Evaluation of the Performance of SiPM-on-Tiles at the End of Life of the CMS HGCAL Upgrade

Phase-II Upgrade of the CMS Endcap Calorimeters

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CMS

FTX

DESY.

Overview

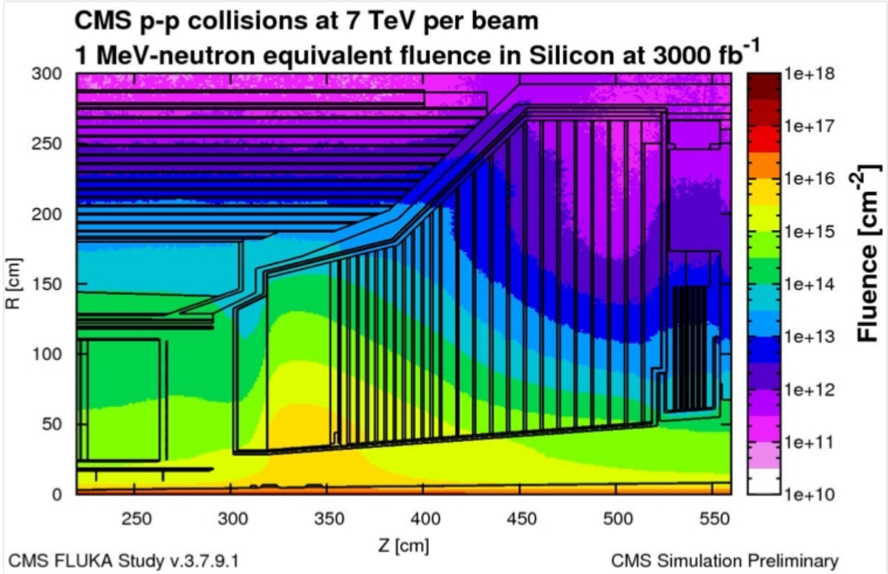
Evaluation of the Performance of SiPM-on-Tiles at the End Of Life of the CMS HGCAL Upgrade

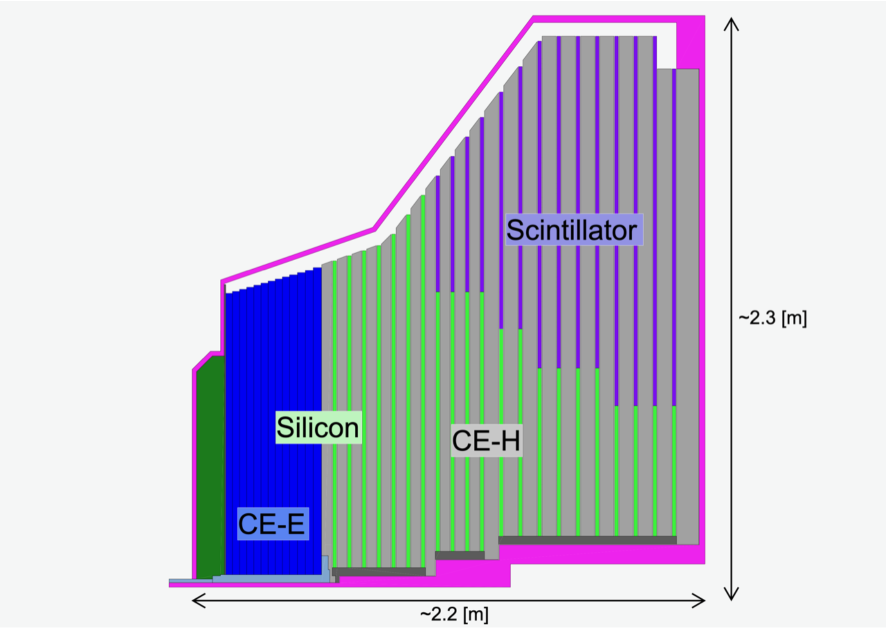
- Introduction to the CMS HGCAL Upgrade
  - Scintillator Section of the HGCAL Upgrade
- Signal-to-Noise Requirement for the Scintillator Section
- Model, Data Acquisition and Results used for SNR Extrapolations
- Updated Signal-to-Noise Ratios at end of life
- Summary

High Granularity for the High Luminosity LHC

Phase II Upgrade of the CMS Endcap Calorimeter (HGCAL)

- HL-LHC aims to achieve an integrated luminosity of 3000 fb^{-1} by its end of life
  - **Ten times higher** than the LHC
  - Poses significant challenges for radiation tolerance and event pileup on detectors
- CMS endcap calorimeter to be replaced with a **5D (imaging) calorimeter using particle flow**
- The active area of CMS endcap calorimeter (HGCAL) will consist of:
  - silicon detector section
  - **scintillator section: where radiation levels permit (neutron fluence < 5×10^{13} n/cm^2)**

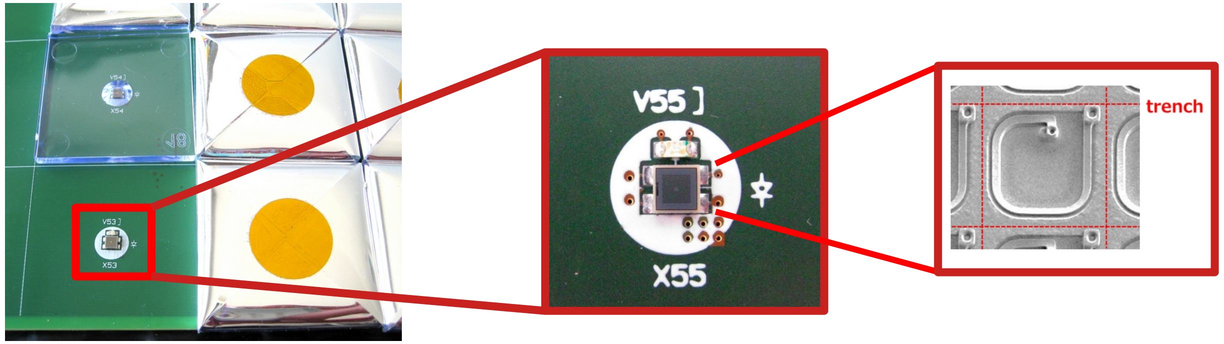




Scintillator Component of the Hadronic Endcap Calorimeter

SiPM-on-Tile Based Read-out

- SiPM-on-tiles consist of individually wrapped plastic scintillator tiles placed on silicon photomultipliers (SiPM)

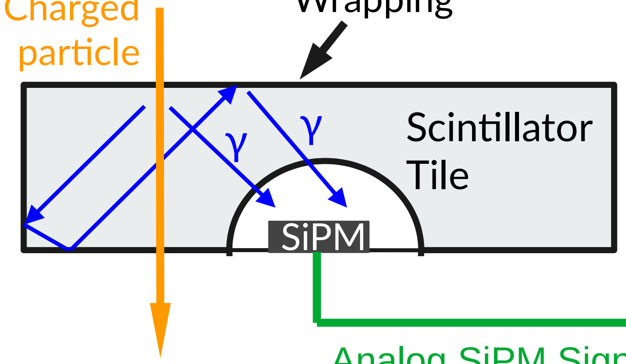


SiPM consists of 1000s of Single Photon Avalanche Diode (SPAD)

- The signals from SiPM-on-tiles are read out by the HGCROC front end electronic ASIC

