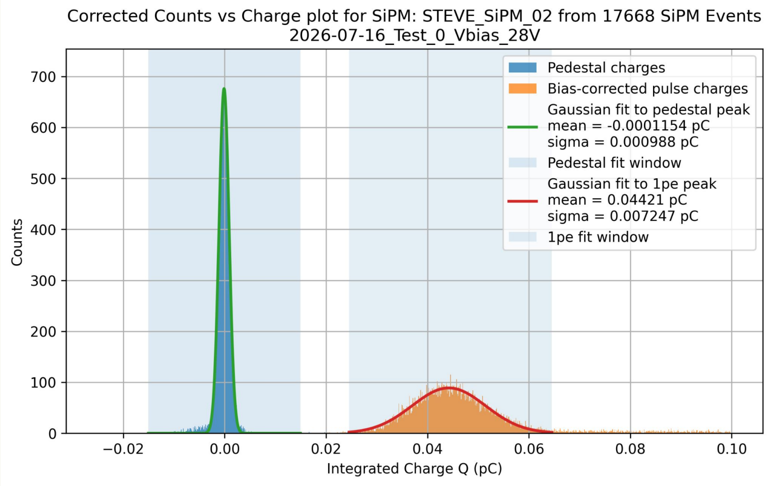


a.) Raw Waveforms



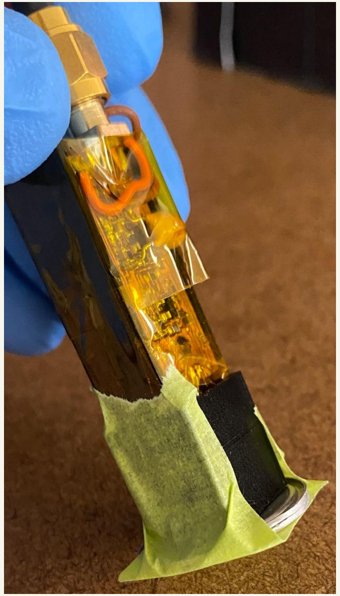
b.) SC v PC

c.) C v Ch

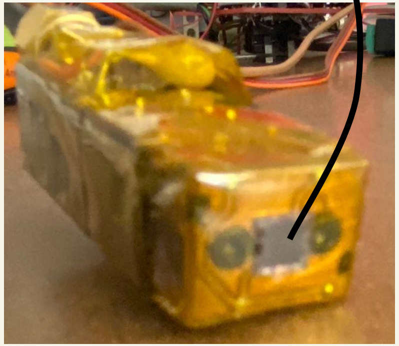


Experimental Setup

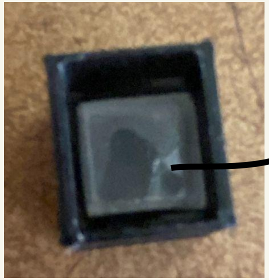
What the SiPM looks like



SiPM



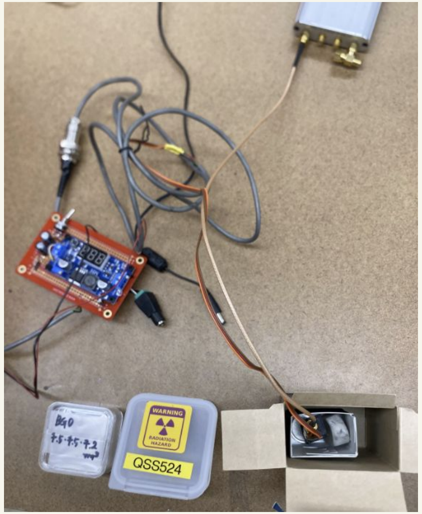
Crystal

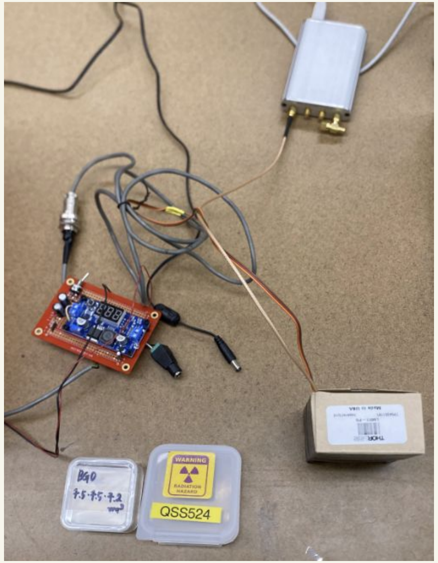


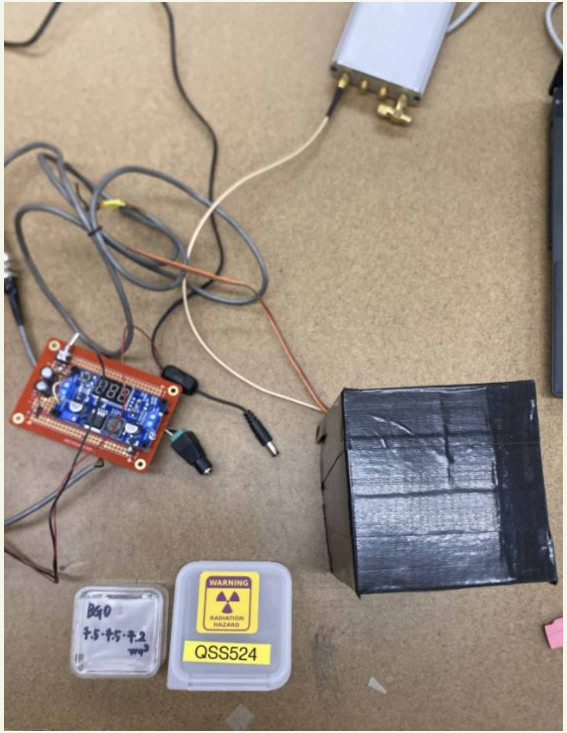
Gamma source (Am-241)

Experimental Setup

Where the SiPM will live







We **want to detect single photons**, so if you **expose the SiPM with light** while supplying voltage, it **can damage the detector.**

Hence the box in a box in a box!

Theoretical Results

A well trained SiPM

$$P_{\text{interaction}}(E_j) = 1 - \exp\left[-\left(\frac{\mu}{\rho}\right)(E_j)\rho d\right]$$

Probability the gammas from the source will **interact in any way with the crystal**

$$\langle P_{\text{interaction}} \rangle = \frac{\sum_j \text{BR}_j \, P_{\text{interaction}}(E_j)}{\sum_j \text{BR}_j}$$

Probability of those gammas **interacting based on their Branching Ratios (BR)**

$$\text{PDE}_{\text{effective}} = \sum_\lambda f_{\text{emission}}(\lambda) \, \text{PDE}(\lambda, 28\,\text{V})$$

