DarkQuest EMCal Calibration Studies

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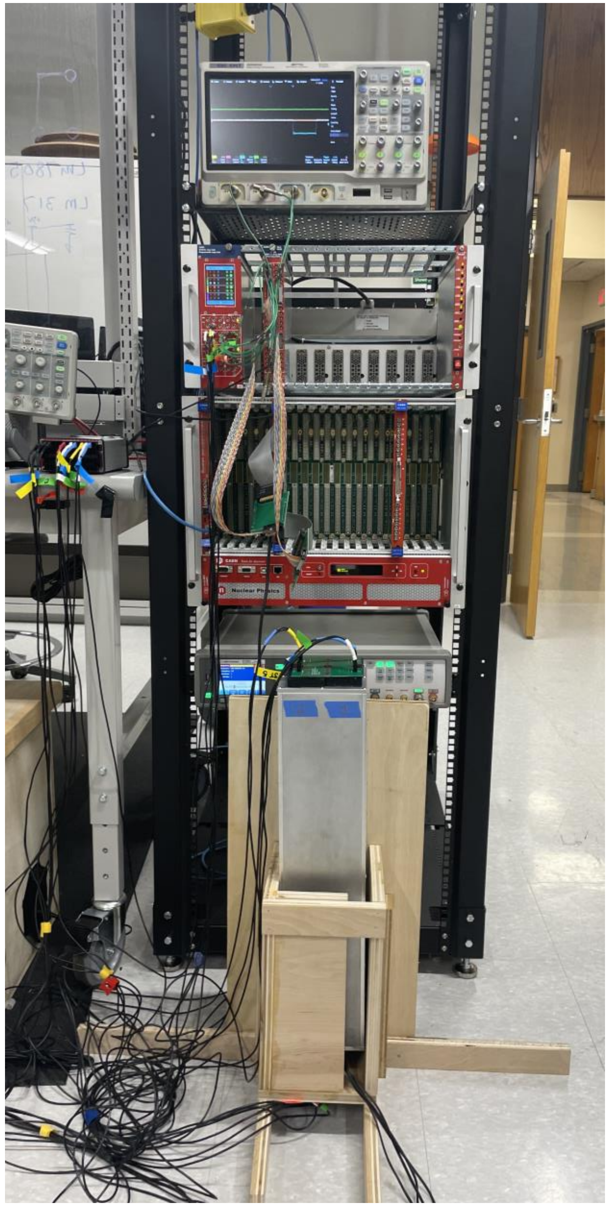
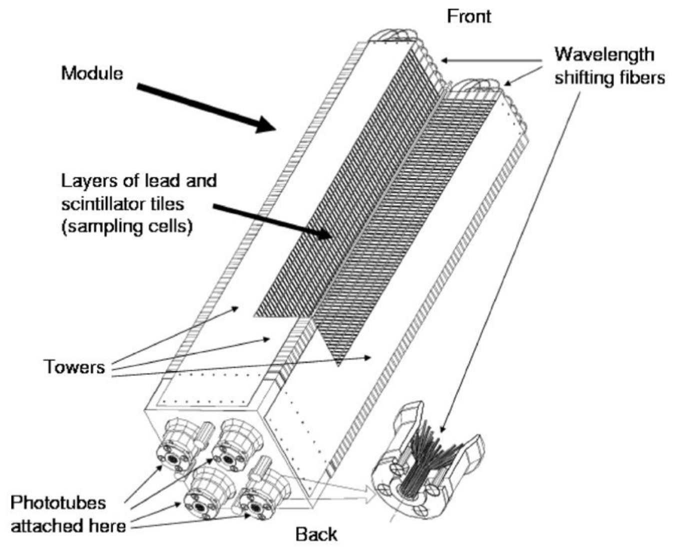
Calibration Overview

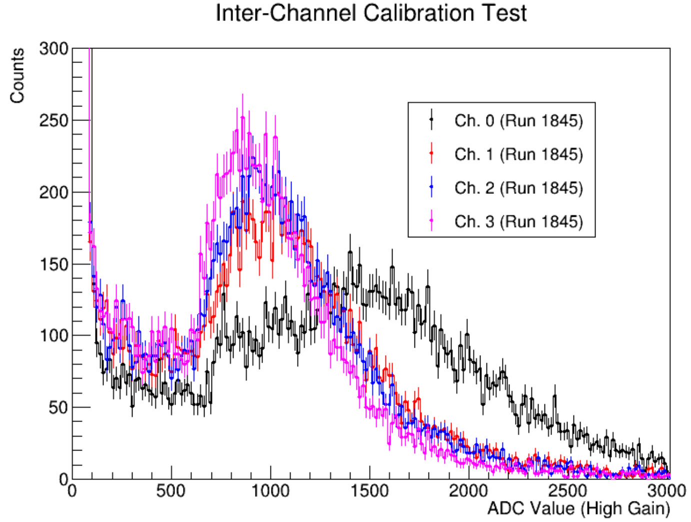
- BU has one module of the PHENIX EMCal, which we use as a cosmic ray test stand
- Calibration studies include:
    1. Inter-calibration of the four channels
    2. Absolute energy calibration
    3. SiPM calibration with an LED pulser
- The detector produces a lot of light (~12,500 photons/GeV), so in order to prevent saturation of the SiPM and the CAEN readout electronics, we're pursuing various means of electrical and optical attenuation
- The goal is to maximize both the dynamic range of the detector and its resolution



Inter-Channel Calibration

- Due to non-uniformities in the detector, each channel (tower) produces a different amount of light in response to the same energy deposition
  - Radiation damage/loss of transparency, broken fibers
- It is necessary to inter-calibrate the channels: adjust the gain channel to ensure the same response
- There are two ways to adjust the gain of the SiPM: by changing the bias voltage or the “gain setting”—we chose to adjust gain setting
- For the purposes of this calibration, we self-trigger the EMCal on cosmic rays