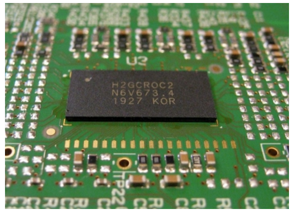
Reflective Foil Wrapping

Charged particle



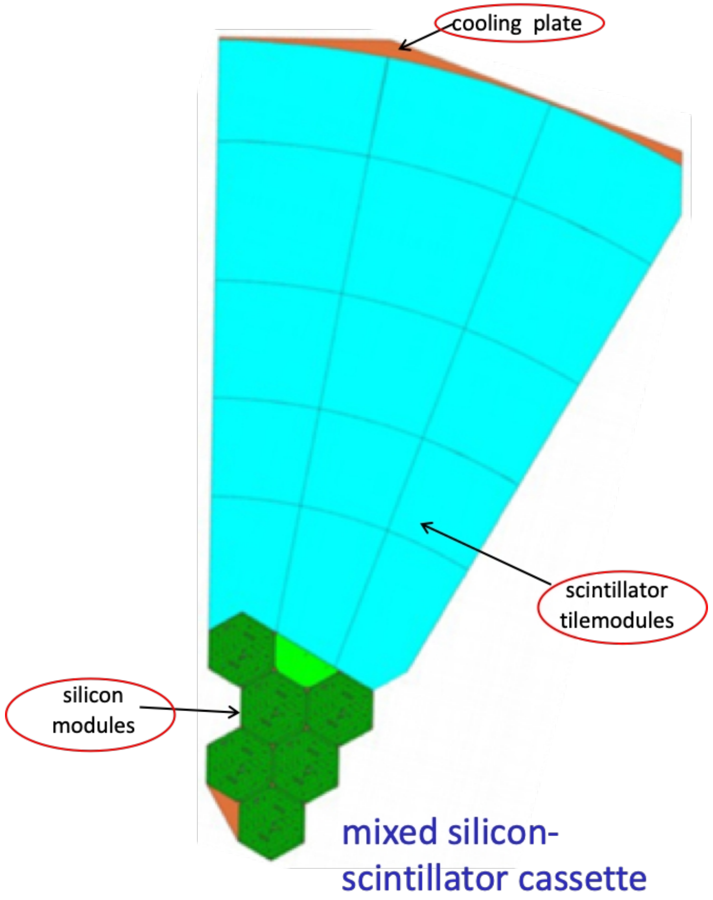
Analog SiPM Signal

HGCROC
(HGCAL Read Out Chip)
Mixed-Signal ASIC



Signal Amplification And Digitization

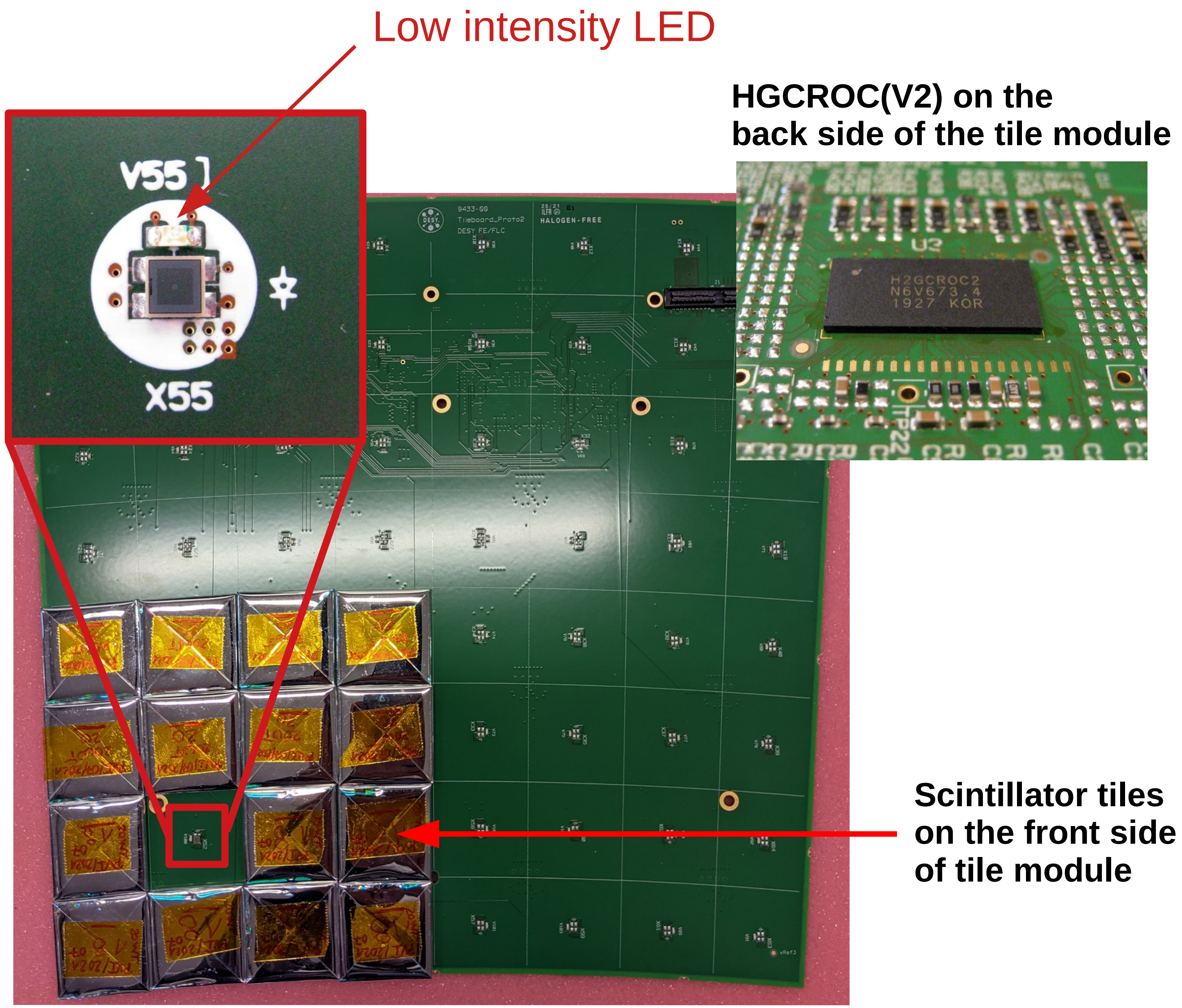
Digital Output Data



CMS HGCAL Tile Module

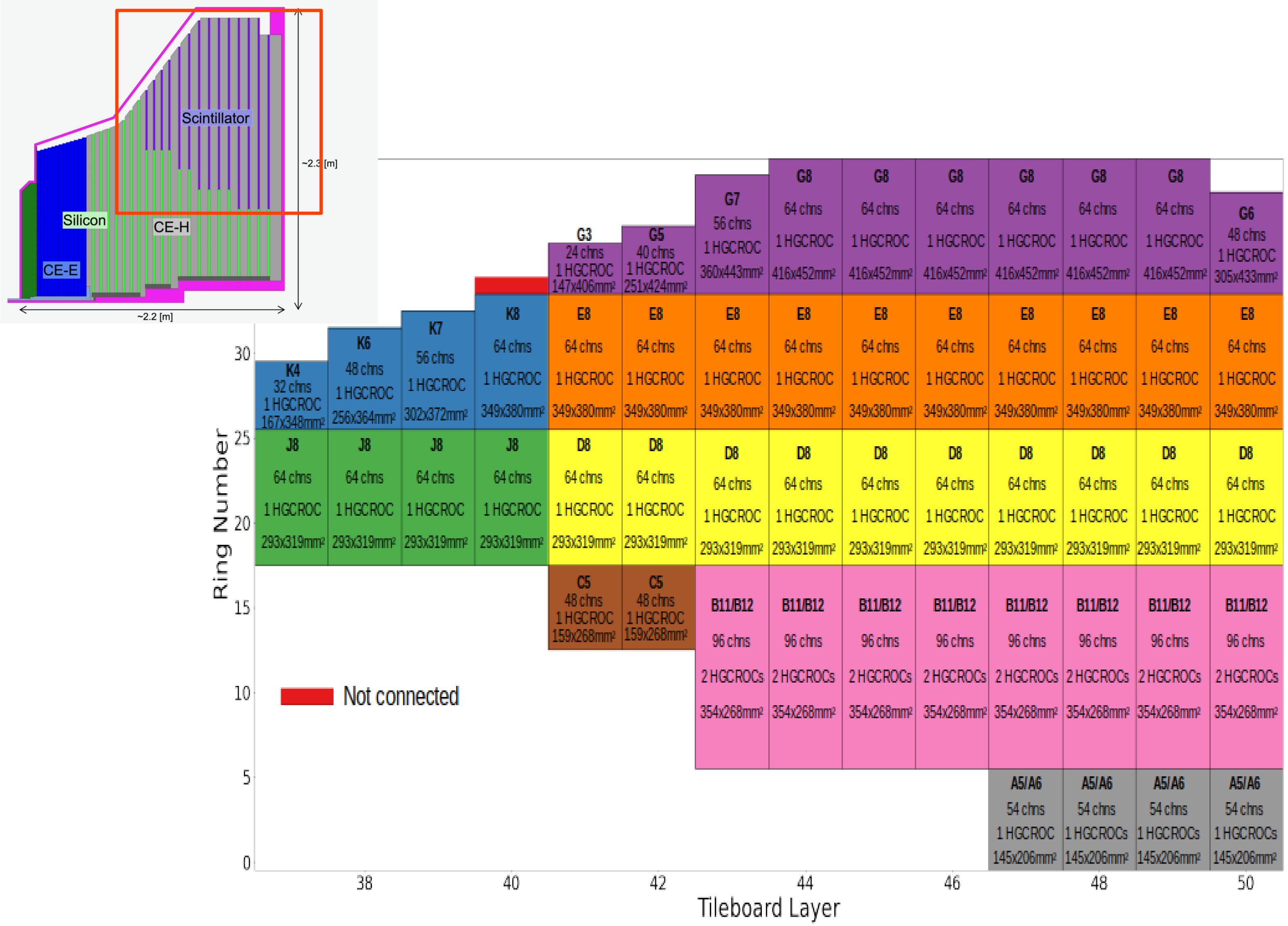
For the Scintillator Section of the CMS HGCAL

- The **basic detector unit** in the SiPM-on-tile section is the **tile module**.
- Consists of a PCB, HGCROC, SiPMs, scintilators and other on-board electronic systems.
- Most tile modules will hold one HGCROC
- HGCROC can reads out up to 72 channels simultaneously.



