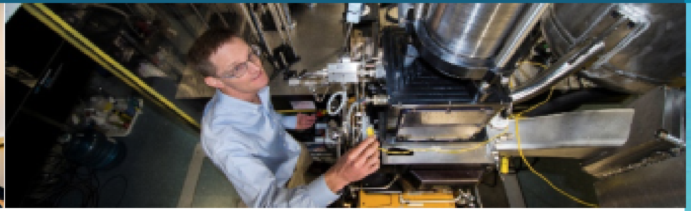
SAND2021-13000C

Sandia National Laboratories

# Design and Commissioning of a Monolithic Neutron Scatter Camera

*PRESENTED BY*

Jon Balajthy

on behalf of the SVSC collaboration

***With contributions from***

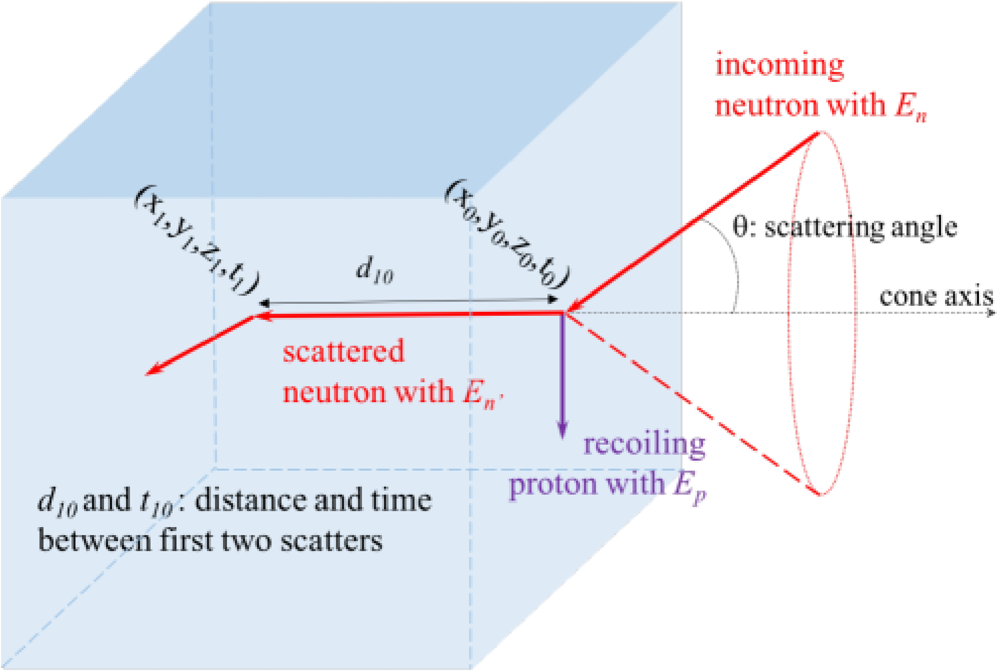
E. Brubaker, J. Cates, V. Negut, J. Steele

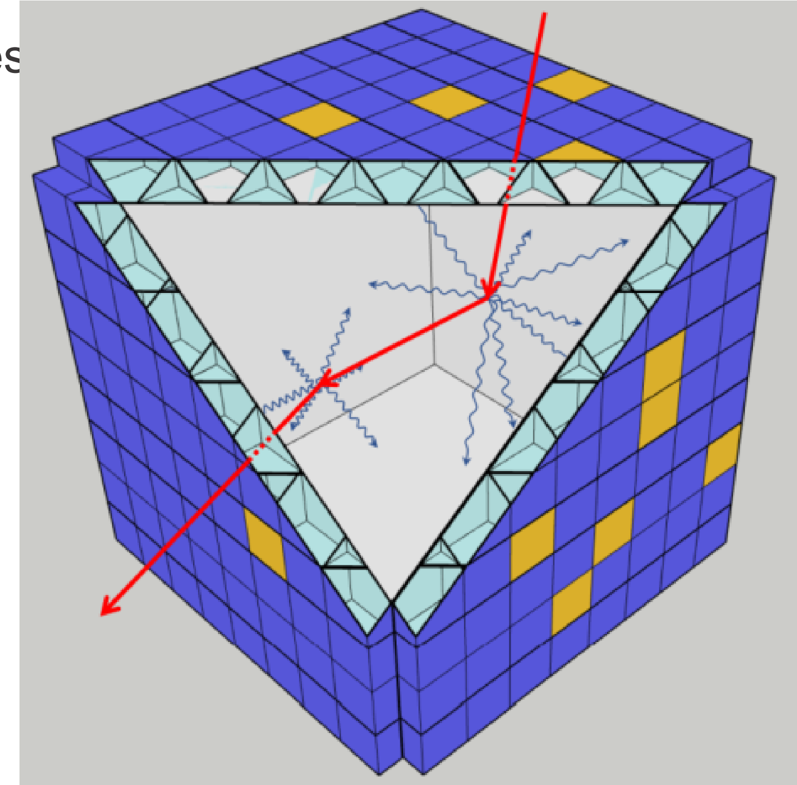
U.S. DEPARTMENT OF ENERGY  NNSA National Nuclear Security Administration

# Overview

The Single Volume Scatter Camera (SVSC) Collaboration is a multi-institution effort led by Sandia National Laboratories to develop a novel type of kinematic neutron imager that utilizes a single, compact detector volume.

- Significant improvement over conventional imagers in size and geometric efficiency
- Use arrays of state-of-the-art photon detectors to reconstruct the positions and times of neutron scatters within the detector volume.
- Pursuing several geometries, including two monolithic prototypes



# The SVSC Team

**@Sandia National Laboratories (Lead Laboratory)**
- Erik Brubaker (PI)
- Jon Balajthy (post-doc)
- Belkis Cabrera-Palmer
- Kevin Keefe
- Patrick Feng
- Paul Maggi (post-doc)
- Peter Marleau
- John Steele
- Melinda Sweany

**@Argonne National Laboratory**
- Jeff Elam (PI)
- Anil Mane

**@Oak Ridge National Laboratory**
- Paul Hausladen (PI)
- Micah Folsom (grad)
- Jason Nattress (post-doc)
- Klaus Ziock

**@North Carolina State University**
- John Mattingly (PI)
- Mudit Mishra (grad)
- Ahmed Moustafa (grad)

**@Lawrence Berkeley National Laboratory/UC Berkeley**
- Bethany Goldblum (PI)
- Josh Brown
- Josh Cates
- Gino Gabella (post-bac)
- Thibault Laplace
- Juan Manfredi (post-doc)
- Victor Negut

**@UH Mānoa**
- Kurtis Nishimura (PI)
- Evan Adamek (post-doc)
- Hassam Alhajaji (undergrad)
- Brian Crow (grad)
- Andrew Druetzler
- Aline Galindo-Tellez (post-doc)
- Kevin Keefe (grad)
- John Learned
- Benjamim Pinto Souza (undergrad)
- Eric Takahashi (post-bac)

# Second Monolithic Prototype

50mm x 56.2mm x 60.2mm block of Eljen-204 plastic scintillator

- Selected as a compromise of light yield and timing
- 0.7ns rise time
- High light-yield (10400 ph/MeV e-)
- Negligible attenuation (400cm)