Cosmic ray energy distributions before calibration

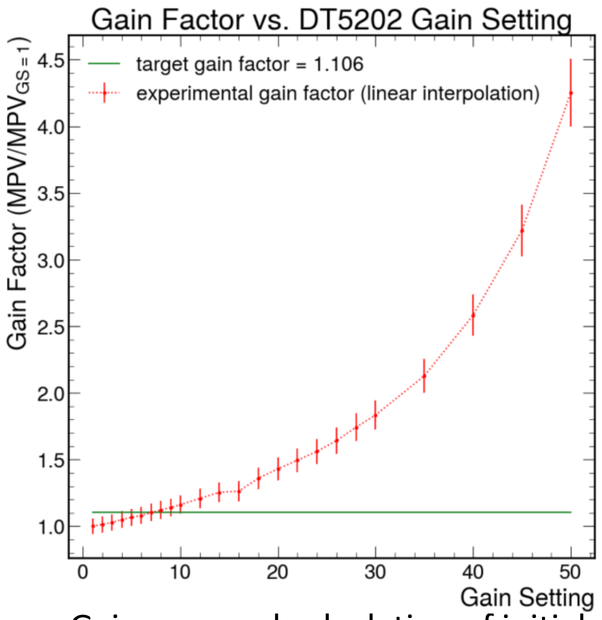
Inter-Channel Calibration

- Calibrated by adjusting gain to align cosmic ray energy distributions (self-triggering on all four channels)

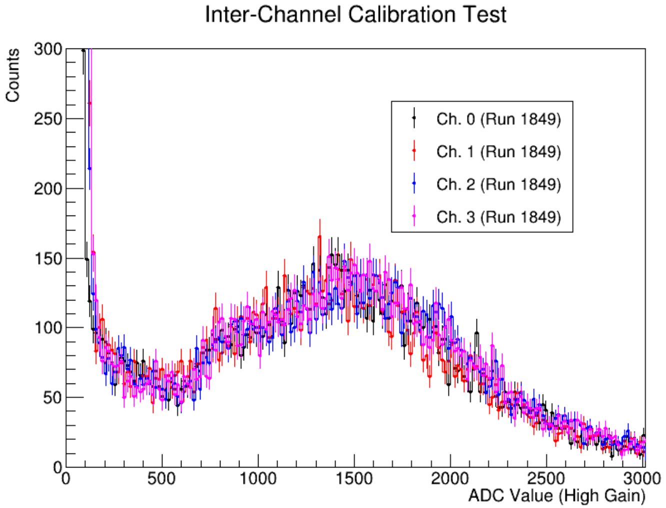
Calibration method

1. Take an initial run with gain set to 1 for all channels
2. Determine an initial calibration by calculating the gain factor necessary to align MIP peaks, and finding the corresponding gain setting
3. Scan gain settings around calculated setting
4. For each channel, calculate closest gain setting to achieve desired MIP peak

Channel	0	1	2	3
Gain Setting	1	21	24	27
Average ADC	1596 ± 8	1580 ± 8	1599 ± 7	1595 ± 7



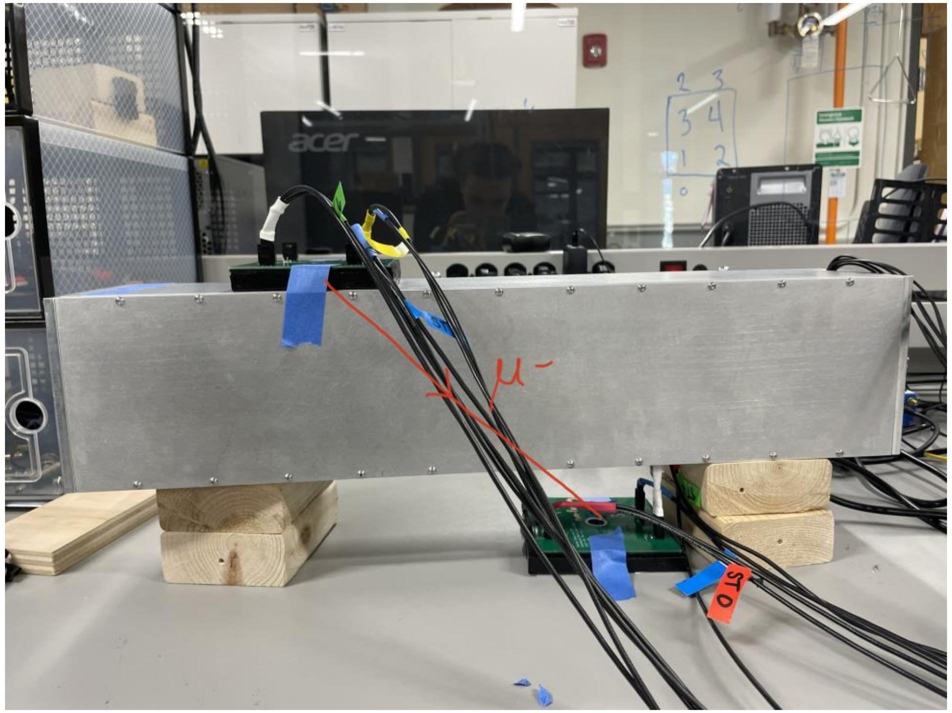
Gain scan and calculation of initial gain setting



MIP energy distributions for four channels after calibration

Absolute Energy Calibration

- We performed a rough absolute energy calibration with cosmic muons
- Using the mini-DP hodoscope coincidence trigger, we can fix the path length of muons through the detector
- By varying the configuration of the CosmicWatches and calculating the theoretical energy deposition for each configuration, we can determine a relationship between energy deposited and ADC



Theoretical Energy Deposition

- We use the Bethe-Bloch equation (omitting the density and shell corrections) to find energy deposited per unit path length

$$\left\langle -\frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I^2} T_{max} \right) - 2\beta^2 \right]$$

- We assume momentum to be 4 GeV (not MIP momentum), the average momentum of a cosmic ray muon [Ref.]
- Each cell in the tower is composed of 0.15 cm lead and 0.40 cm polystyrene scintillator

$$\left\langle -\frac{dE}{dx} \right\rangle_{\text{Pb, 4 GeV}} = 16.60 \text{ MeV/cm}$$

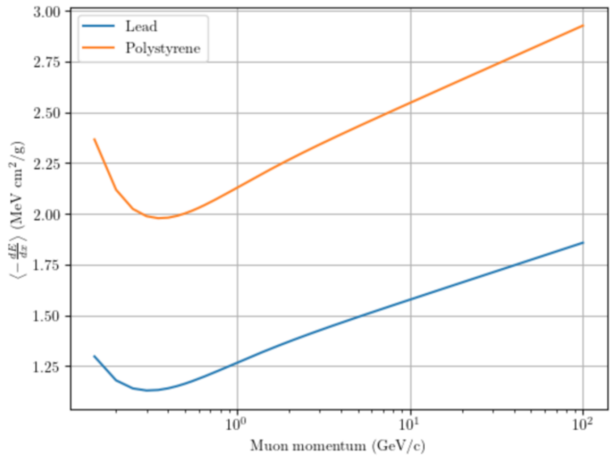
$$\left\langle -\frac{dE}{dx} \right\rangle_{\text{PS, 4 GeV}} = 2.51 \text{ MeV/cm}$$

$$\left\langle -\frac{dE}{dx} \right\rangle_{\text{combined}} = 6.24 \text{ MeV/cm}$$