Current Tile Module Plans For the HGCAL Scintillator Section

Tile Module Layout in a 10° Sector



- **8 tileboard types cover the entire area**
  - Includes 35 tileboard variants
- More than 240,000 SiPM-on-tile channels
- **Scintillator tiles:**
  - 21 different tile sizes
  - 23 mm to 55 mm side length
  - Covering an area of 340 m²
- **SiPMs:** Hamamatsu HDR-2, 15 µm pitch sized SiPMs with custom radiation hard packaging with good thermal conductivity
  - 2x2 mm² active area SiPMs
  - 3x3 mm² active area SiPMs

Signal-to-Noise Requirement for Scintillator Section of HGCAL

At End-of-Life : integrated luminosity of 3000 fb^{-1}

- Minimum ionizing particles (MIP) will be used as a standard candle for energy calibration for each SiPM-on-tile until end of life

- SiPM-on-tiles are not as radiation hard as silicon sensors:
  - Will be used in areas where a **signal-to-noise ratio (SNR) > 3 for MIPs** can be maintained

- **Mathematical model used to predict the SNR at end of life:**
  - SiPM-on-tile performance before irradiation
  - Increase in SiPM noise with irradiation
  - Degradation of scintillator performance with irradiation rate

- Model needs to be updated with the latest results to ensure that the performance of the detector maintains SNR > 3

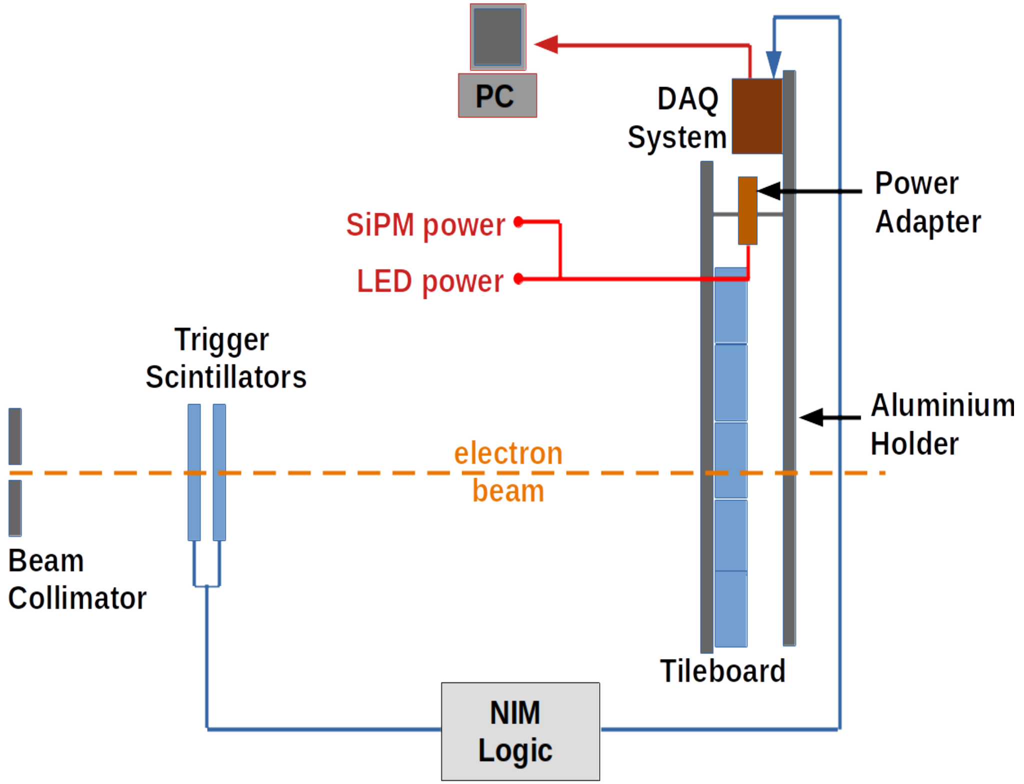
Quantifying SiPM-on-Tile Performance at Start Of Life

At Beam Tests

- Unirradiated SiPMs and scintillators on HGCAL tileboard prototypes measure the performance expected at the starting conditions of the detector

- SiPM-on-tile performance measured at DESY II test beam facility
  - 3 GeV electrons (has similar response to MIPs)
  - 30,000-100,000 events at a SiPM over-voltage of 2V

- 11 test beams to date since 2020



Light Yields of SiPM-on-Tiles

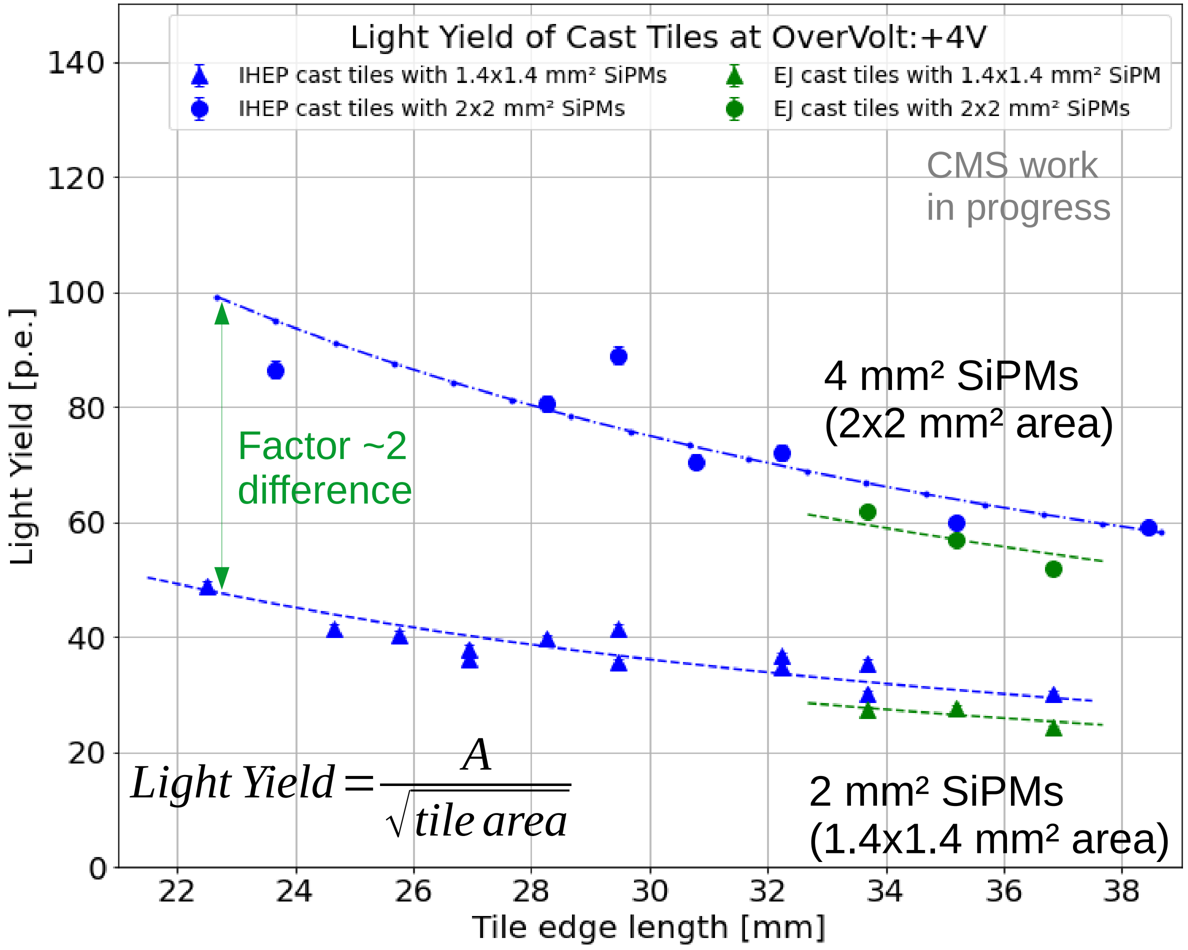
Using MIP and SiPM Gain measurements

- The SiPM signal response to MIPs re-scaled by the SiPM's gain is defined as **light yield**
  - Purely optical property solely dependent on the SiPM and scintillator