Instrumented on two sides with four 2x8 arrays of Hamamatsu S13360-6075PE SiPMs

EJ560 Silicone rubber optical interface

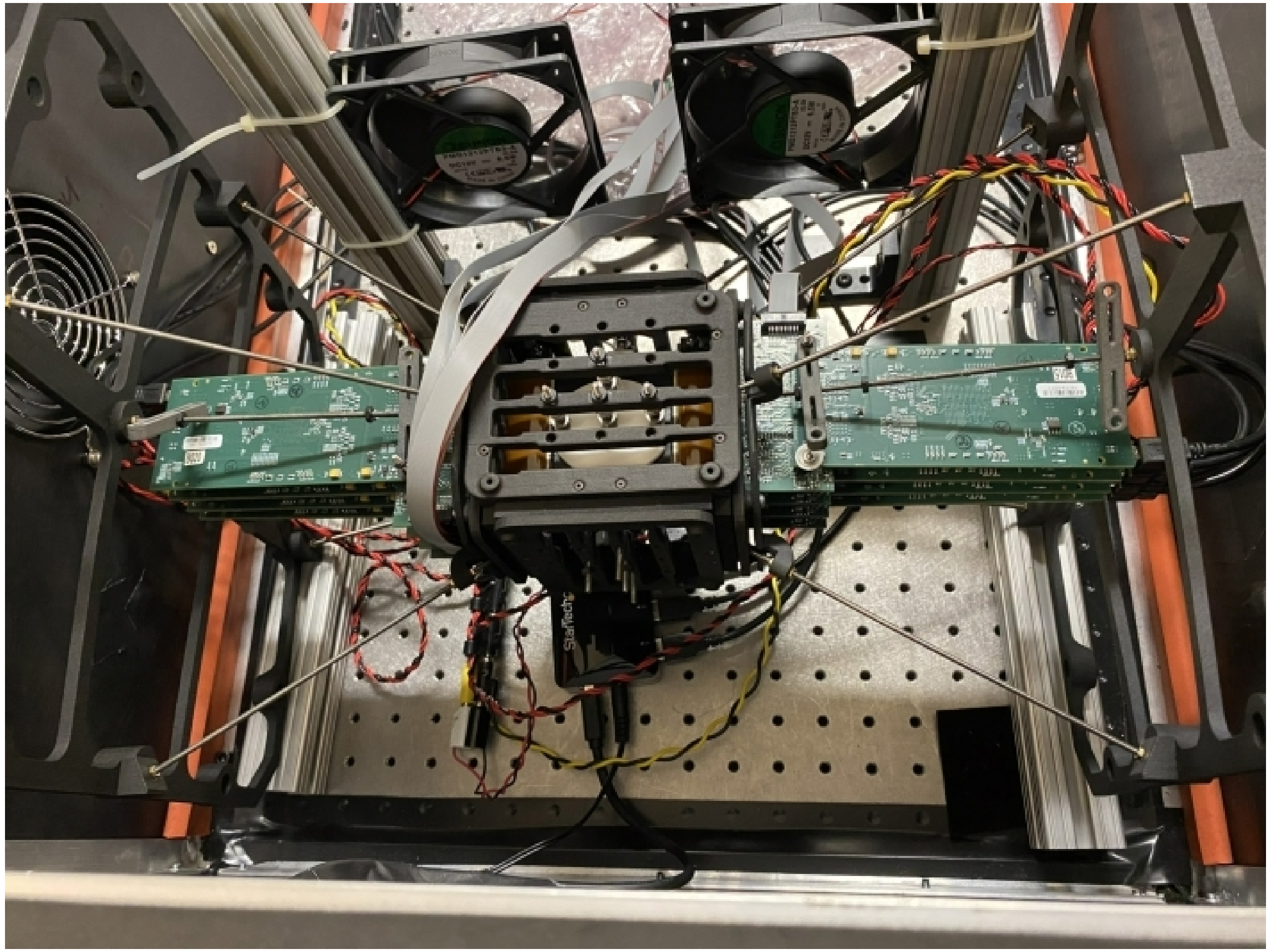
- Allows for more time-stable connection than grease
- Easier to apply and remove

Digitized using SCEMA electronics boards

- J. Steele et al. *Journal of Instrumentation* **14** (2019) P02031.

Mechanical structure provided by LBL

- Each 2x8 array of SiPMs is secured to the



# Electronic readout

Analog readout and digitizer boards are designed by LBL and SNL, respectively

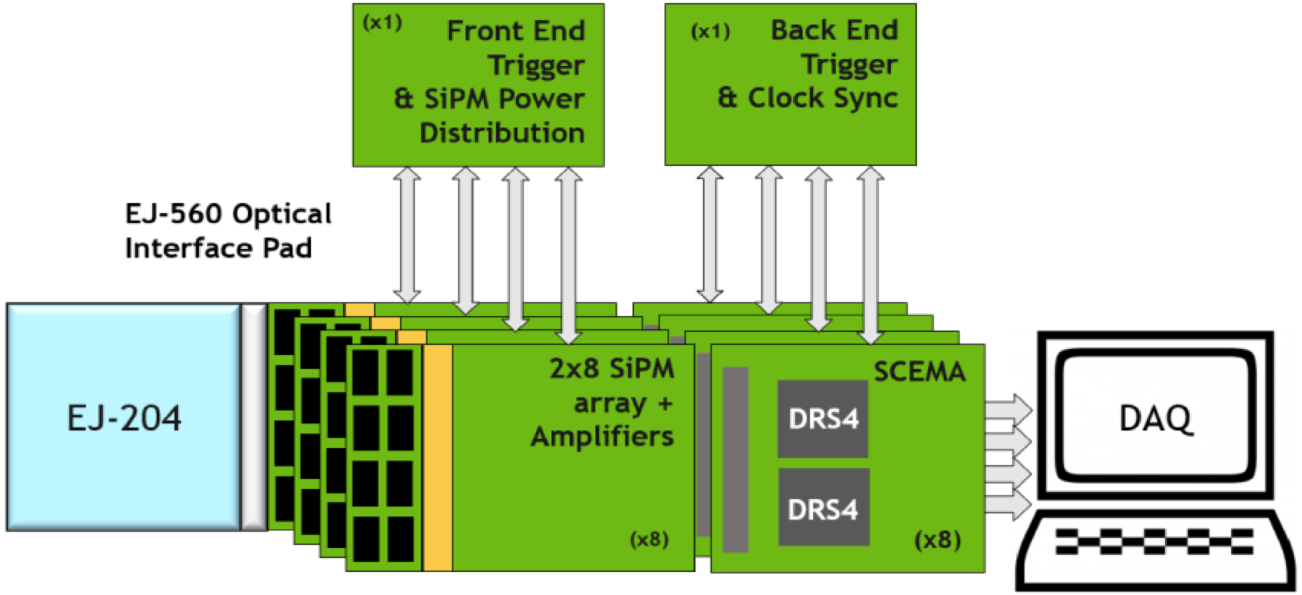
The front-end SiPM readout boards:

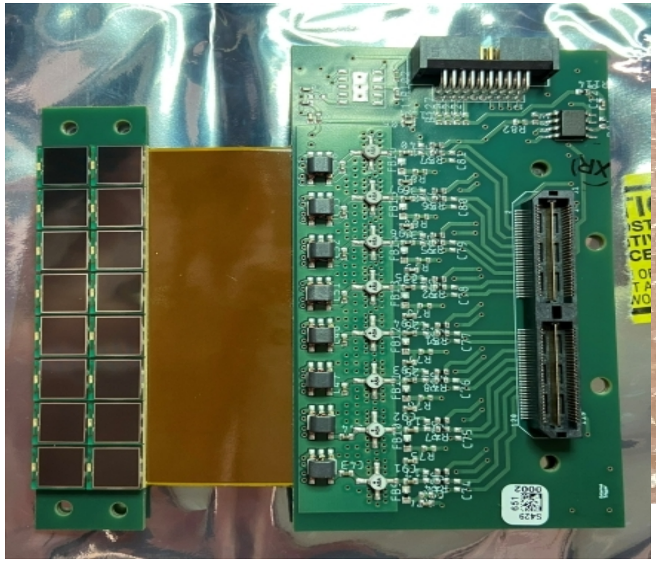
- 2x8 array of SiPMs
- RF amplifiers for single PE sensitivity
- Summing circuit

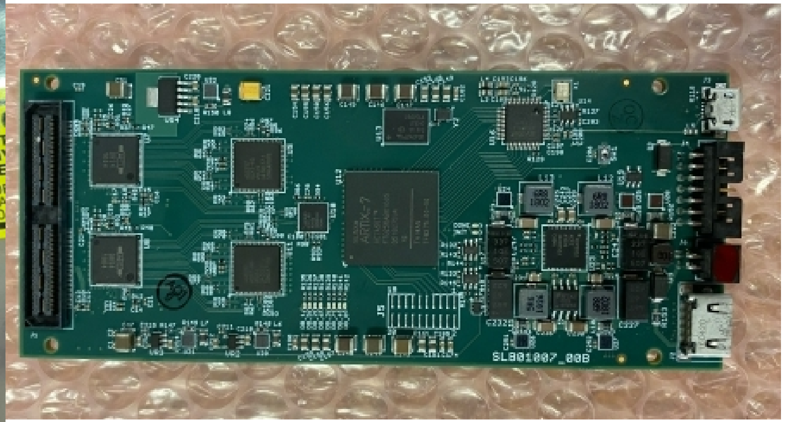
Digital readout boards (SCEMA):