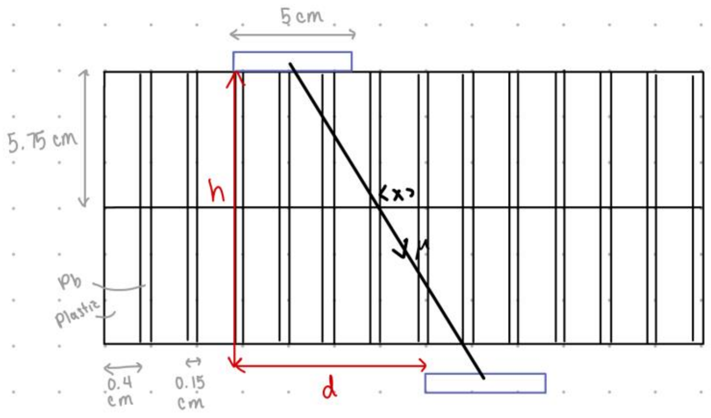
- The path length through one tower is given by

$$\langle x \rangle \approx \frac{\sqrt{h^2 + d^2}}{h} * 5.535 \text{ cm}$$

- We find a cosmic muon deposits 34.5 MeV passing through a tower laterally, 230.6 MeV longitudinally
- Error of ~15% compared to experimental values obtained in PHENIX EMCal paper: 38 MeV (lateral), 270 MeV (longitudinal)

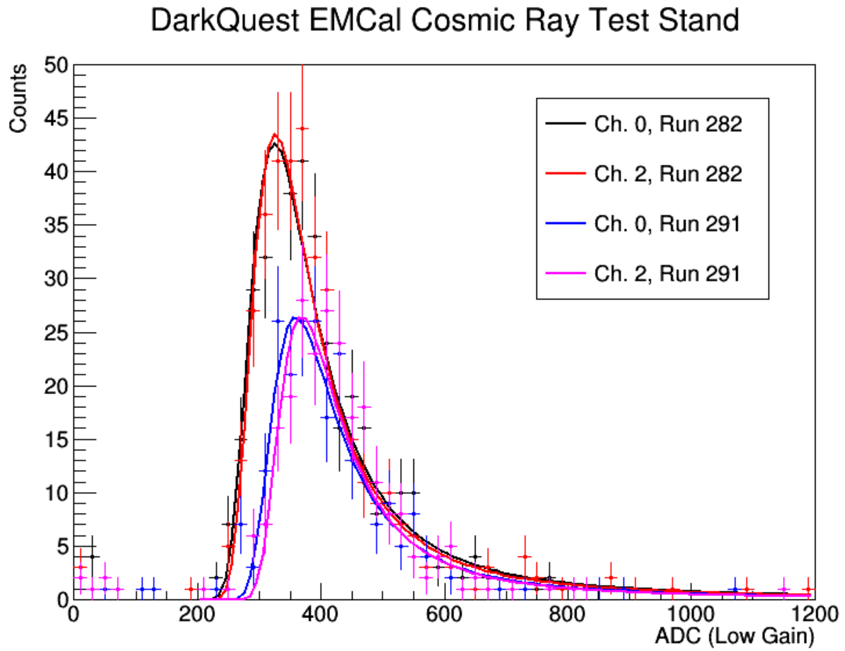


Theoretical energy deposition vs. momentum

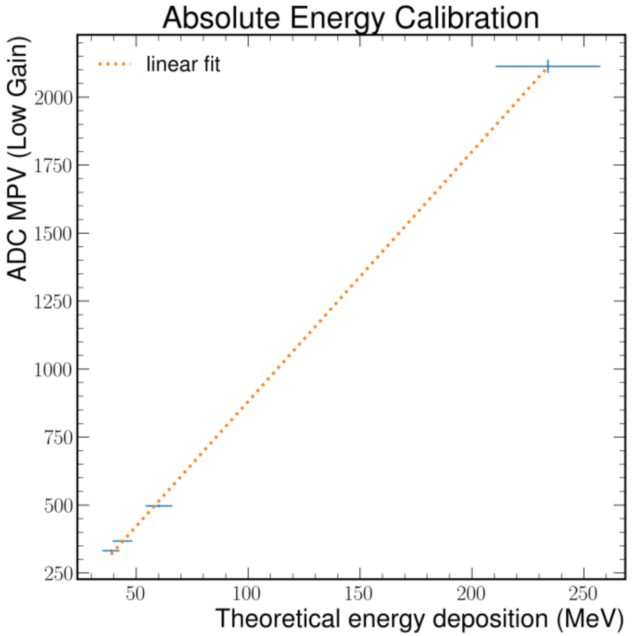


Path of a cosmic ray muon through EMCal, fixed by coincidence trigger

Absolute Energy Calibration



Runs with two different configurations of hodoscope stations, fitted to a Landau distribution