- Light yields measured for different scintillator sizes and SiPM sizes can be fitted using relation :

$$Light\ Yield = \frac{A(4\,mm^2)}{\sqrt{tile\ area}} \times \frac{SiPM\ active\ area}{4\,mm^2}$$

- Smaller tiles and larger SiPMs give larger light yields



SiPM Noise Measurements with Irradiated SiPMs

Results

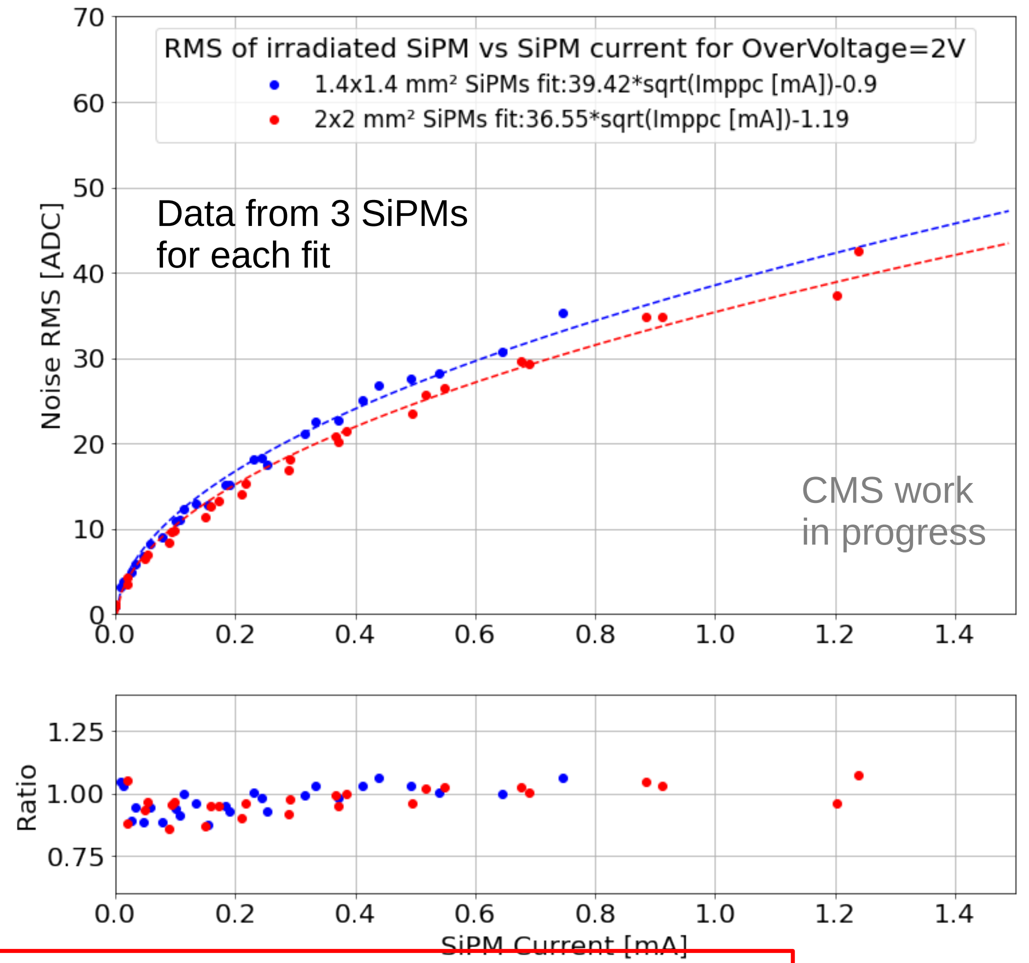
- Fluence increases the leakage current passing through of SiPMs

- Leakage current increases the SiPM noise

$$Pedestal\,noise = \left(A \times \sqrt{SiPM\ current} + B\right)$$

- Methodology:
  - Measure noise and current at different temperature while maintaining a 2V over-voltage

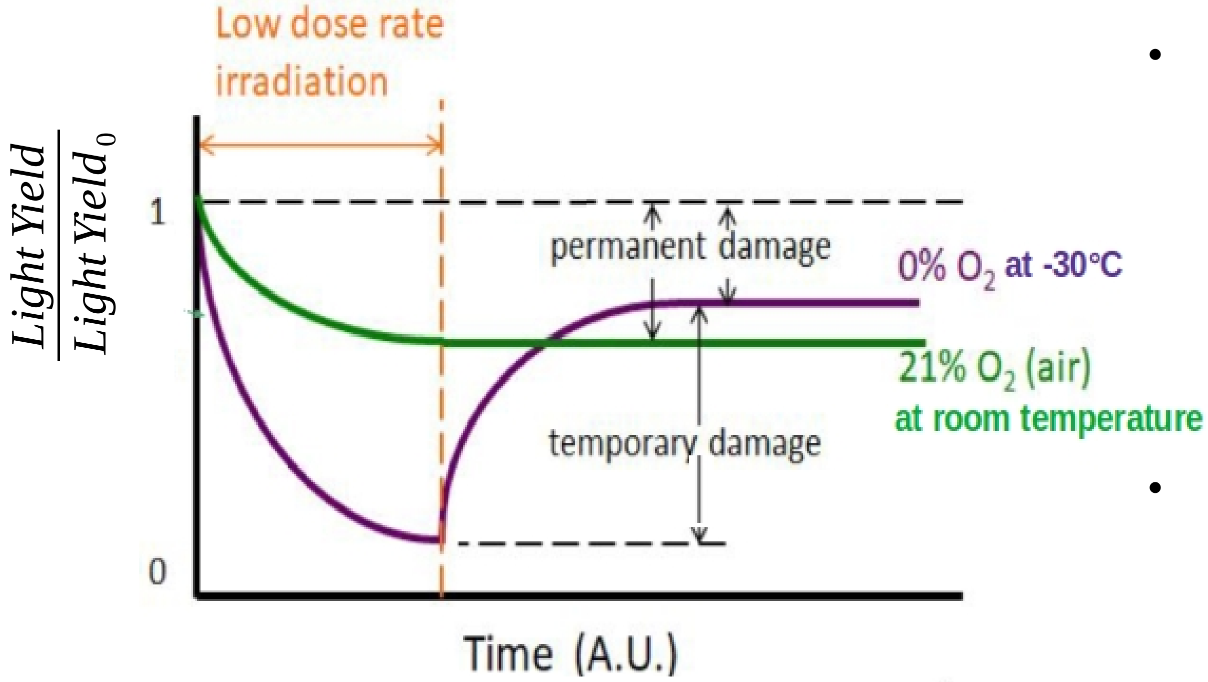
- The fit parameters can be used to re-scale the expected noise at any fluence and luminosity of all SiPMs of all sizes