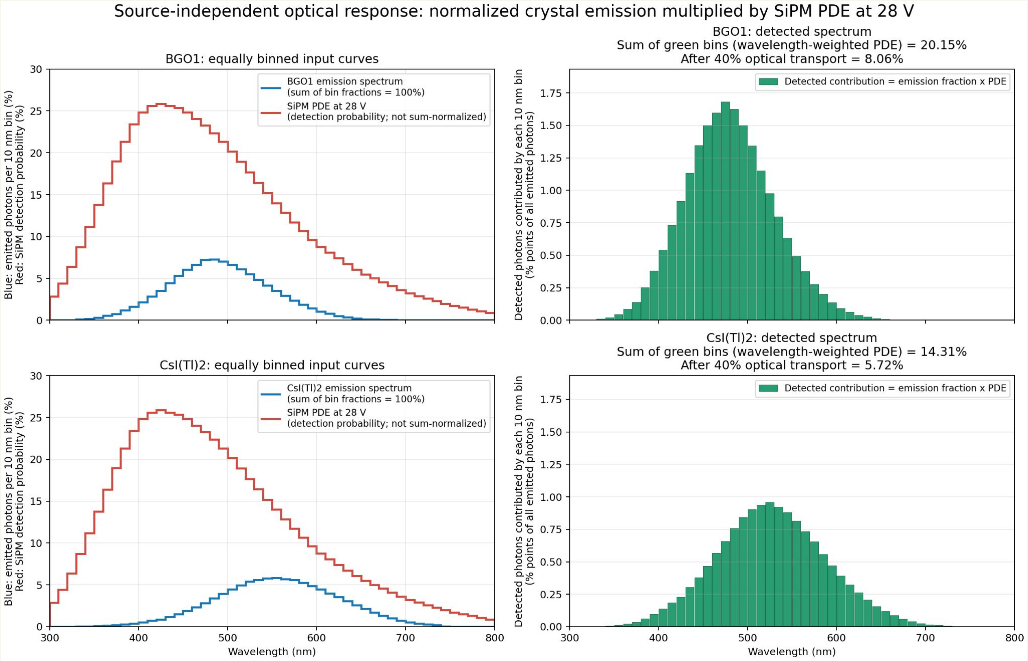
How effective the SiPM will detect specific wavelengths

$$P_{\text{det,theory}} = \langle P_{\text{interaction}} \rangle \, \eta_{\text{optical}} \text{PDE}_{\text{effective}}$$

Probability of photons being detected

Photon-Detection Efficiency

The well trained SiPM



Wavelength weighted PDE after optical efficiency (PDE_eff):

BGO = 8.06%
CsI(Tl) = 5.72%

Wavelengths where the crystal emits more light will contribute more strongly to the average PDE

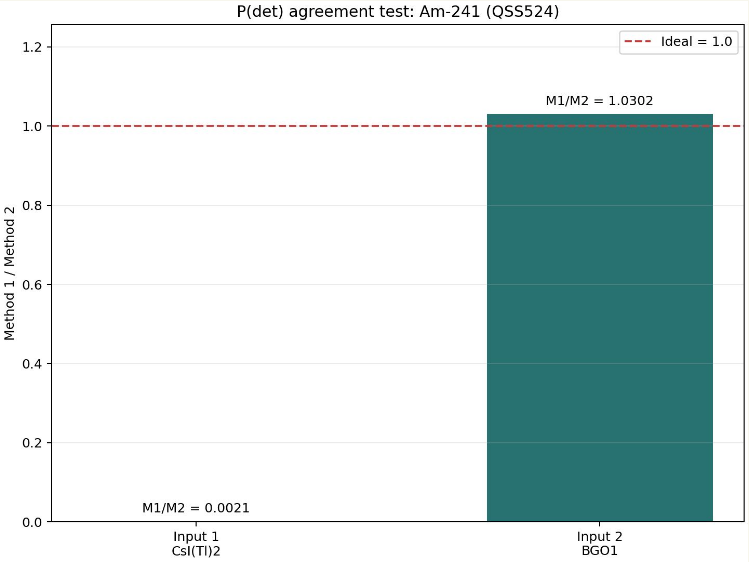
Results

The untrained SiPM

$$P_{\text{det,theory}} = \langle P_{\text{interaction}} \rangle \, \eta_{\text{optical}} \text{PDE}_{\text{effective}}$$

$$P_{\text{det,exp}} = \frac{(R_{\text{Scaler0}} - R_{\text{background}})\,(N_{\text{accepted}}/N_{\text{saved}})}{A(t)\, f_{\text{geometry}} \sum_j \text{BR}_j}$$