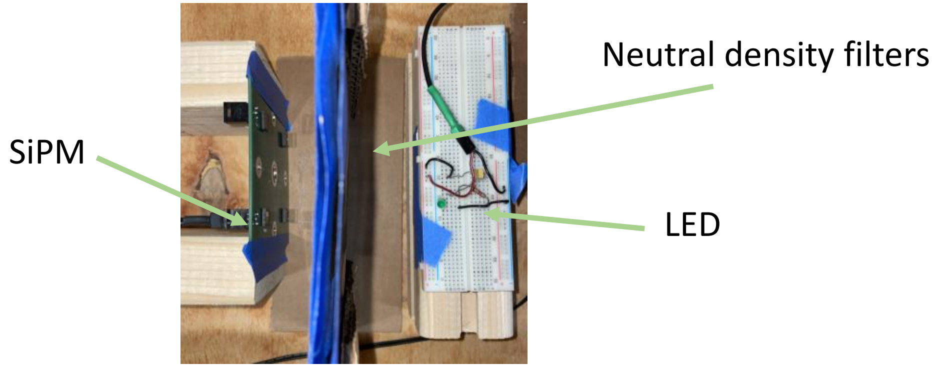


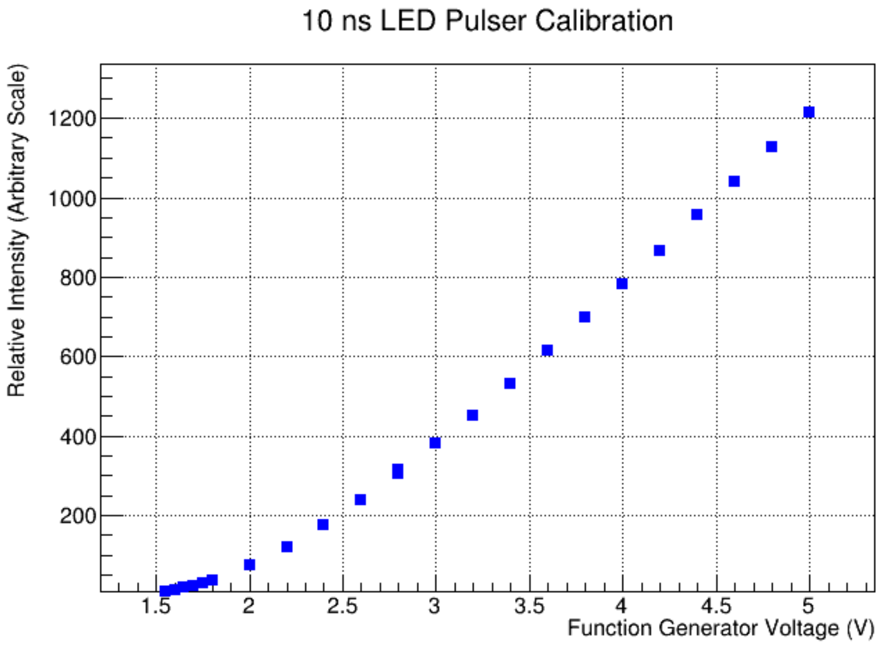
ADC-energy calibration. Each point is a run with hodoscope stations in a different orientation.

- We obtain an ADC-energy calibration that is linear in the low energy range
- Next question: how to extrapolate from this to predict the detector response at higher energies

LED Pulser Calibration

- By scanning the amplitude of the voltage pulse we use to drive the LED, we can vary intensity
- Using a SiPM and the LED in a darkbox, obtained a relative intensity calibration of LED—this calibration relies on the linearity of the SiPM response in low light
- Problem: we want to calibrate LED at high light levels, but during the calibration we need to stay in the low light, linear region of the SiPM
- Solution: add neutral density filters at higher voltages/intensities
  - Take a run before and after adding filters to determine factor by which to scale intensity
- Result is a voltage-relative intensity calibration of our green LED

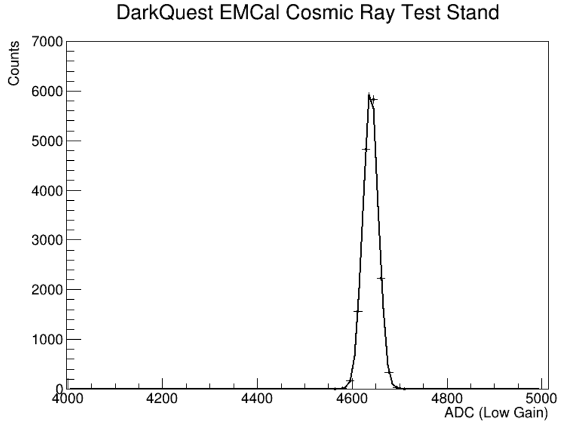




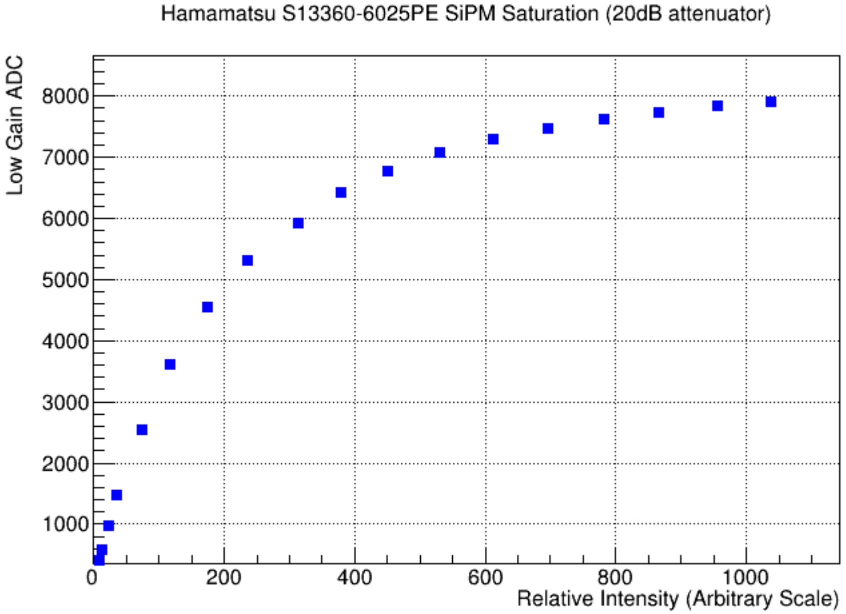
LED pulser calibration. Each point is a 30-second run; function generator voltage changes between runs.

SiPM Calibration and Saturation

- We do not expect SiPM response to be linear for all energies; as more photons are incident on the face of the SiPM, some photons hit pixels that have already fired
- In order to study this saturation behavior, carried out experiments with calibrated LED and SiPM in darkbox
- Varied LED intensity and measured SiPM response