- Use 2x DRS4 switched capacitor arrays
- ~5GHz sampling rate
- ~50ps back-end timing resolution
- HDMI LVDS readout available for high-speed data transfer

Front and back-end triggers allow for sophisticated event selection





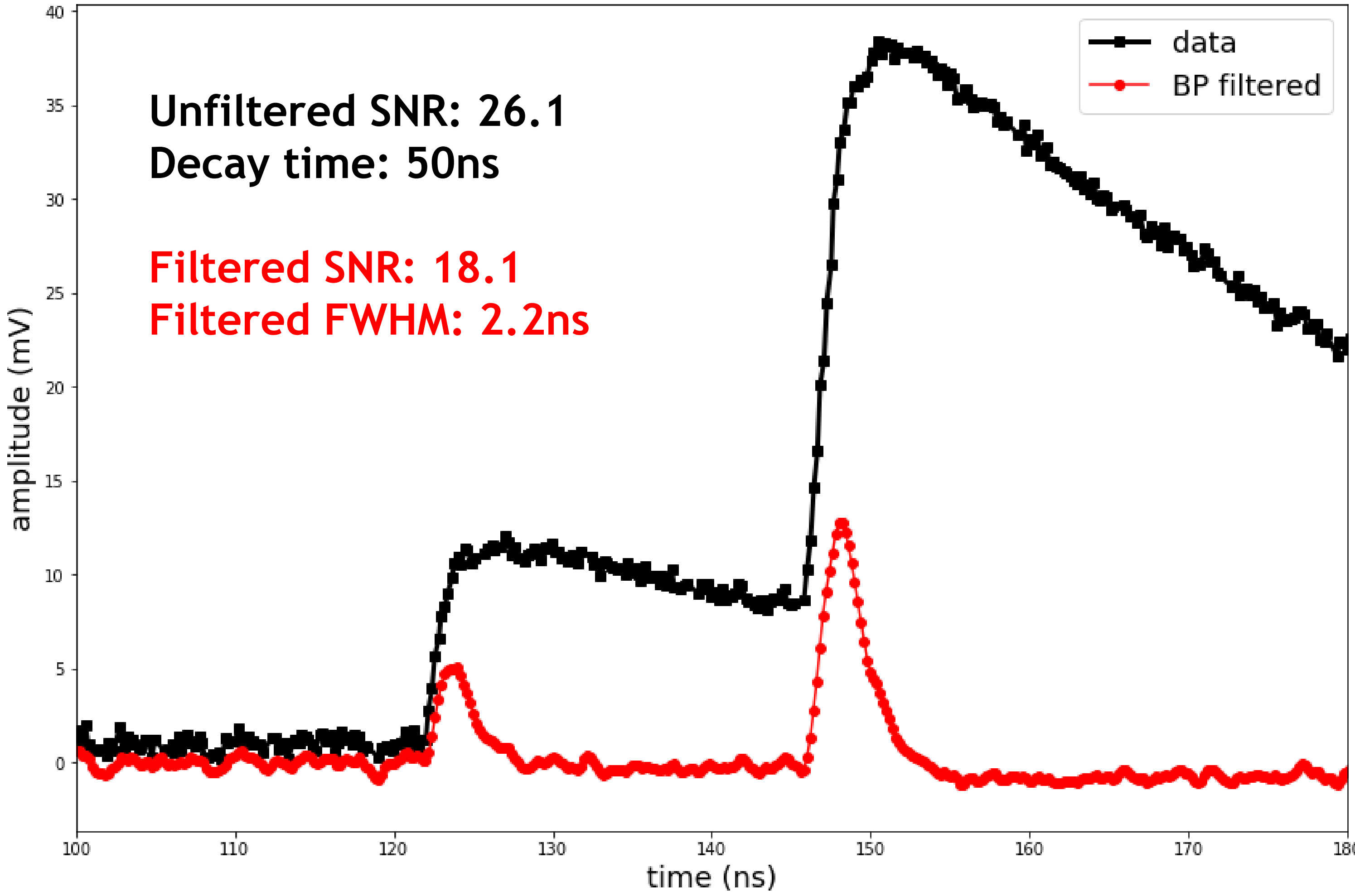
# SiPM Pulse Processing

Need to optimize pulse-processing to find single photons

Use software bandpass filter
- Scipy.signal.butter, 100 to 600 MHz
- Hand optimized to minimize pulse width and maintain SNR
- Reduce pileup due to long decay time
- Need to resample the data due to nonuniform sampling time

First pass pulse-level analysis using simple peak-finding algorithm
- Limited to noise on a single voltage measurement

Second pass using template fitting
- Need to know how many peaks to include in fit
- Very accurate- utilize entire pulse
- SPTR contribution of 44ps



# SiPM Qualification Testing: Dark Count Tests

Utilize dark count data for single-photon characterization:

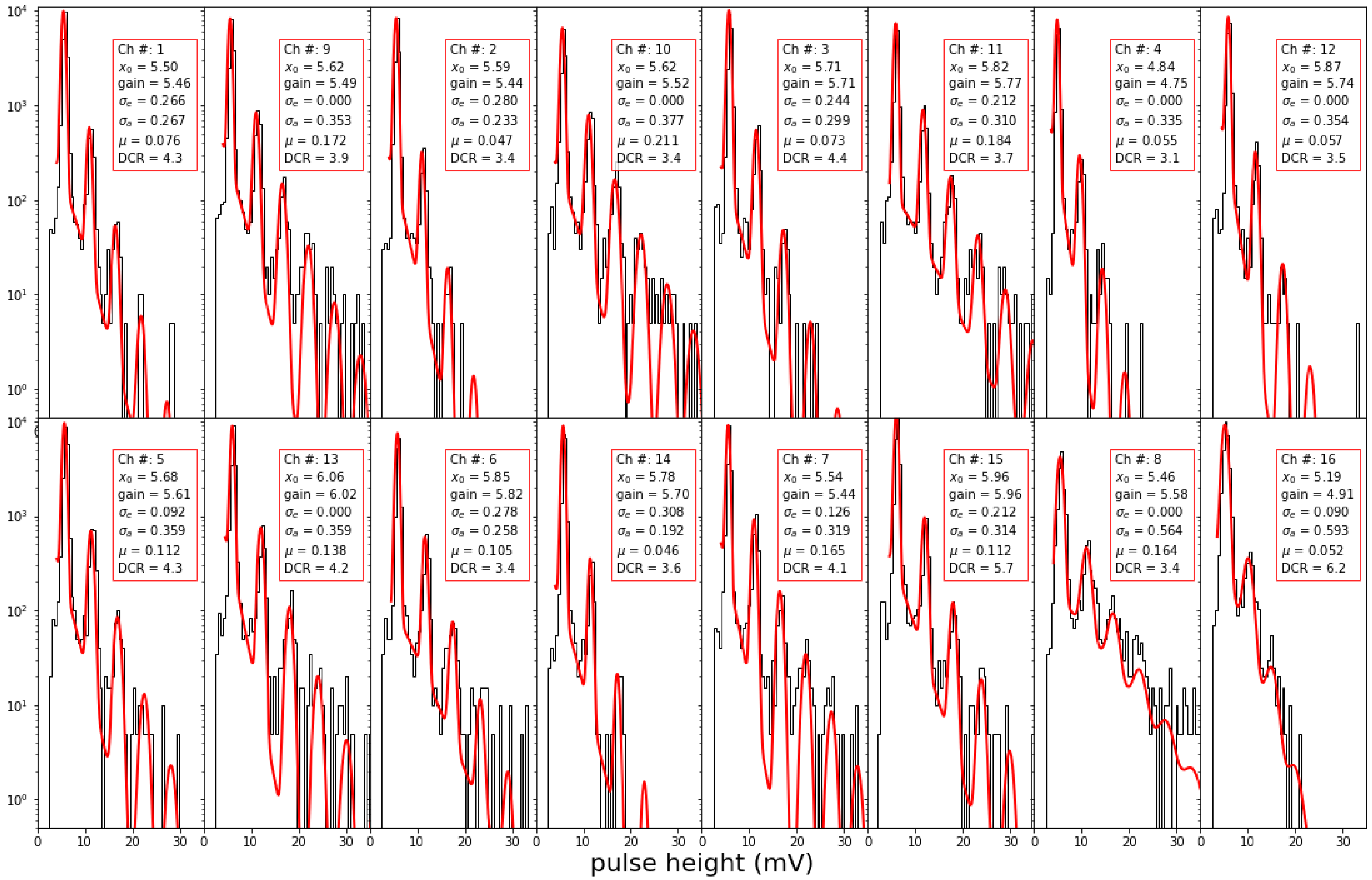
- Pulse-height spectrum modeled by sum of Gaussians on an exponential background
- Peak multiplicity modeled by Borel distribution

