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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(on behalf of the DESY HGCAL team)

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CMS
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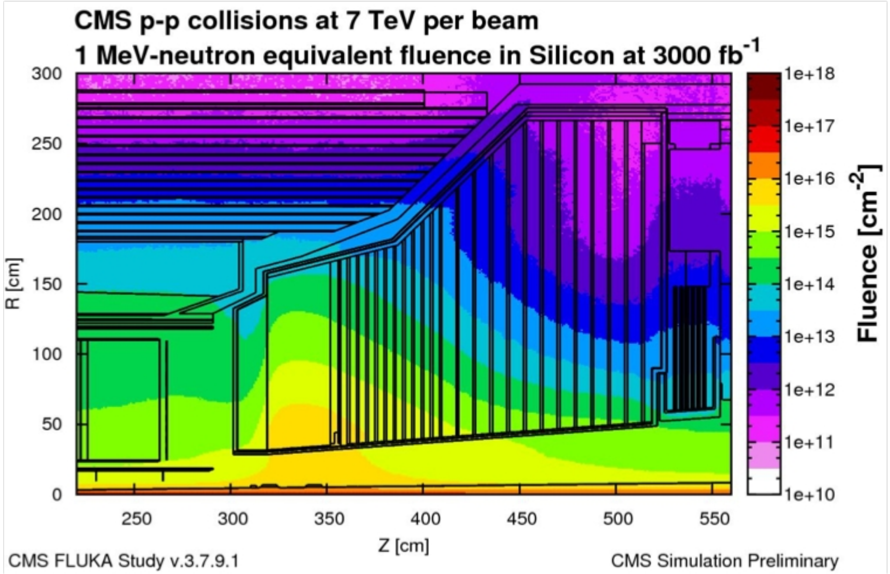
DESY.

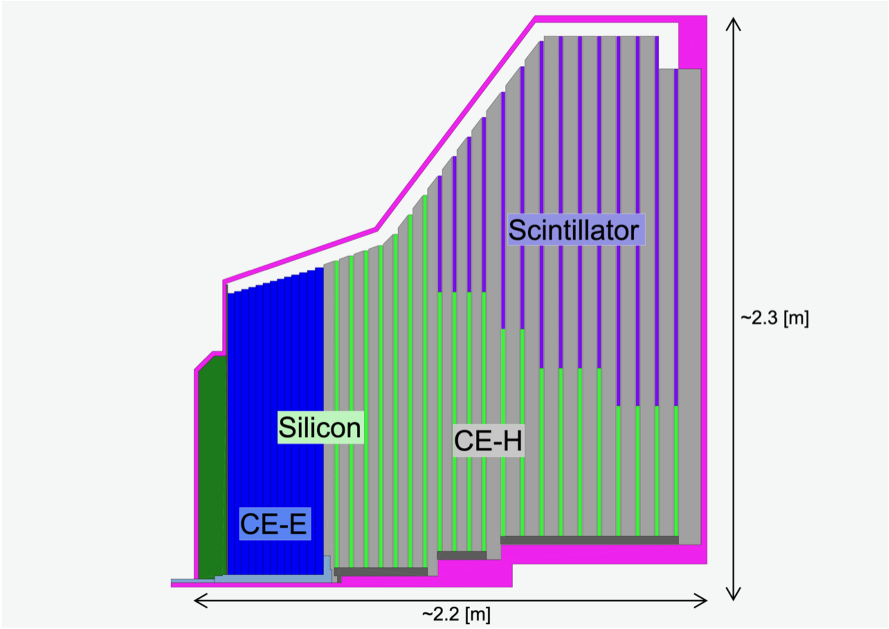
High Granularity for the High Luminosity LHC

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



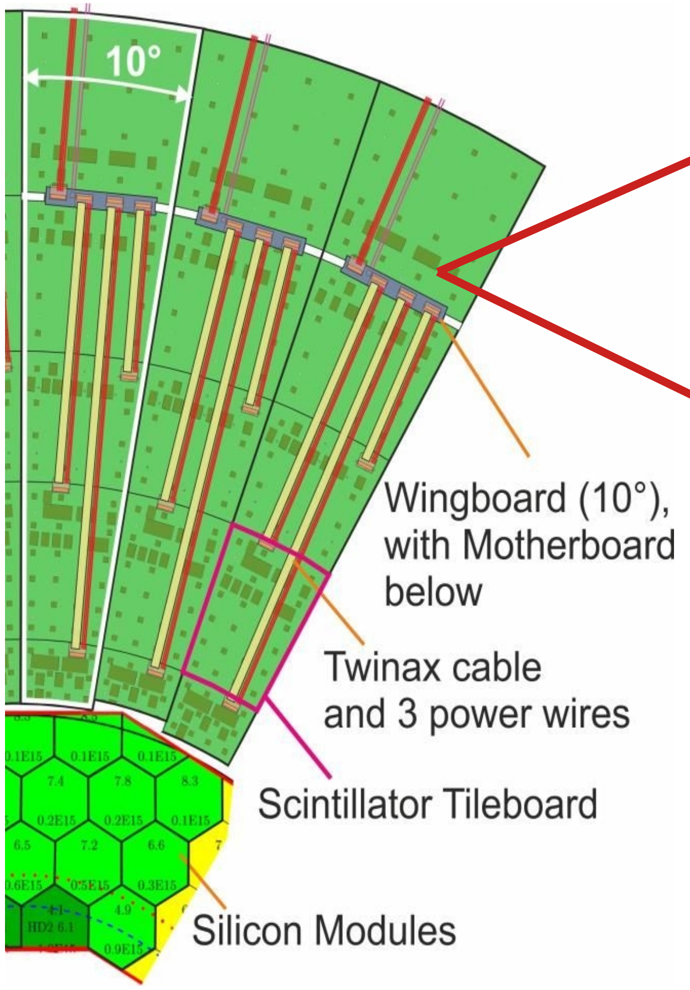
- CMS endcap calorimeter to be replaced with a **5D (imaging) calorimeter using particle flow**