$$\text{Agreement} = \frac{P_{\text{det,exp}}}{P_{\text{det,theory}}}$$

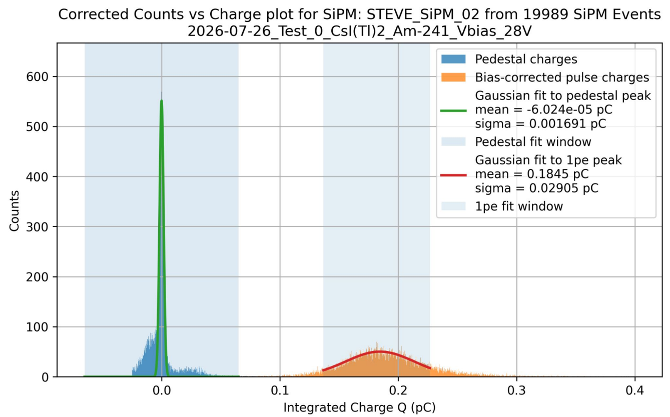


The results say they DO NOT agree
(the **ratio is not close to 1 for most results**).

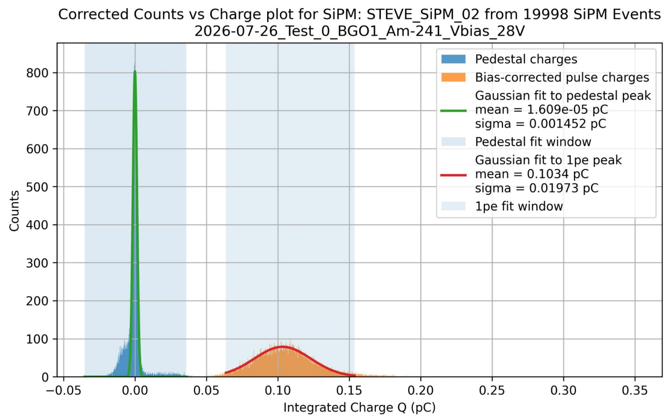
Experimental Results

The untrained SiPM

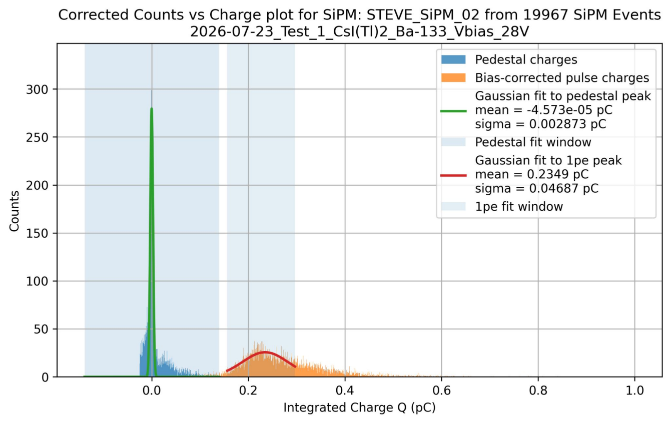
CsI(Tl) with Am-241



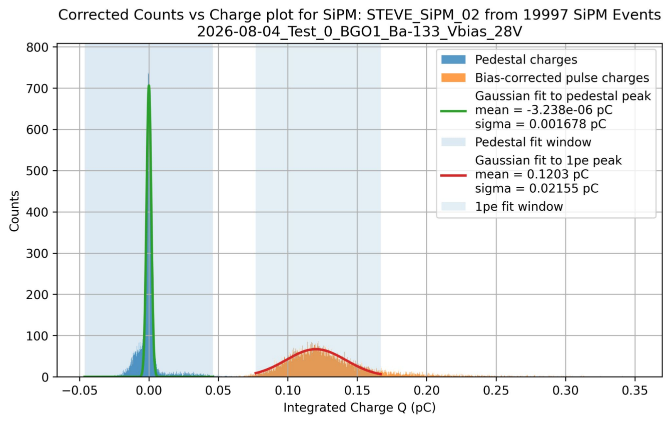
BGO with Am-241



CsI(Tl) with Ba-133



BGO with Ba-133



Why This Is Helpful

- Low-energy gammas should often interact, so charge peaks should be visible. The **results confirmed the success of this via the CvCh plots**.