Extended DC tests indicated additional cooling was required

- Added more DC fans
- Piped in cool air from a server room AC unit

With additional cooling in place, all channels are performing within spec:

- Crosstalk parameter varies broadly, from ~3% to 21%
- DCR ranges from 3MHz to 7 MHz



# SiPM Qualification Testing: Laser Tests

Low intensity 405nm laser focused on 1 or 2 SiPMs

- Not well collimated

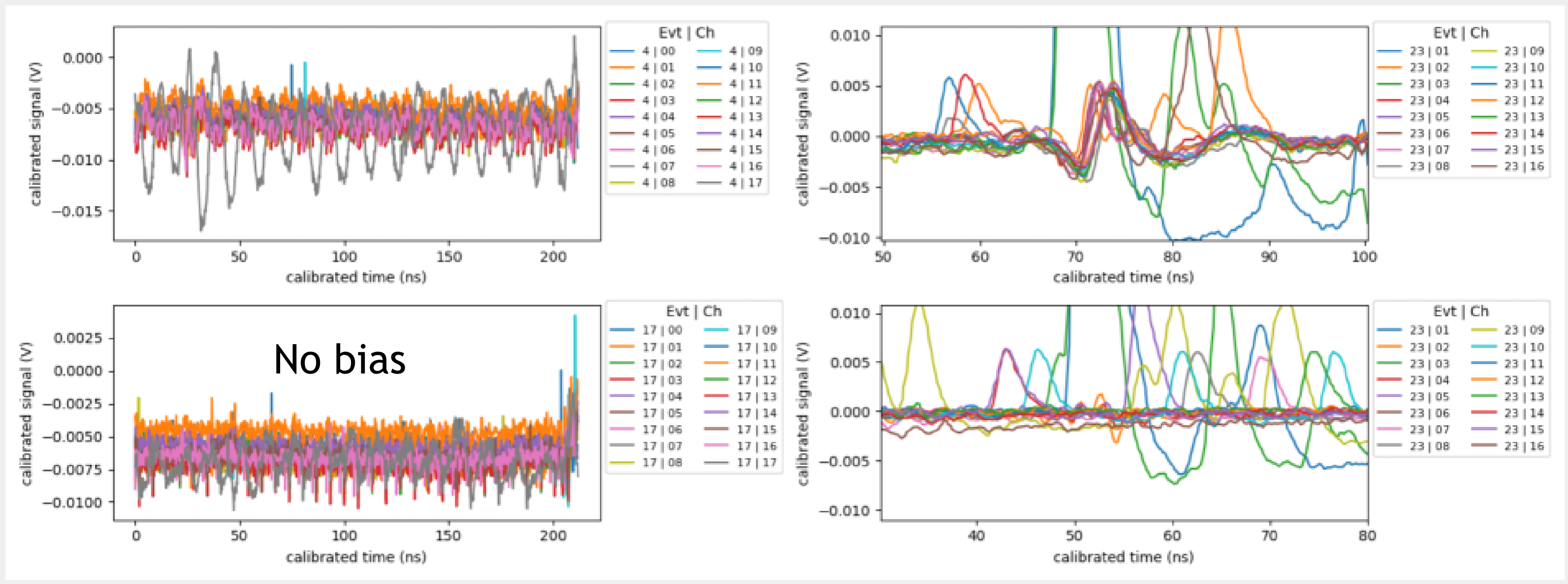
SPTR measured to be <220ps

Found unexpected electrical crosstalk:

- ~2% for all channels in a board
- Found to be stemming from the sum signal trace
- Added additional capacitance to ground and the crosstalk was reduced to a nonissue

Laser amplitude: 100-150mV in channels 1 and 3
Electronic crosstalk: ~5mV in all channels (2% of summed signal)

Before repair




After Repair

Electronic crosstalk: <2mV in neighboring channels only

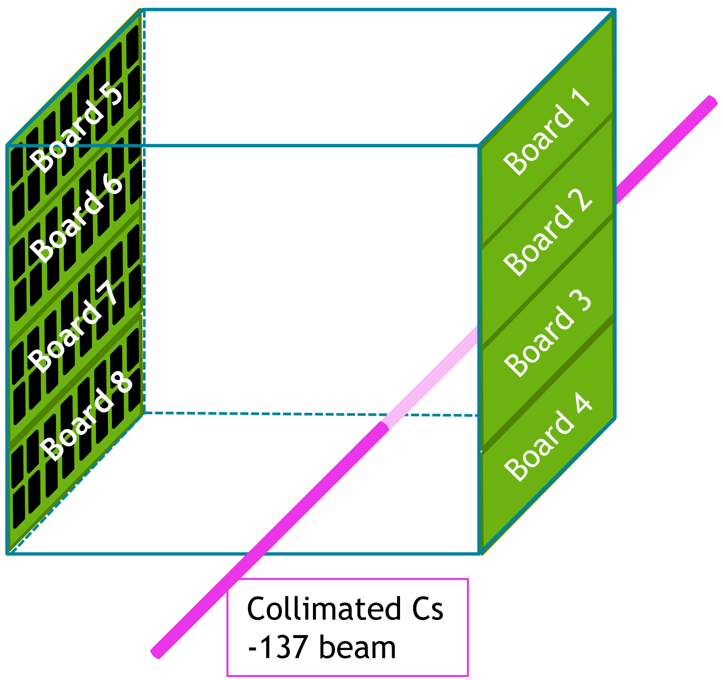
# Collimated Cs-137 Source

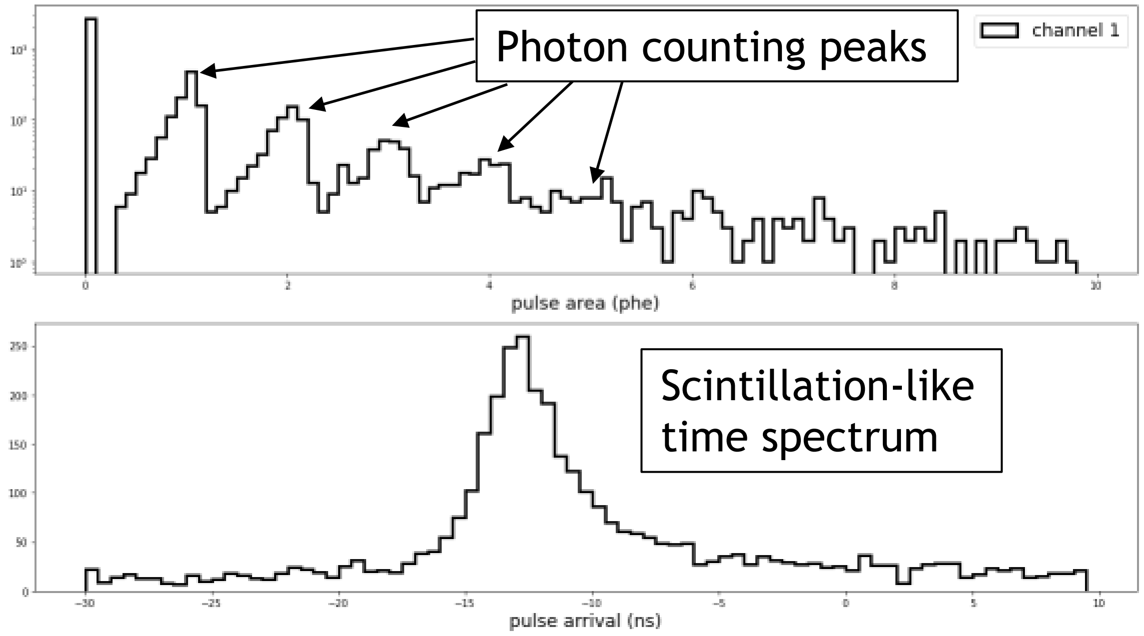
Collimated Cs-137 source:

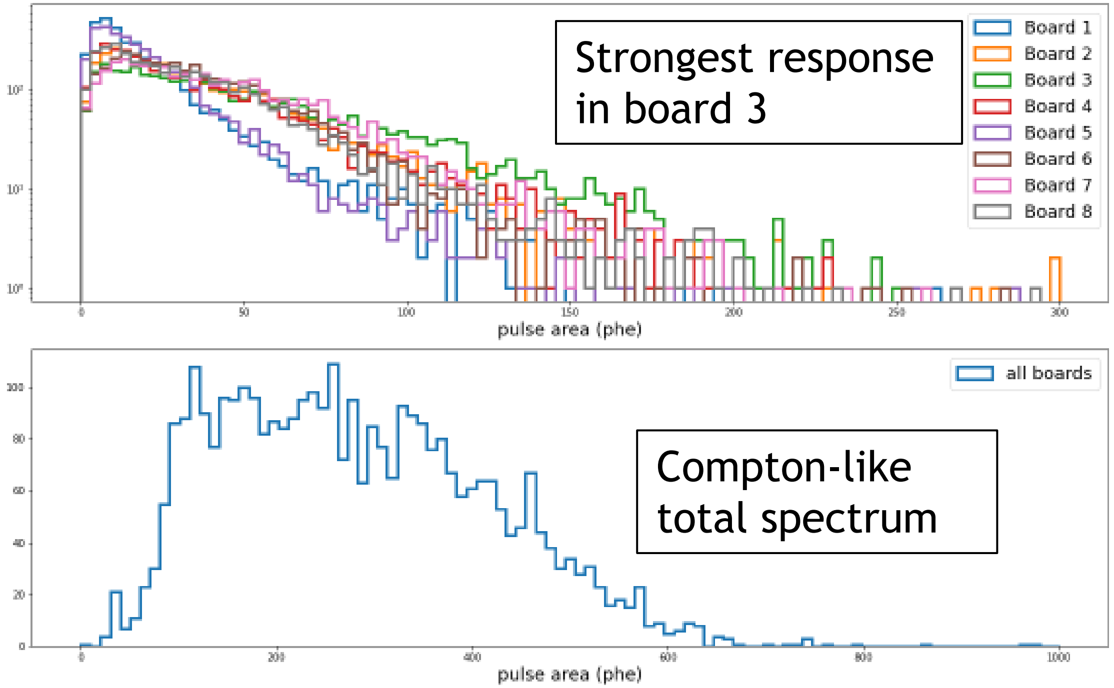
- Aligned along long axis of 2x8 SiPM arrays
- Located nearest to board 3, and furthest from board 5

Pulse area is integrated over 26ns trigger window

We suspect there is some trigger mismatch between the boards



# Remaining Goals

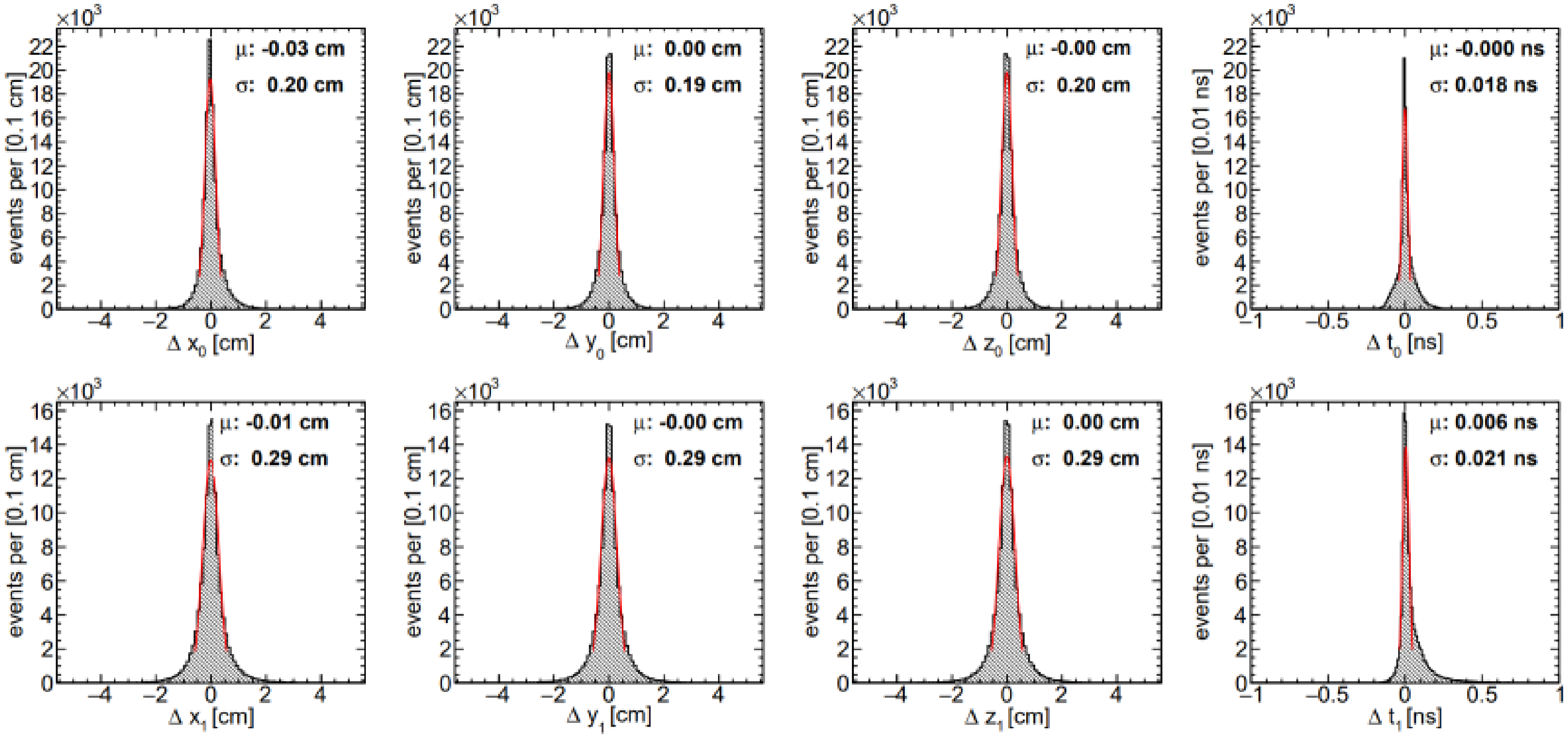
- Remove the trigger mismatches from the scintillation data
  - Implement back-end hub board
- Measure correlation between devices due to optical crosstalk
- Complete analysis of the collimated beam to measure position-dependent response
- Calibrate the position-dependent time response for the each pixel
- Calibrate energy response using additional gamma sources
- Repeat calibration with grid of pencil beams to generate 3D map of detector response
- Take neutron data and feed the response map into the likelihood to produce an image