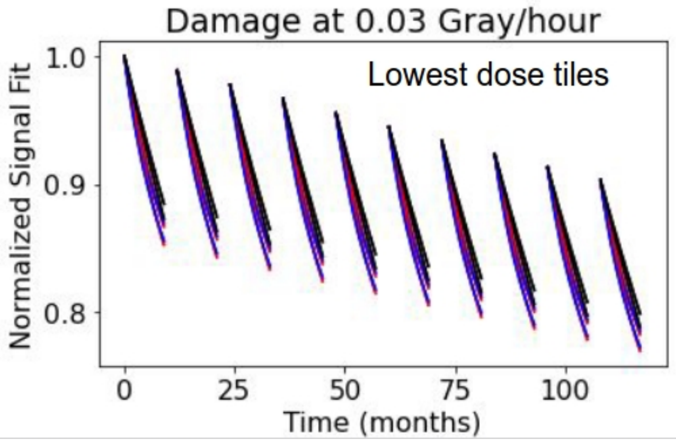
$$\left(\frac{Pedestal\ Noise\ of\ any\ SiPM}{Pedestal\ Noise\ at\ 5\times10^{13}\,n/cm^2}\right) = \sqrt{\left(\frac{fluence}{5\times10^{13}\,n/cm^2}\right)\times\left(\frac{integ.lumi}{3000\,fb^{-1}}\right)\times\left(\frac{SiPM\ active\ area}{2\,mm^2}\right)}$$

Degradation of Scintillator Tile with Radiation

Permanant and Temporary Damage



* Plots courtesy of S. Eno and B. Kronheim (Maryland University)



- Two types of damage to scintillator:
  - Permanent light loss in scintillator
  - Temporary (annealing) light loss
- **For light yield extrapolation model**
  - 9 months of operation causing both temporary and permanent damage
  - 3 months of total annealing of temporary damage during shutdown

Signal to Noise Ratios at End of Life (at 3000 fb^{-1})

10° sector of the scintillator section of the HGCAL

- Since Light Yield is known and noise is known for a given fluence and dose rate, the SNR at any given time can be calculated using:

$$SNR = \frac{Light\ Yield}{Pedestal\ Noise}$$

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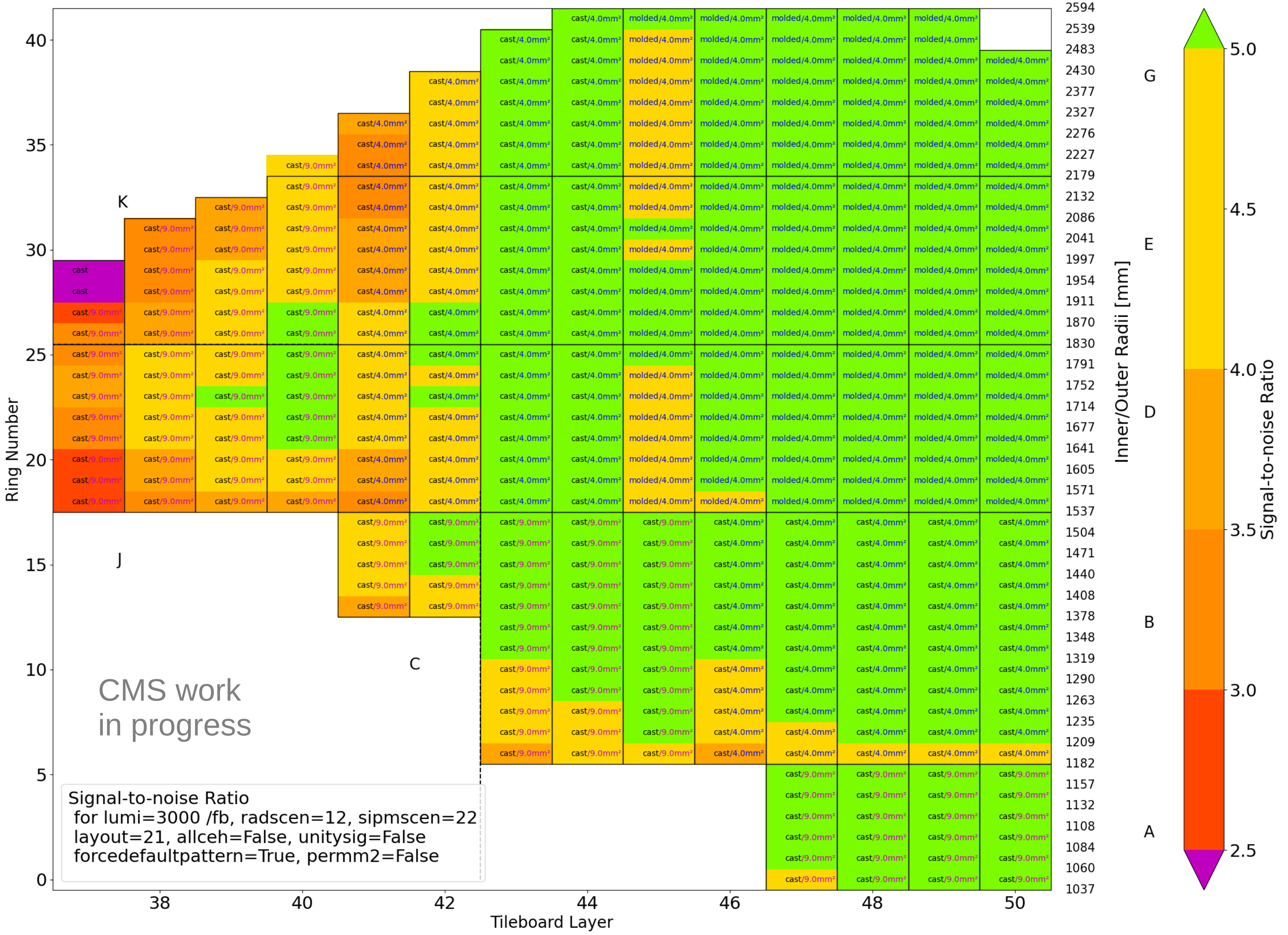
- Each layer consists of 8 SiPM-on-tile channels

- Most SiPM-on-tile channels maintains SNR>3 at end of life (3000 fb^{-1})
  - Front layer are the only exception



Possible Solutions to Improve SNR for J and K Tileboards

More SiPM-on-Tile Channels

- It is possible to improve the SNR in first 4 layers to have smaller tiles and more SiPM
  - Fit 3x3 channels in an area previously containing 2x2 channels
  - Will require the change in hardware design of tileboard types J and K
- Alternative solution: Convert layer 37 to a fully silicon layer

Summary

Extrapolation of Signal-to-Noise Ratios for End of Life Conditions

- HGCAL uses SiPM-on-Tile technology in demanding radiation conditions for the first time
  - Scintillation light decreases with irradiation
  - SiPM noise increases with irradiation
- However, MIP sensitivity is required for the calibration up to end of life
- Studies of initial performance with realistic prototypes, and with irradiated SiPMs provide firm basis for optimised configuration of detector and safe operation throughout HL-LHC
- Commissioning period will be challenging with rapidly varying conditions

Thank you for your attention!

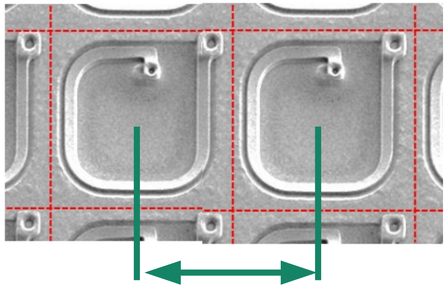
Backup

SiPM-on-Tile technology

SiPM Paramater Definitions

- **Pitch size :**

  The distance between two adjacent cell (SPAD) centers in the SiPM



- **SiPM active area :**

  The SiPM area capable of detecting photons

- **Overvoltage (OV):**

  Difference between **bias voltage** and **breakdown voltage** above which Geiger discharge becomes possible

$$Overvoltage = (Bias\ voltage) - (breakdown\ voltage)$$

- **SiPM gain :**

  The charge amplification factor of the SiPM cells

$$SiPM\ Gain = \frac{(Charge\ Collected\ per\ SPAD)}{(Charge\ of\ an\ electron)}$$