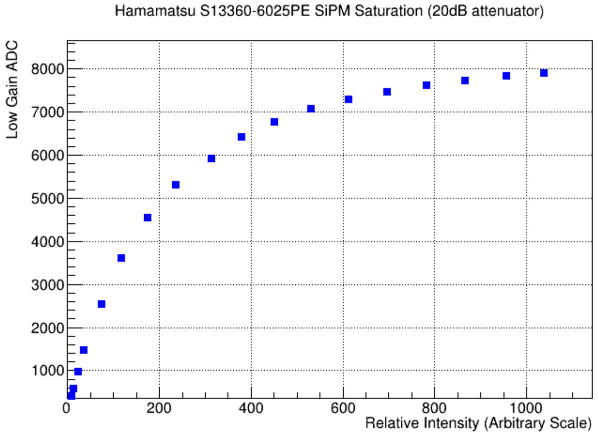


Run used in SiPM calibration: function generator voltage 4.2 V

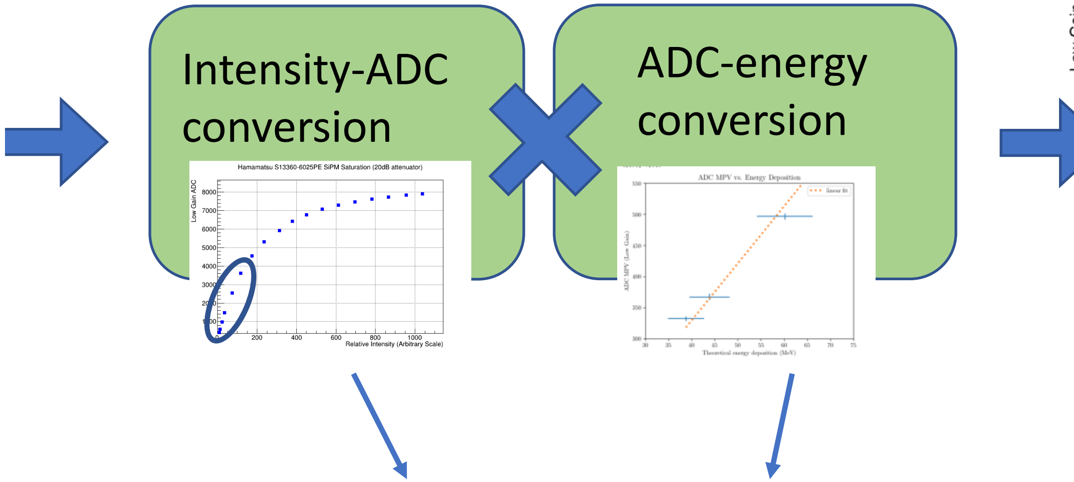


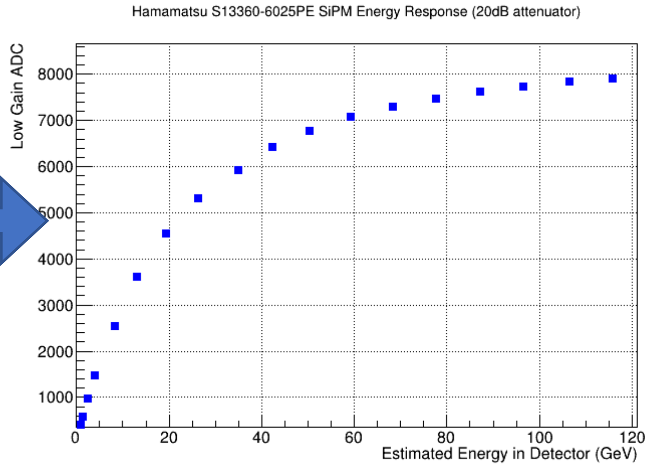
SiPM Energy Response

Using our absolute energy calibration and relying on the linearity of the SiPM in the low light region, it is possible to convert between relative intensity and energy to obtain a SiPM saturation curve in terms of equivalent EMCal energy.



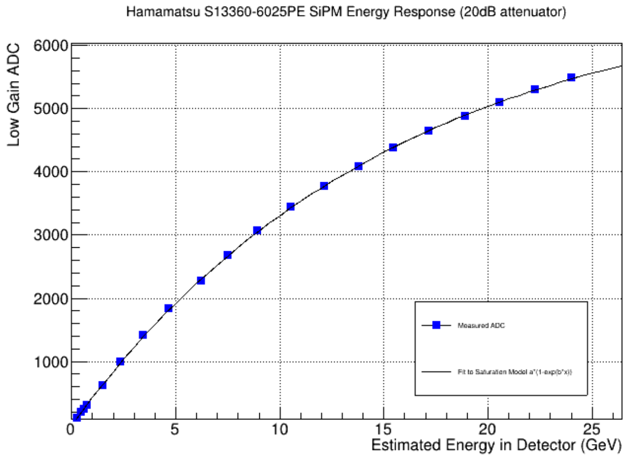
Conversion factor

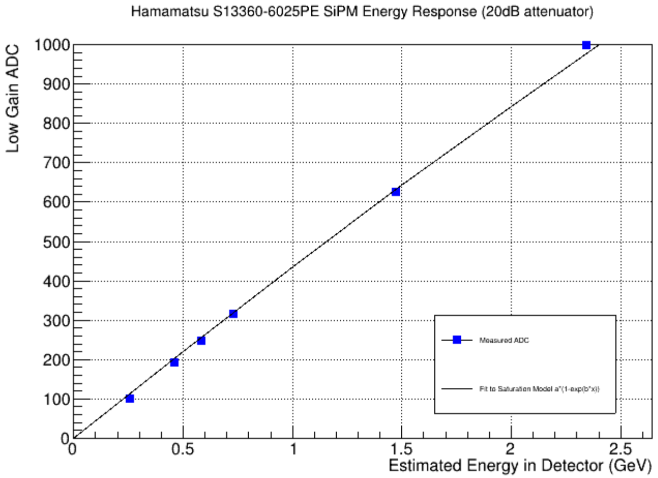




$$E_i = I_i * \left(\frac{\mathrm{ADC}_0}{I_0}\right) * \left(\frac{dE}{\mathrm{dADC}}\right)$$

SiPM Saturation Model





- Our saturation curves fit well to the SiPM saturation model:

$$\text{ADC} = a\left(1 - \exp\left(\frac{-\text{PDE} * n_{\text{photons}}}{n_{\text{pixels}}}\right)\right)$$

$$\text{ADC} = a\,(1 - \exp\,(-b * E))\,, \quad b = \frac{PDE}{n_{\text{pixels}}} * \frac{n_{\text{photons}}}{E}$$

- We can compare the fitted exponential parameter, b, to a theoretical estimate calculated using the photon detection efficiency (PDE) given by Hamamatsu (25%) [ref.], the number of SiPM pixels (57,600), and the energy-light conversion given by PHENIX (12,500 photons/GeV) [ref.]