# Extra Slides

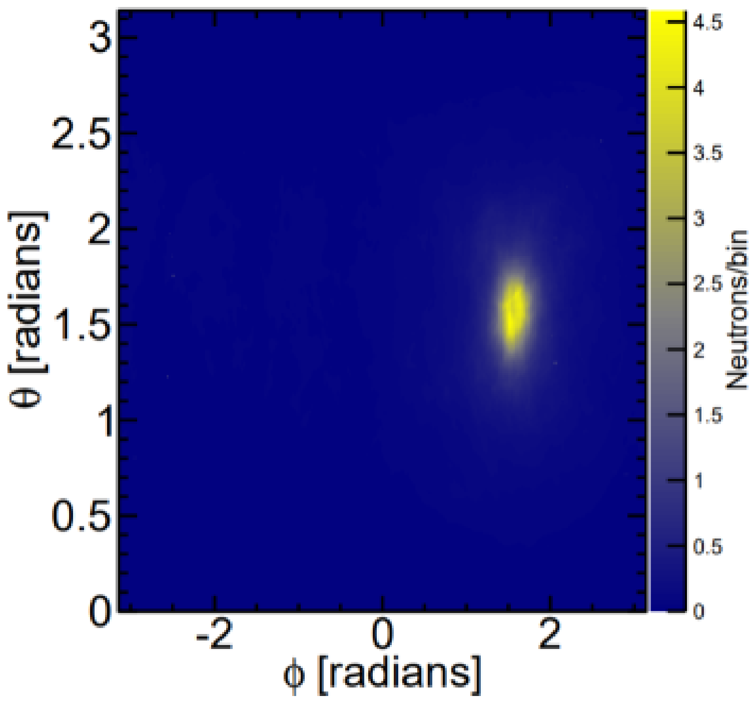
# Initial modelling and expected performance

- Simulations using Geant4
- 10cm cube of EJ-232Q
- Instrumented on 6-sides with 16x16 MA-PMT's
- Assume 100ps single-photon time resolution
- Cf-252 1m from cube along y-axis
- ~100,000 double-scatter events were collected
- Interaction and image reconstruction was done using maximum likelihood methods

- **Spatial resolution is ~2mm**
- **Timing resolution is ~20ps**
- **Angular resolution is ~0.09 radians**




(Figures from B. Cabrera-Palmer @SNL)

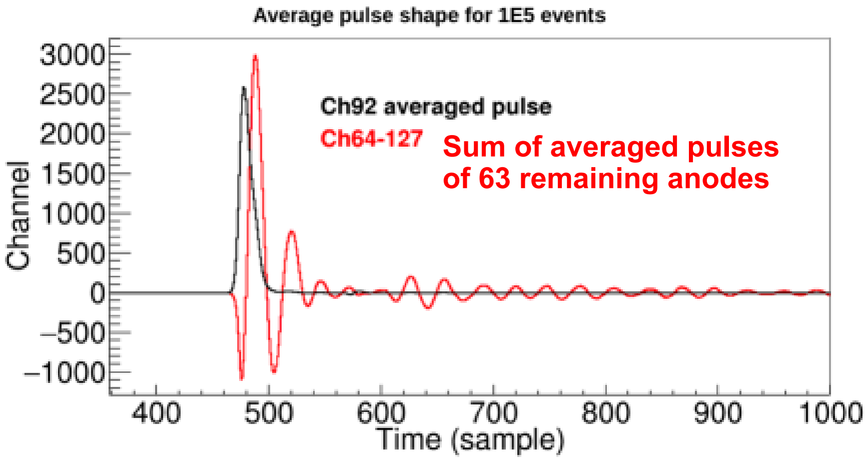


# SiPM’s vs PMT’s

First prototype used Hamamatsu 12700 MA-PMT’s

- TTS ~350ps
- Negligible dark-count rate for our purpose
- QE ~25%
- ~2% electronic crosstalk

The first prototype found that the 2% electronic crosstalk was too high. Contamination of the sum signal limited the capability of the trigger




Second prototype will move to Hamamatsu S13360 SiPM’s

- SPTR contribution = ~200ps
- Higher DCR (~1-5 dark counts per side per 15ns)
- QE ~40-50%
- Delayed crosstalk and after-pulsing is ~3%
- Electronic crosstalk can be highly constrained by laying out our own array
- ~45% optical crosstalk (~20% internal, ~25% external)

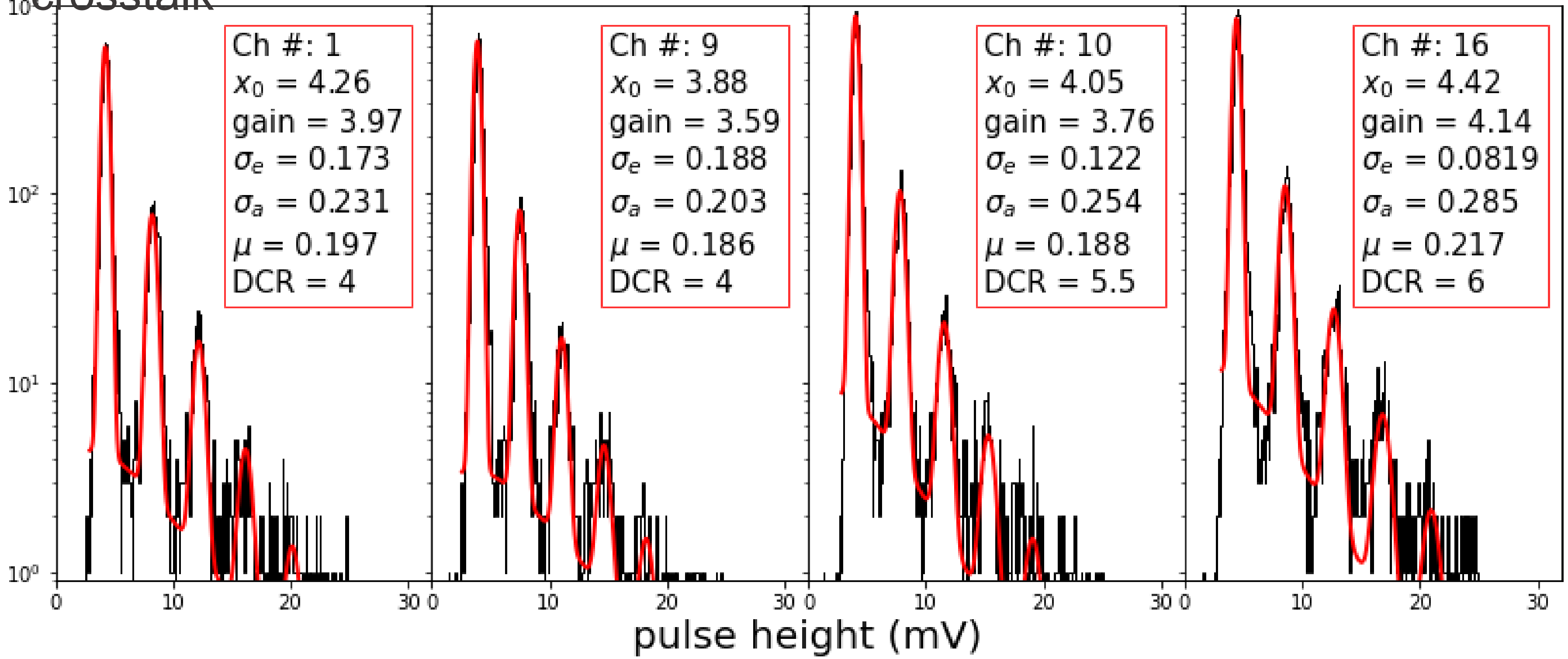
Optical crosstalk is the biggest challenge for the 2$^{nd}$ monolithic prototype.

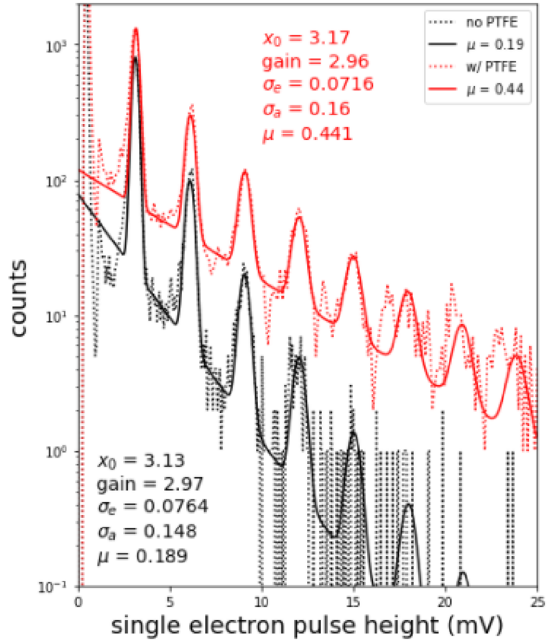
45% optical crosstalk -> 0.82 crosstalk/primary

# Dark count rate and crosstalk measurement

Dark-count data is taken from 200ns random trigger windows

Fit using Gaussian response + Borel distribution for crosstalk




Single pixel data from J. Cates @LBL.