- Differences from expectation can come from **optical coupling**, **quality of crystals, or quality cuts placed on waveform integrations**. This allows us to understand more about the process of **how to treat data from scintillation light compared to background events.**

- Serves as a great experiment for the upper year students as it **requires one to develop knowledge of a highly used detector**.

Where to Go From Here

Outlook

- Measure or **constrain the optical-coupling factor** instead of guessing it.
- Use **measured PDE and crystal emission spectra in the detection-probability model** rather than using the reported PDE at given bias voltages.
- Attempt **Coincidence tests** after **understanding DRS4 logic**

Thank you!
Any Questions?

Get to know your SiPM

How to handle the noise

Propagating the uncertainty on the theoretical probability of detection

$$\frac{\sigma_{P_{\text{det}}}}{P_{\text{det}}} = \sqrt{\left(\frac{\sigma_\eta}{\eta_{\text{opt}}}\right)^2 + \left(\frac{\sigma_{\langle \text{PDE} \rangle}}{\langle \text{PDE} \rangle}\right)^2}$$

$$\eta_{\text{opt}} = 0.40 \pm 0.10$$

$$\frac{0.10}{0.40} = 0.25$$

NIST and XCOM are evaluated reference values with **uncertainties that I am taking to be much smaller than my approximate for optical efficiency.**

PDE wavelength weighted, source independent

$$\mathrm{PDE}_{\mathrm{weighted}} = \frac{\int S(\lambda)\,\mathrm{PDE}(\lambda)\,d\lambda}{\int S(\lambda)\,d\lambda}.$$

where

$$\begin{aligned}
\lambda &: \text{ wavelength,} \\
S(\lambda) &: \text{ scintillation emission spectrum,} \\
\mathrm{PDE}(\lambda) &: \text{ SiPM photon-detection efficiency at wavelength } \lambda, \\
N_\gamma &: \text{ total number of scintillation photons,} \\
f(\lambda) &: \text{ normalized emission-spectrum shape,} \qquad \int f(\lambda)\,d\lambda = 1.
\end{aligned}$$

The emission spectrum can be written as

$$S(\lambda) = N_\gamma f(\lambda).$$

Substituting this into the weighted-PDE equation gives

$$\begin{aligned}
\mathrm{PDE}_{\mathrm{weighted}} &= \frac{N_\gamma \int f(\lambda)\,\mathrm{PDE}(\lambda)\,d\lambda}{N_\gamma \int f(\lambda)\,d\lambda} \\
&= \frac{N_\gamma \int f(\lambda)\,\mathrm{PDE}(\lambda)\,d\lambda}{N_\gamma \int f(\lambda)\,d\lambda} \\
&= \int f(\lambda)\,\mathrm{PDE}(\lambda)\,d\lambda.
\end{aligned}$$

How Experimental Probability Is Calculated

$$R_{\text{source}} = R_{\text{Scaler0}} - R_{\text{background}}$$

$$R_{\text{accepted}} = (R_{\text{Scaler0}} - R_{\text{background}}) \frac{N_{\text{accepted}}}{N_{\text{saved}}}$$

$$R_{\text{possible}} = A(t)\, f_{\text{geometry}} \sum_j \text{BR}_j$$

$$P_{\text{det,exp}} = \frac{(R_{\text{Scaler0}} - R_{\text{background}})\,(N_{\text{accepted}}/N_{\text{saved}})}{A(t)\, f_{\text{geometry}} \sum_j \text{BR}_j}$$

What Affects Its Resolution?

- Resolution depends on photon statistics, PDE, gain variation, and electronics noise.
- Integration window size and pedestal subtraction change the measured charge width.
- Bias voltage affects gain, but it can also change noise and avalanche probability.