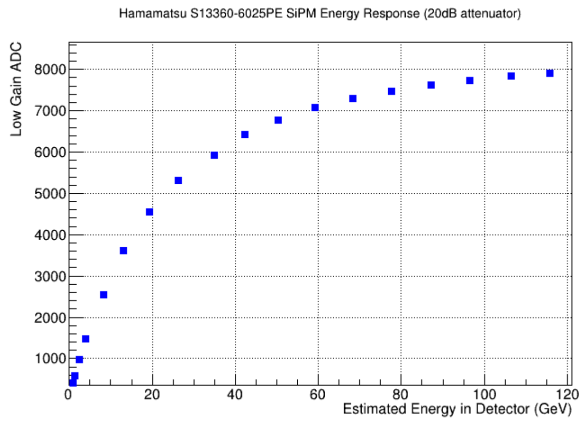
$$b_{\text{measured}} = 6.49 * 10^{-2}\text{GeV}\ ,\ \ b_{theoretical} = 5.43 * 10^{-2}\text{GeV}$$

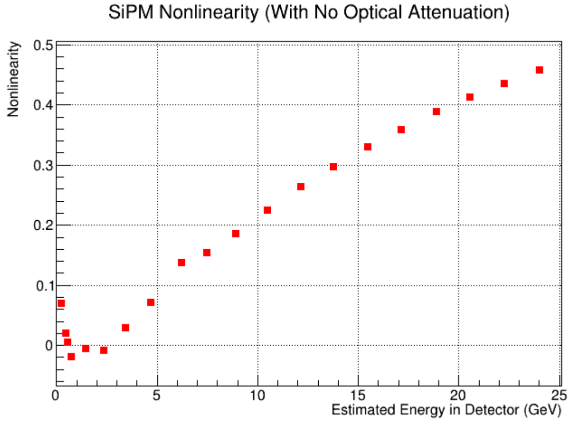
SiPM Nonlinearity

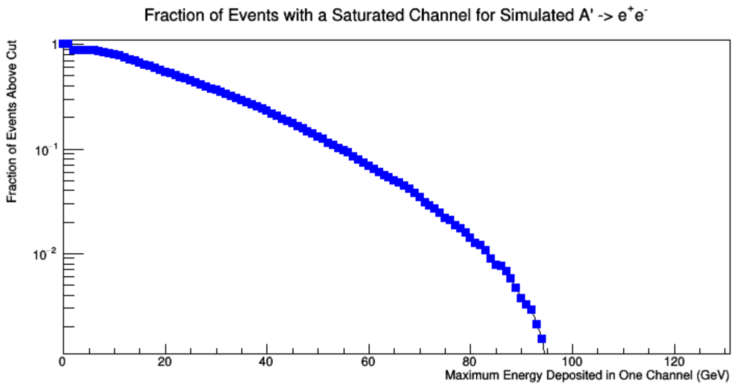
- We can see from our saturation curve that the SiPM response becomes nonlinear around 10 GeV
- Nonlinearity is a problem because:
  1. As the saturation curve flattens, we lose resolution

$$\sigma_E = \left(\frac{dE}{d\mathrm{ADC}}\right)\sigma_{\mathrm{ADC}}$$

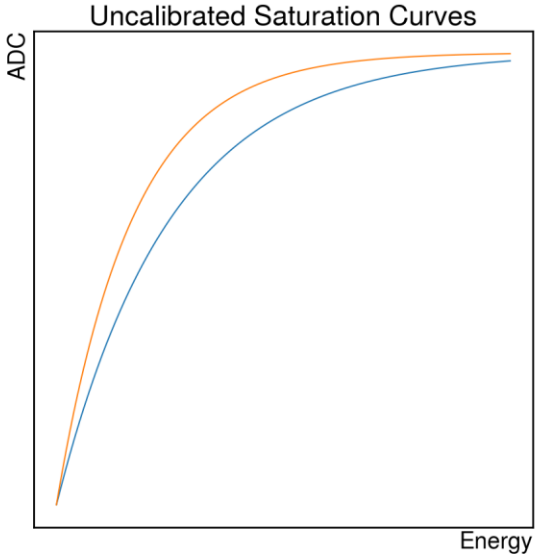
  2. We can't inter-calibrate non-linear curves by gain adjustment (next slide)
  3. It becomes difficult to do calculations involving energy online (though this may be unnecessary)
- About 1% of simulated A' → e^+e^- events have a channel with energy deposition > 80 GeV