External CT data taken by wrapping pixel in PTFE

- DCR = 2.3 MHz
- Internal CT = 0.19
- External CT =

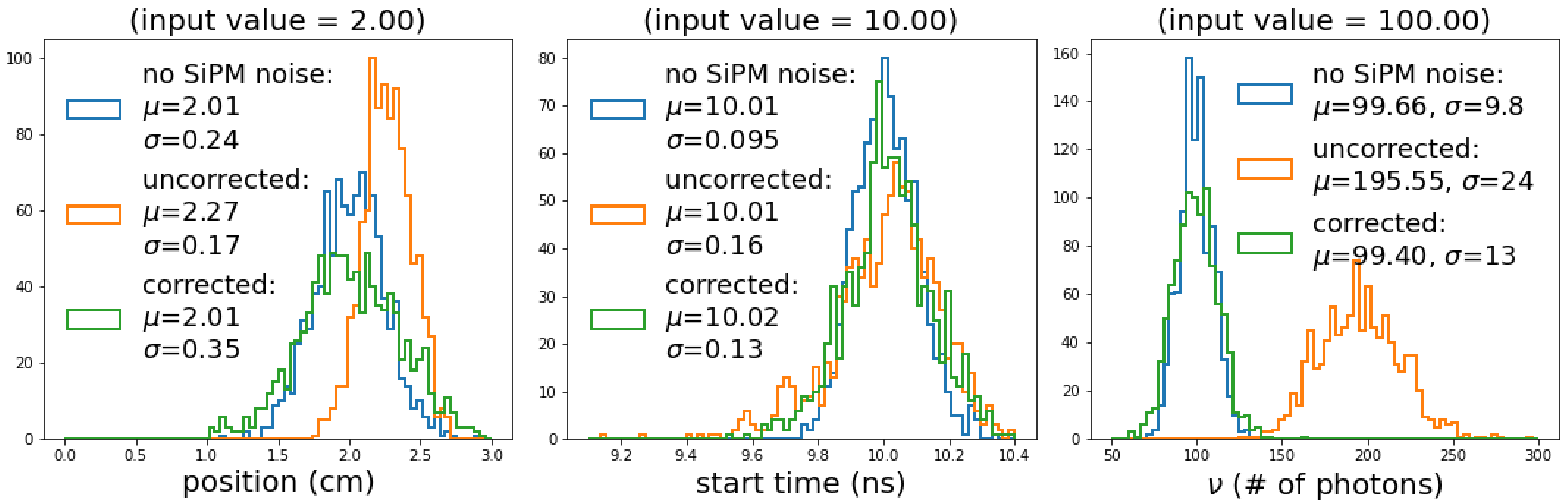
# SiPM likelihood proof of concept: 1-D model

- Need to check that likelihood model for SiPM effects works
- Run 1000 trials of simplified 1-D model, storing photon hits both before and after SiPM effects are applied
- Run 3 separate optimizations on each trial
  - Fit naïve likelihood to ideal photon set
  - Fit naïve likelihood to SiPM photon set
  - Fit adjusted likelihood to SiPM photon set

- Naïve fitting parameters are both smeared and biased by SiPM effects

**Corrected model:**

- **Removes all bias from best-fit parameters**
- **Reduces resolution by ~30%**



# Likelihood model including SiPM effects

| Symbol | Definition |
|---|---|
| $\nu$ | Total expected number of detected photons in an event. Approximately equal to $(\sum \nu_i + R\,\Delta t)/(1-\mu)$ |
| $n$ | Number of detected photons |
| $N$ | Number of interaction sites |
| $\vec{x}_j, t_j$ | Position and time of the jth interaction |
| $\nu_j$ | Expected number of events from the j[th] interaction |
| $\alpha(i), t_i$ | Pixel in which the i[th] photon was detected and its detection time |
| $G_{\alpha(i)}(\vec{x}_j)$ | Normalized probability that a photon from the j[th] interaction will be detected in the i[th] pixel |
| $F(t_i - t_j - d_{ij}/c_p)$ | Differential probability that a photon from the j[th] interaction will be detected at time $t_i$ in pixel α(i). |
| $C_{\alpha(i)}(t_i, (\vec{x}_j, t_j))$ | Unnormalized probability that a correlated count will occur a time $t_i$ in pixel α(i) given the set of interactions. |
| $\mu$ | Expected number of correlated counts per count |
| $R_{\alpha(i)}$ | Dark rate in pixel α(i) |
| $\nu$ | Total expected number of photons in an event. Approximately equal to $(\sum \nu_i + R\,\Delta t)/(1-\mu)$ |

## SiPM effect terms for pixel $\alpha$

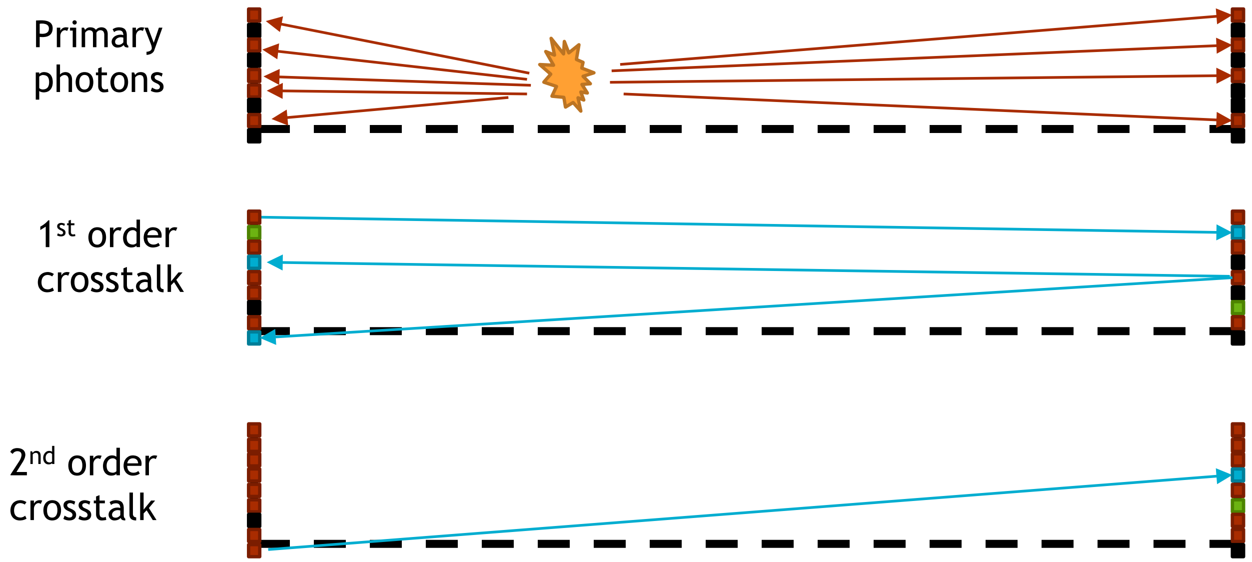
- $C_\alpha$ is the crosstalk profile
  - The characteristic parameter (μ) is equal to the expected number of additional crosstalk photons per detected photon.
  - Modeled by a Borel distribution (cascading Poisson)
  - Profile depends upon the interaction locations and times
  - Can be constructed iteratively by propagating the number of expected primary photons and crosstalk photons between all the pixels for an event set
  - Is unnormalized and has a weight of approximately $\mu\Sigma\nu_j/(1-\mu)$
- $R_\alpha$ is the dark rate
  - This is scaled by 1/(1-μ) account for crosstalk from dark counts

$$\mathcal{L} = \frac{\nu^n}{n!} e^{-\nu} \prod_{i=1}^{n} \frac{1}{\nu} \left[ \sum_{j=1}^{N} \nu_j\, \mathcal{G}_{\alpha(i)}(\vec{x}_j)\, \mathcal{F}(t_i - t_j - d_{ij}/c_p) + \mathcal{C}_{\alpha(i)}\left(t_i;\ (\vec{x}_j, t_j)\right) + \frac{R_{\alpha(i)}}{1-\mu} \right]$$