- **Photon detection efficiency (PDE) :**

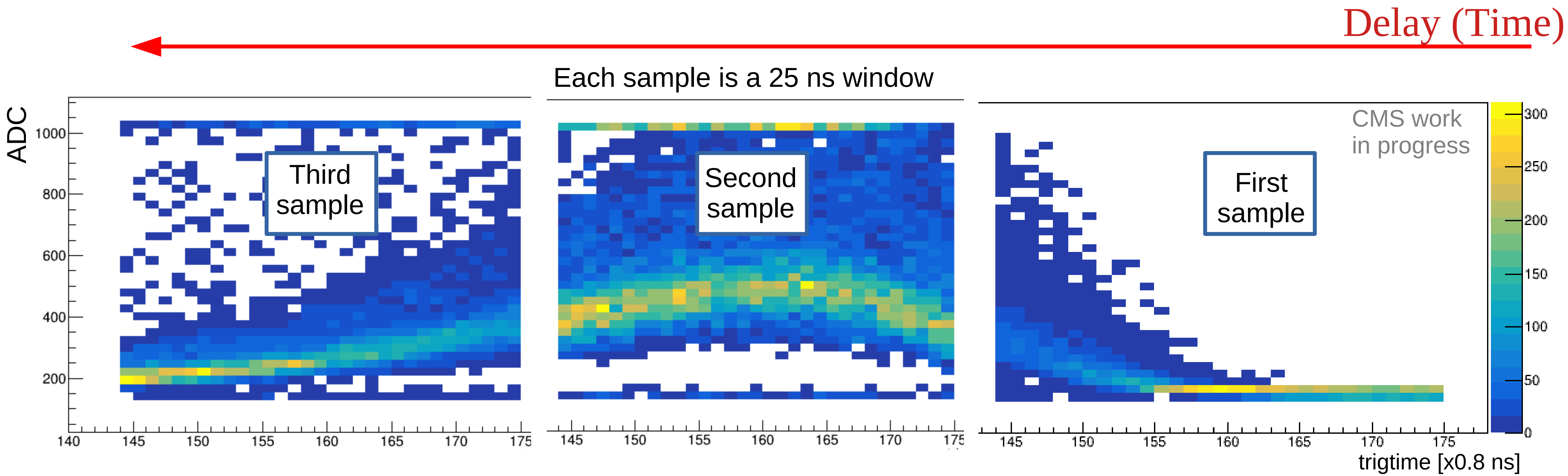
  Efficiency at which SiPMs can detect photons

- Both SiPM gain and PDE depend on the overvoltage

Data Analysis with Trigger Time Readout

Pulse Shape of 3GeV Electron Events

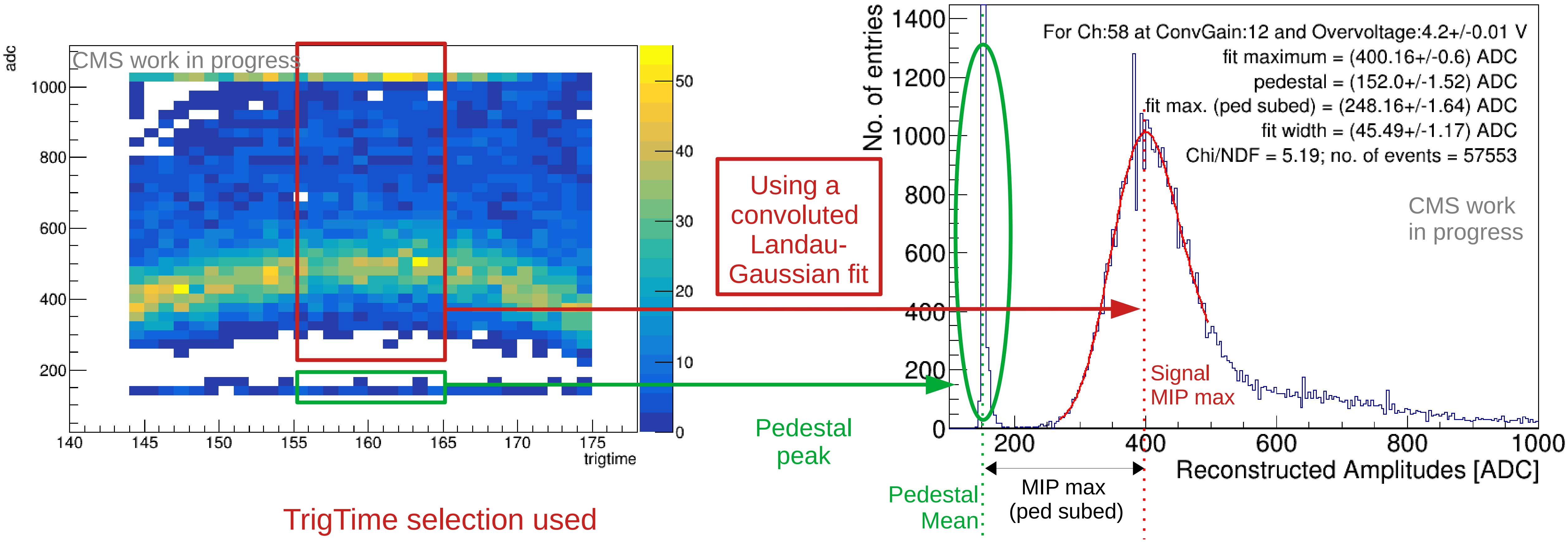
- DESY II beam is asynchronous to the HGCROC clock.
  - Introduces a 25 ns uncertainty to the pulse amplitude position
- The TB-tester DAQ used, saves the time stamp of trigger with ~0.8 ns resolution



MIP Extraction using Pulse Shape and Trigger Information

Using Trigger Time and Signal Amplitude

- Using a simple time selection for in-time MIP signals, it was possible to extract the MIP spectra

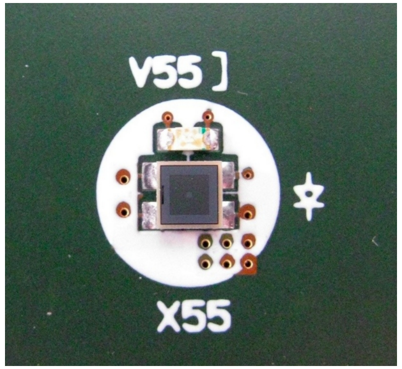


(Pedestal subtracted MIP max.) = (MIP max. of signal) – (Pedestal mean)

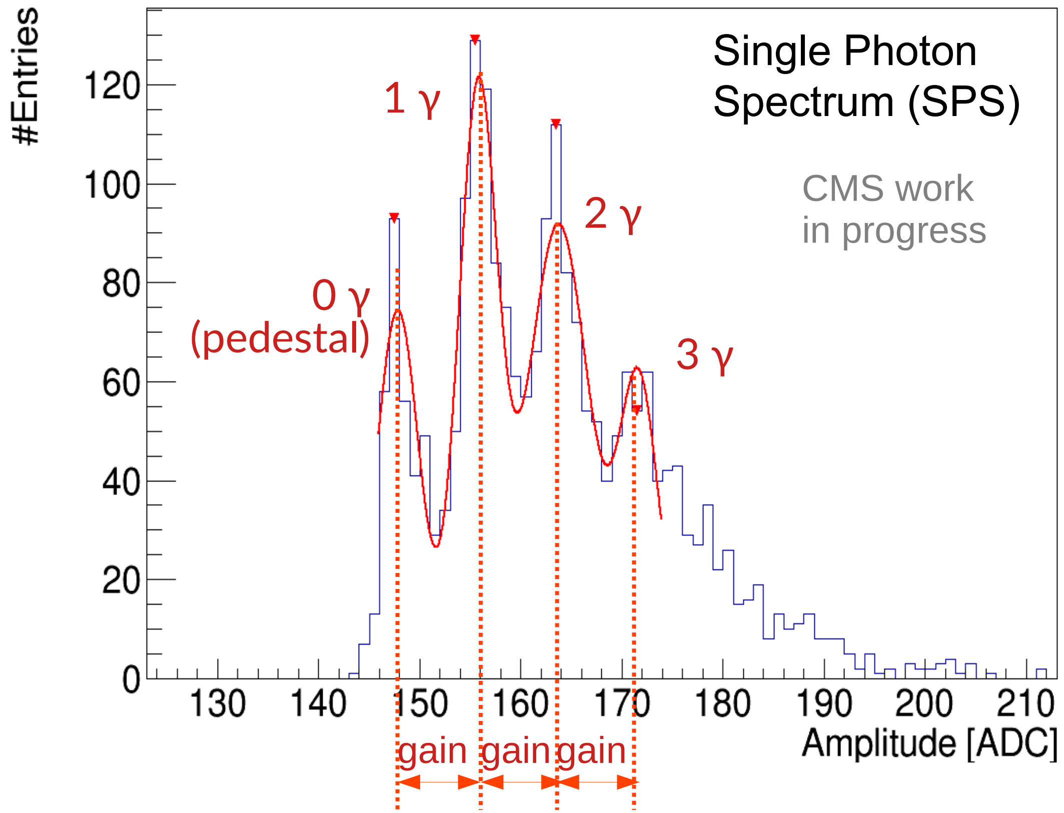
Overview of SiPM Gain Analysis

Using Single Photon Spectra (SPS) from On-Board LED System

- The LED system on-board the tileboard pulses the low intensity LEDs.