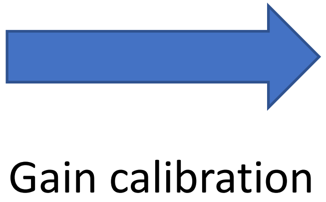


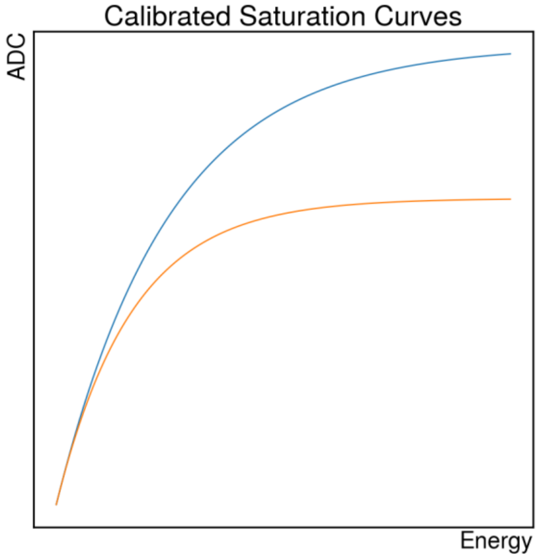




A Note on Inter-Calibration



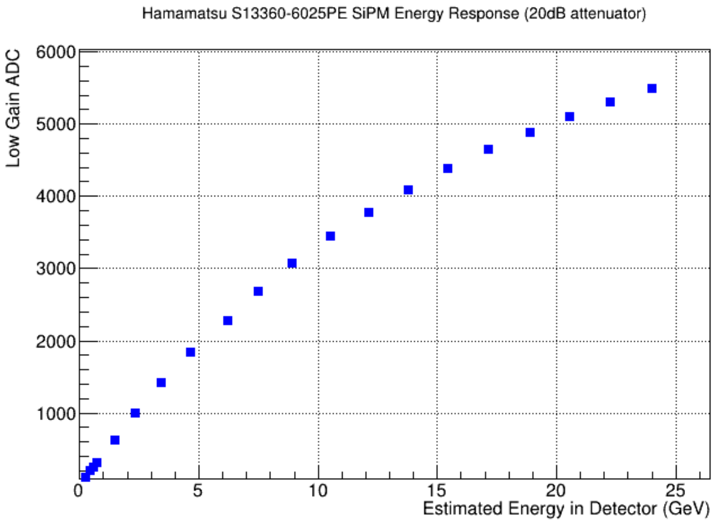


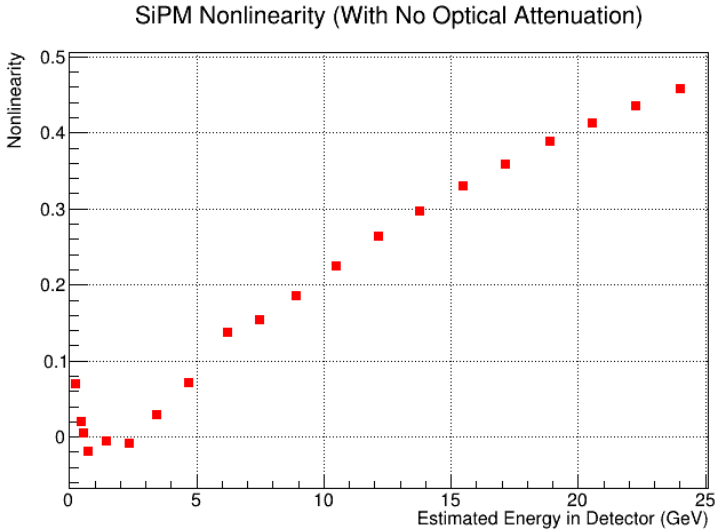


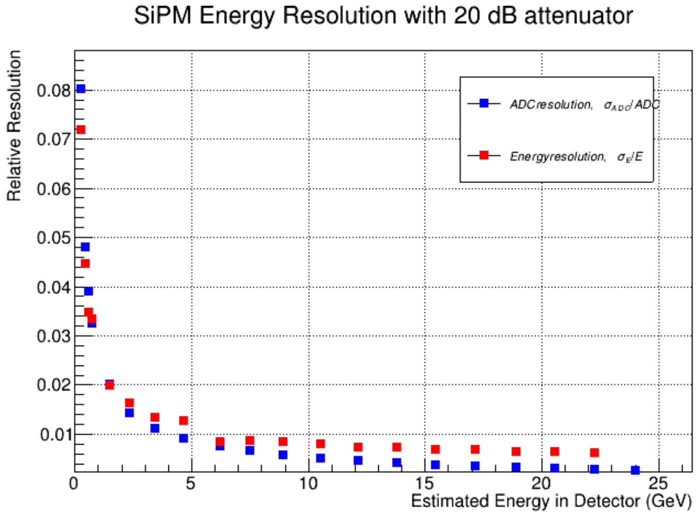
$$\mathrm{ADC} = a\left(1 - \exp\left(\frac{-\mathrm{PDE} * n_{\mathrm{photons}}}{n_{\mathrm{pixels}}}\right)\right)$$

Whereas the towers differ in their photon detection efficiency, gain calibration only changes the overall factor *a* to align the linear region of the saturation curves .