# SiPM likelihood proof of concept: 1-D model

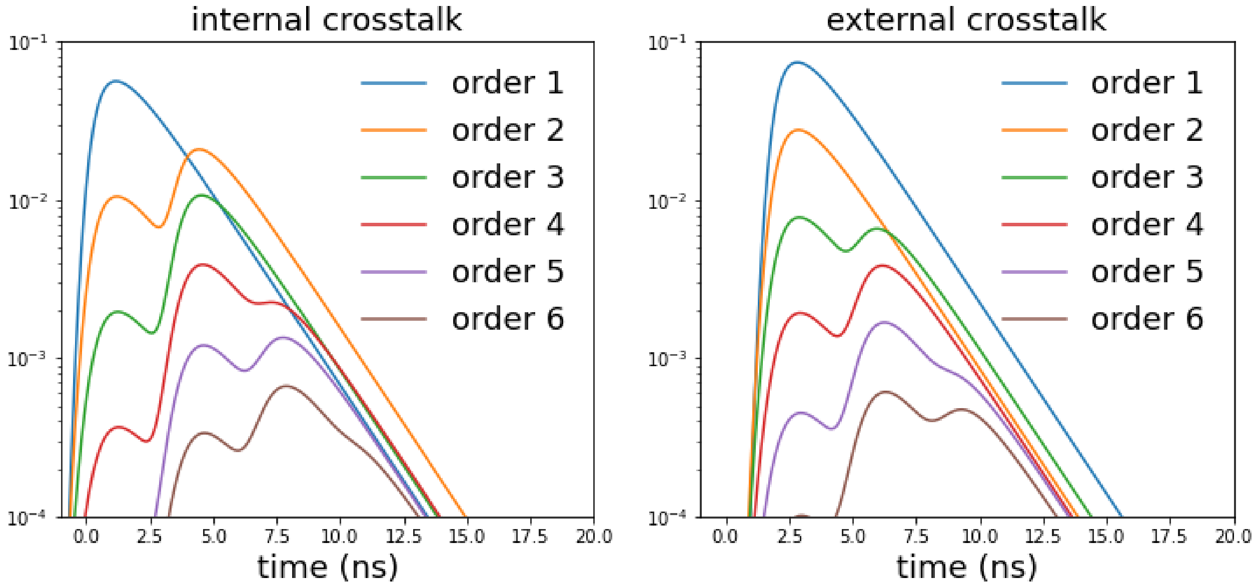
## Simplified, 1-D model

- Photon travel time is equal to $\Delta x/c_p$
- Pixel responses are linear with distance
  - $v_1 = v_S * x0/L$
  - $v_2 = v_S * (L - x0)/L$
- SPTR is 200ps
- EJ204-like pulse generated at x = 2cm
  - rise time = 0.7ns
  - fall time = 1.8ns




## Crosstalk profile is generated iteratively.

- First order internal and external crosstalk profile is generated for both pixels based on expected scintillation response
- $N^{th}$ order photons are calculated based on $(N-1)^{th}$ crosstalk profile
- 10 orders were used in the fit




First 6 orders of crosstalk. Speed of light is reduced to 3 cm/ns to resolve external and internal contributions

# After-pulsing/Delayed Crosstalk

Quantify after-pulsing and delayed crosstalk together (hard to separate the two)

Take set of 10,000 random triggers (200ns windows)

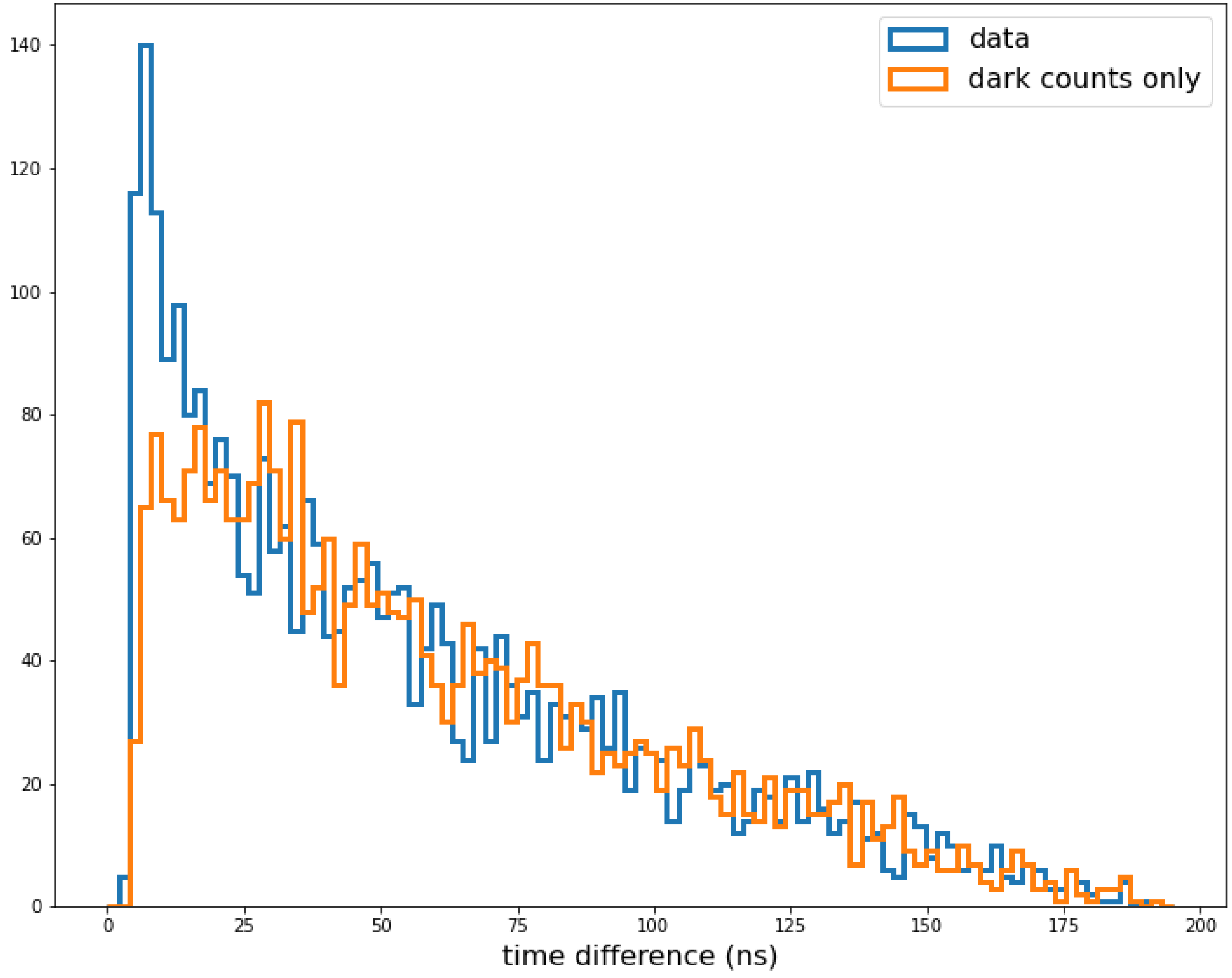
Look at time differences between peaks in the windows

After-pulsing/delayed crosstalk should create excess at low time separations above what is expected from dark counts alone.

Generate 10,000 simulated dark-count windows, drawing Poisson number of peaks and distributing uniformly

**Excess of ~300 events at low time separation indicates an after-pulsing probability of ~3%.**

Not expected to be a dominant source of noise



# Hub Board and Front End Trigger Board

Front End Trigger Board:

- Distributes SiPM and amplifier bias
- Fans in the sum signals from the 8 2x8 SiPM boards
- Combines the sum signals for triggering
- Optional on-board comparator for simple threshold trigger
- Fans out trigger logic signal to SiPM boards


Back end hub board

- In hand, but not yet implemented
- Provides clock sync between 8 SCEMAs
- Takes in individual SCEMA triggers for coincidence logic
- Can distribute trigger signal back to SCEMA

# Adding Capacitors

Method:

- Scrape silk screen off of vias using tweezers
- Tin vias with solder
- Solder 1uf 0402 caps between ground vias and V_n vias on each DRS4 channel
- Check resistance and capacitance between ground and V_n to ensure there are no solder bridges or cold joints