- The photons produced by the LEDs are detected by the SiPMs
  - Pulses from SiPM are sampled at the pulse amplitude
  - Resulting histogram shows the pedestal peak and peaks corresponding to the number of SiPM cells discharged due to photon detection
    - Often referred to as a **Single Photon Spectrum (SPS)**



- **A multi-gaussian function** is used to find the mean distance between peaks in the resulting histogram
  - This measures the gain of the SiPM in ADC units

Quantifying SiPM-on-Tile Performance at Start Of Life

At Beam Tests

- MIP extraction from beam data:
  - SiPM pulse sampled at amplitude using trigger timestamps from the DAQ system
  - Resulting histogram follows a Landau-Gaussian function from which the MIP maxima is extracted
    - Pedestal is subtracted from MIP maxima

- SiPM gain extraction from LED data:
  - The photons produced by the LEDs are detected by the SiPMs, whose pulse amplitudes are sampled.
  - Resulting histogram is a single photon spectrum (SPS) where the difference between consecutive peaks is defined as SiPM gain

- Ratio between MIP maxima and SiPM gain gives a purely optical performance measurement defined as light yield

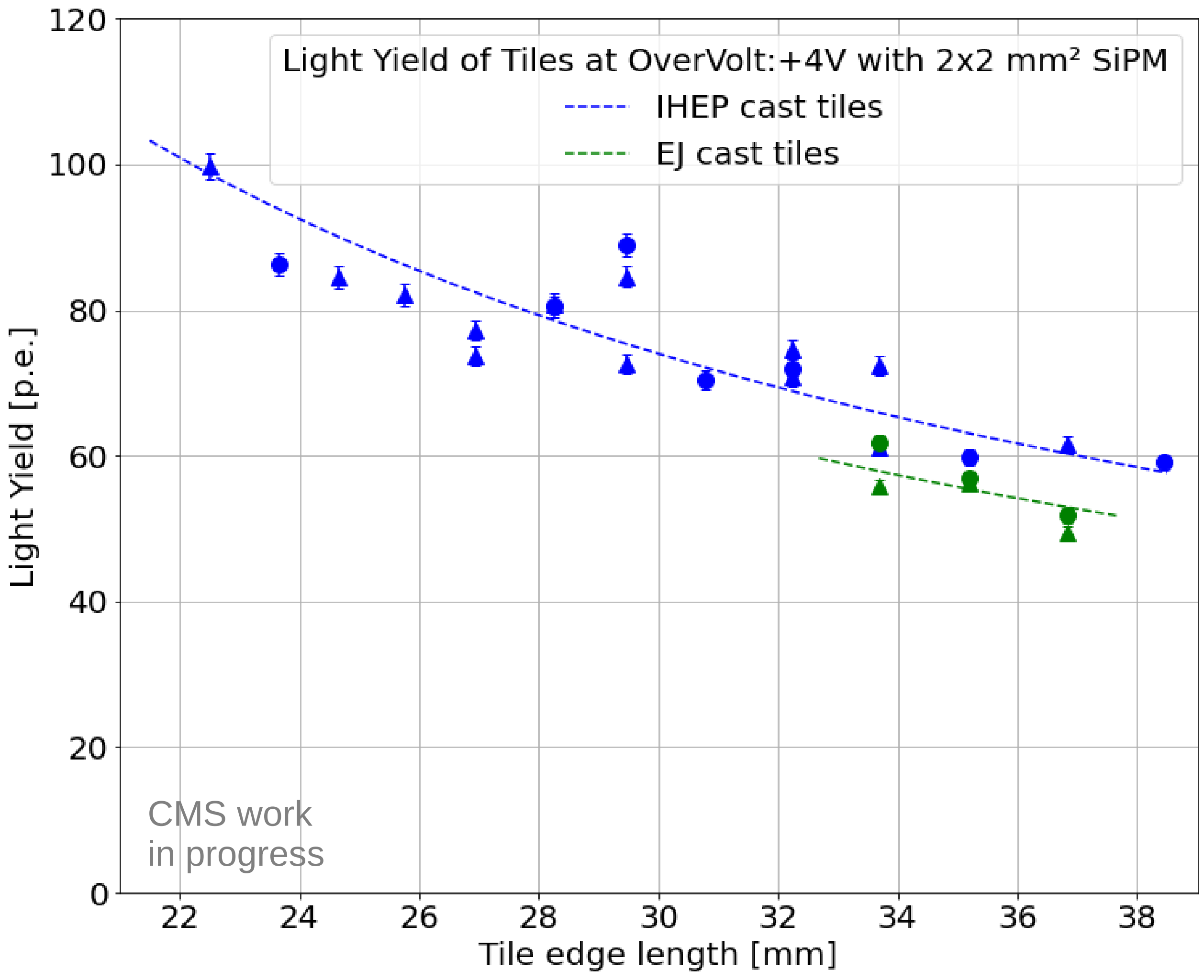
$$Light\ Yield[p.e.] = \frac{MIP\ maxima[ADC]}{SiPM\ gain[ADC]}$$

- Light yield depends on SiPM's active area, tile size and scintillator and wrapping properties

$$Light\ Yield = \frac{A(4\,mm^2)}{\sqrt{tile\ area}} \times \frac{SiPM\ active\ area}{4\,mm^2}$$

Light Yields of SiPM-on-Tiles

Variation with SiPM size



- Light yield also varies as a function of SiPM active area
- Therefore one can calculate all light yields with respect to the 2x2 mm² SiPMs:

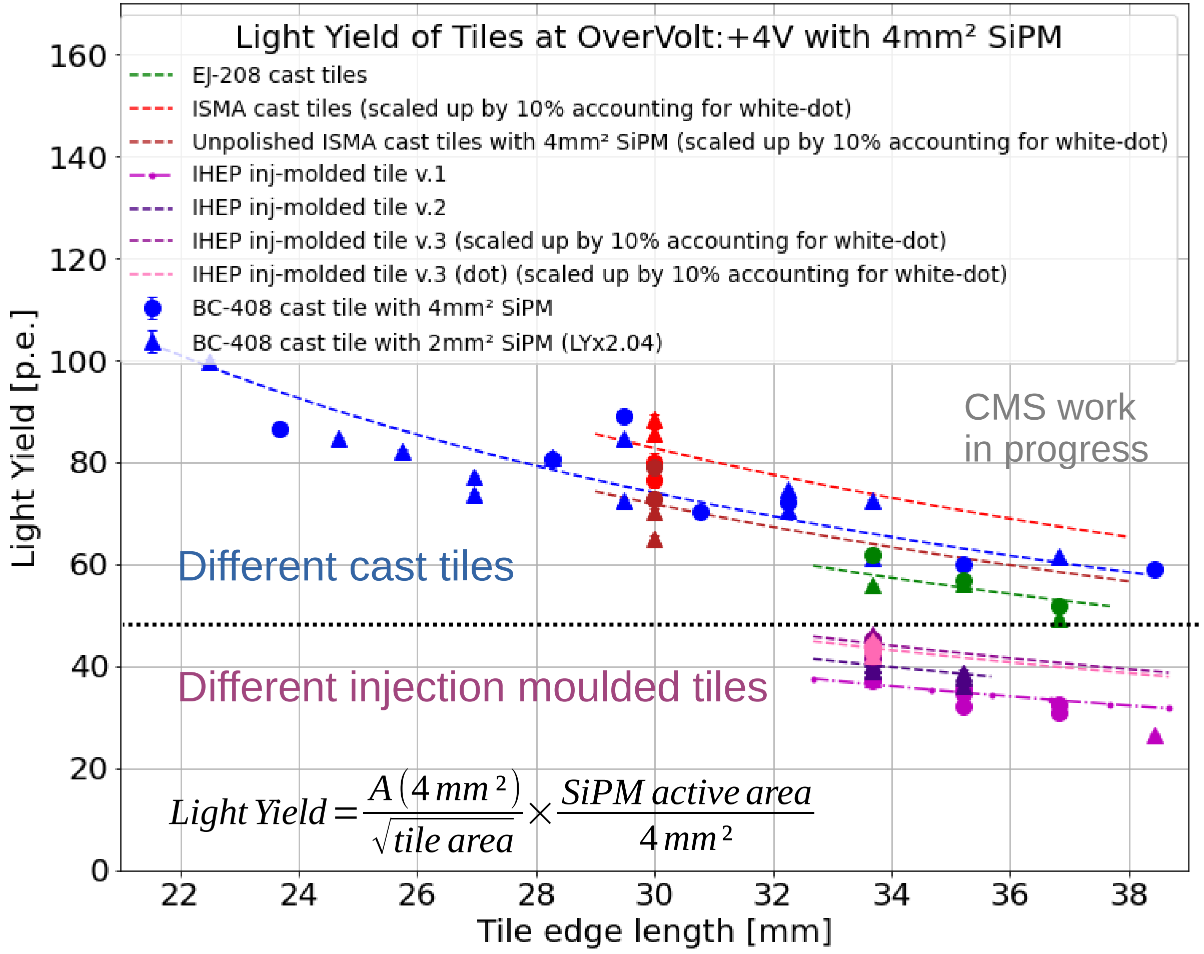
$$Light\ Yield = \frac{A(4\,mm^2)}{\sqrt{tile\ area}} \times \frac{SiPM\ active\ area}{4\,mm^2}$$