Optical Attenuation





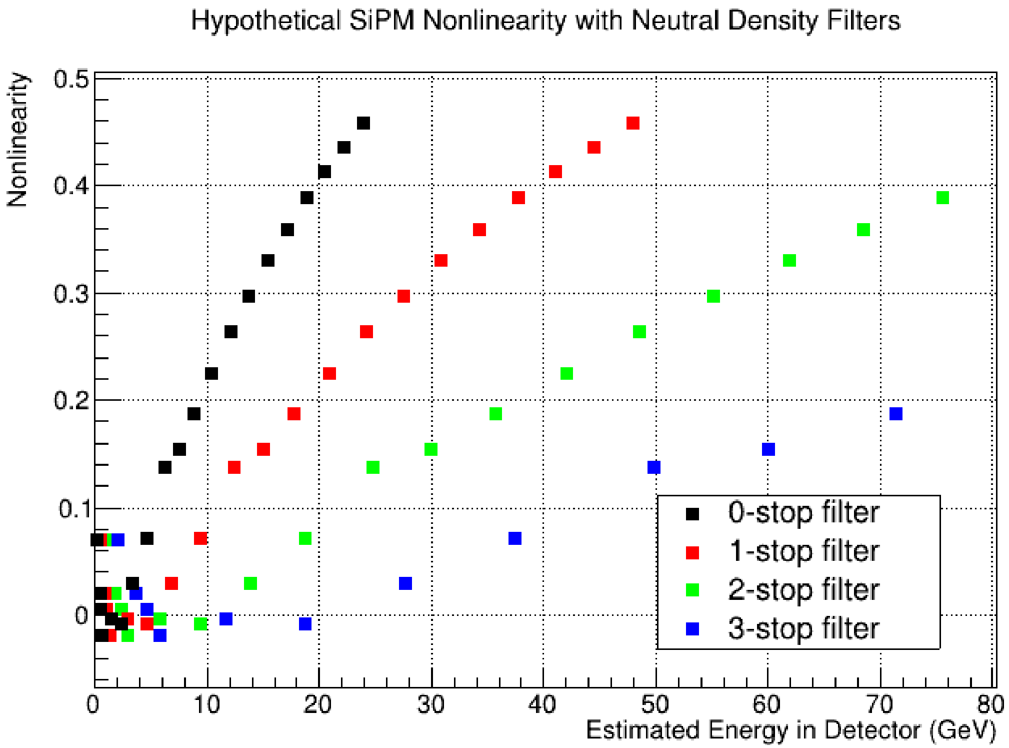


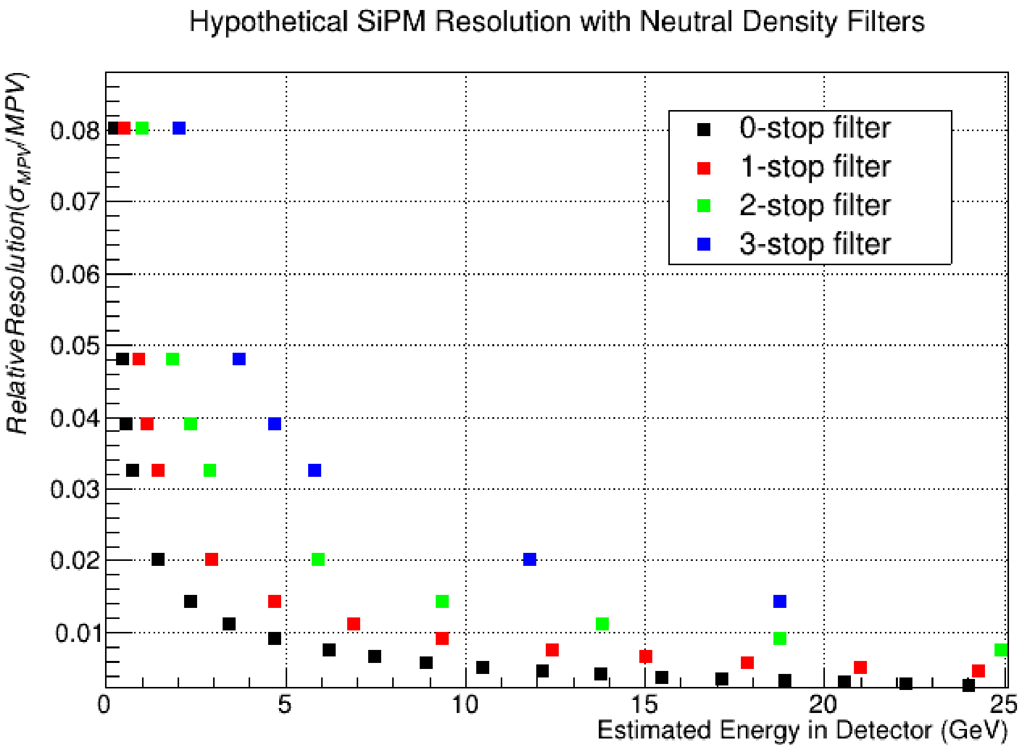
- In order to increase the linear range of the EMCal, we're considering placing a neutral-density filter between the light-collecting fiber bundle and the SiPM
- However, as we decrease the amount of light, we sacrifice resolution

$$\sigma \propto \frac{1}{\sqrt{n_{\text{photons}}}}$$

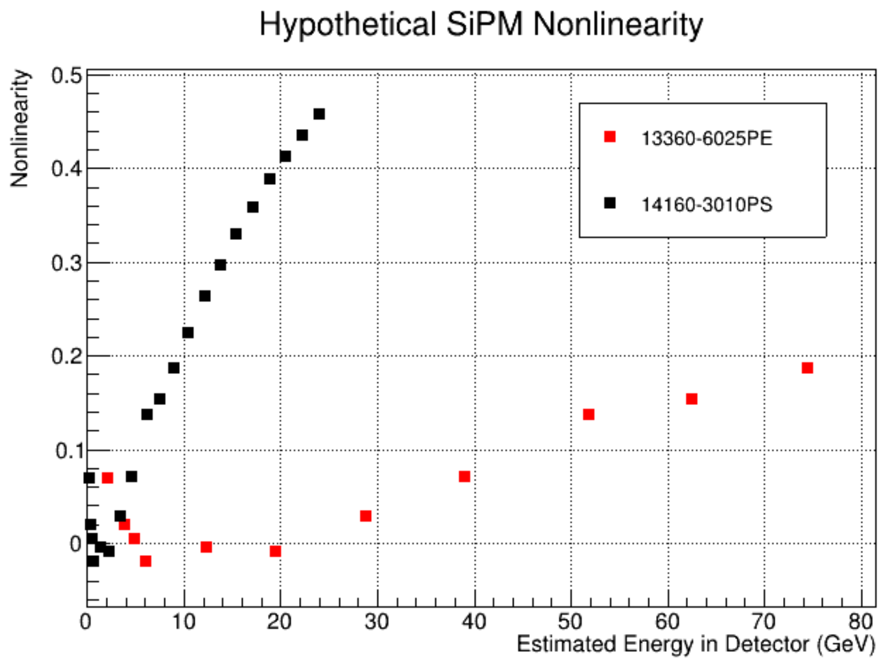
- Another option: buy a SiPM (or SiPM array) with more pixels

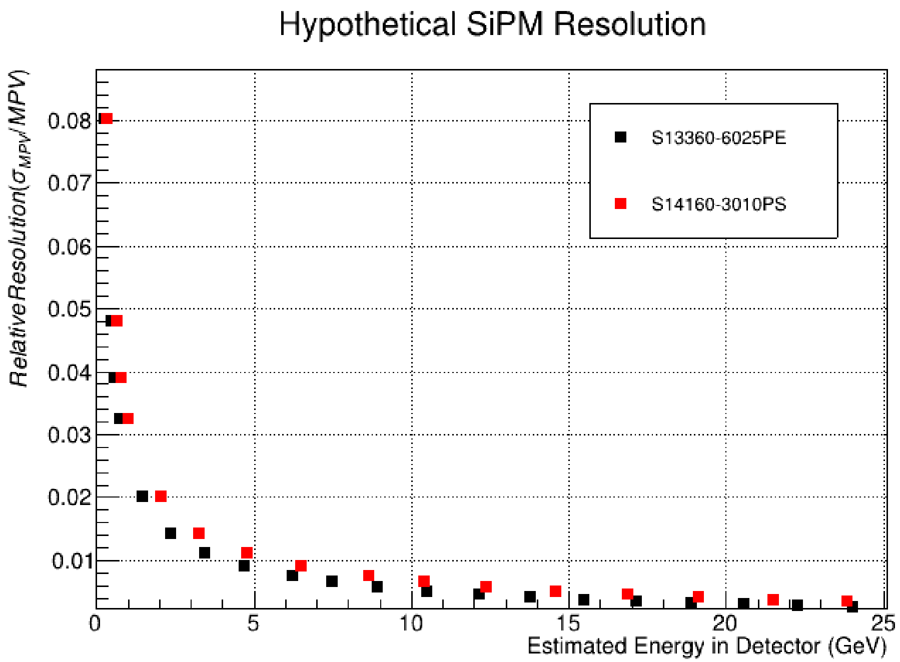
Optical Attenuation: Hypothetical Picture





New SiPM: Hypothetical Picture





Current SiPM: Hamamatsu S13360-6025PE

- 57,600 pixels, 6 x 6 mm^2, 25% PDE

Alternative SiPM: Hamamatsu S14160-3010PS

- 89,984 pixels, 3 x 3 mm^2, 18% PDE
- A 4 x 4 array would have 360,000 pixels—factor of ~6 more

Summary

- We have performed a rough energy calibration of the EMCal
- We estimated a dynamic range have a lower bound on resolution
- We could explore an alternative option for the SiPM, as long as it's not cost-prohibitive
- The test stand is ready for the test beam, with any of the options for electrical or optical attenuation we've shown