- 3x3 mm² SiPMs will have 2.25 times more light yield than 2x2 mm² SiPMs
- More light from smaller scintillators.
- Both these help increase the signal in more irradiated regions

Light Yield Variation with Scintillator Tile

For Different Types of Scintillators

- Light yields shown uses two methods of production:
  - **Cast Tiles:**
    - Produced using polyvinyl toluene (PVT)
    - Bought as sheets which needs to be machines into tiles
    - Expensive but better performance
  - **Injection-moulded Tiles:**
    - Produced using polystyrene
    - Produced by injecting heated molten material to moulds which is then cooled down to solidify
    - Cheaper but lower light yields
- Best performing tiles of both types will be used in final detector such that SNR>3 is maintained



$$Light\ Yield = \frac{A(4\,mm^2)}{\sqrt{tile\ area}} \times \frac{SiPM\ active\ area}{4\,mm^2}$$

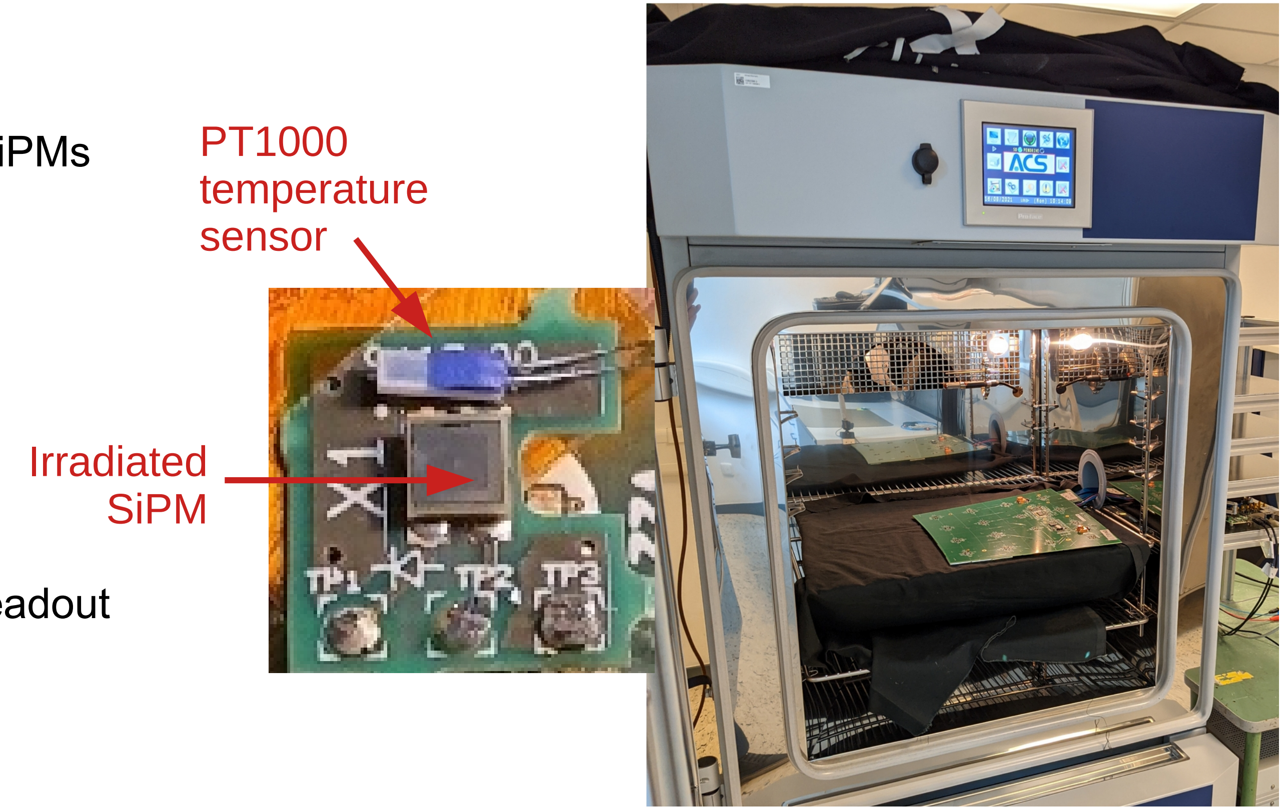
SiPM Noise Measurements with Irradiated SiPMs

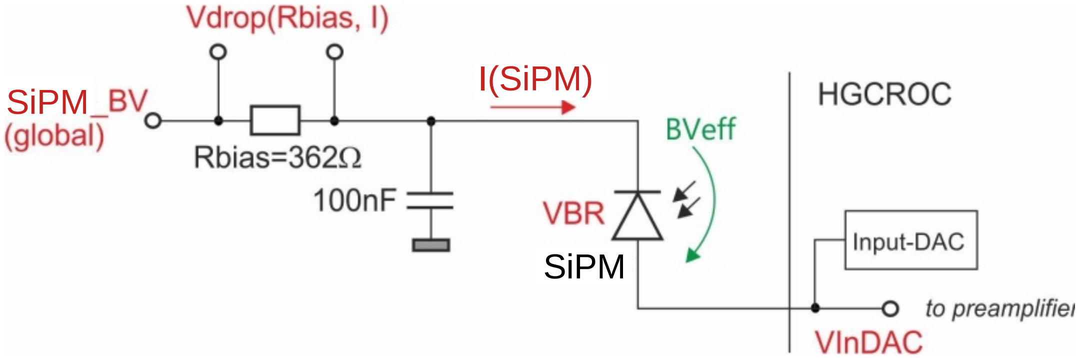
Methodology

- Fluence increases the leakage current passing through of SiPMs
- SiPM noise is an ADC measurement of the fluctuation of leakage current:

$$Pedestal\ noise = \left(A \times \sqrt{SiPM\ current} + B \right)$$

- A and B values measured using tile modules with HGCAL readout can be used to calculate SiPM noise in terms of current





Relationship between Noise and Current passing through SiPM

Theoretical Background

- When using different temperatures (or light intensities) to vary SiPM noise for a fixed overvoltage, the current also increases as a function of SiPM noise

  - For a SiPM with negligible excess noise factor caused by after-pulsing and crosstalk

$$I = \frac{N \cdot G \cdot e}{\Delta t}$$

where I = current through SiPM
N = no. of fired pixel in time Δt
G = SiPM gain
e = electron charge
Δt = time period

- $$Q = \int I \cdot dt = N \cdot G \cdot e$$

  where Q = charge collected by SiPM

- Since the noise scales as a function of $\sqrt{N}$:

$$noise\ RMS = \sqrt{N} \cdot G \cdot e = \sqrt{I} \cdot \sqrt{G \cdot e \cdot \Delta t}$$

- That is, for a given overvoltage: $noise\ RMS \propto \sqrt{SiPM\ current}$

SNR of Best and Worst Performing Channel of Tileboard Type

For Tileboard Type A and B

- Each year delivers 300 fb^{-1} of integrated luminosity
- All Tileboards of type A and B maintains a SNR>3 throughout the detector lifetime
  - Similar plots can be produced for all SiPM-on-Tiles