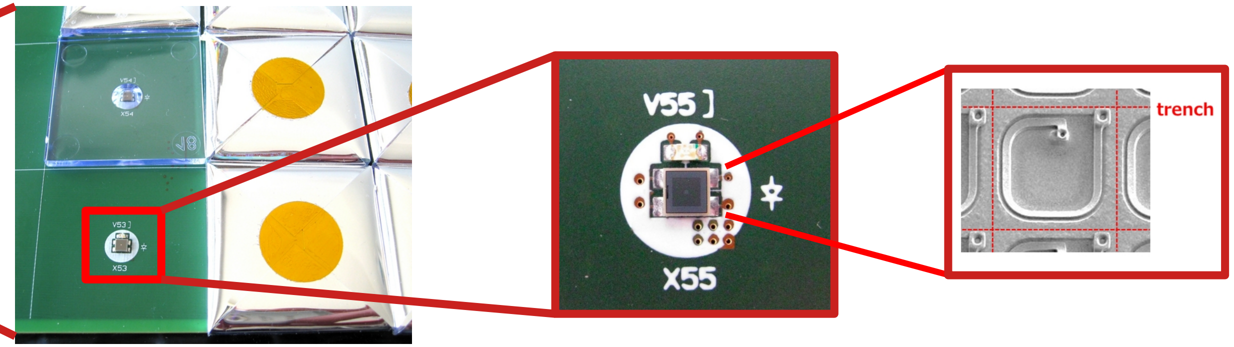
- The active area of CMS endcap calorimeter (HGCAL) will consist of:
  - silicon detector section
  - **scintillator section: where radiation levels permit (neutron fluence < 5×10^{13} n/cm²)**

Scintillator Component of the Hadronic Endcap Calorimeter

SiPM-on-Tile Based Read-out

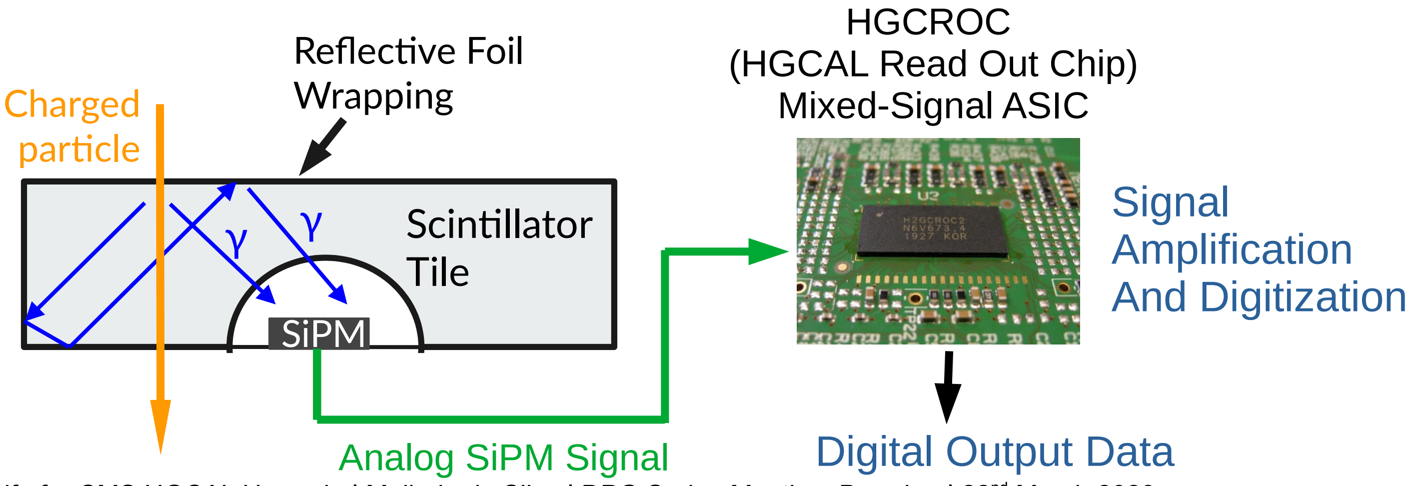


- SiPM-on-tiles consist of individually wrapped plastic scintillator tiles placed on silicon photomultipliers (SiPM)



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

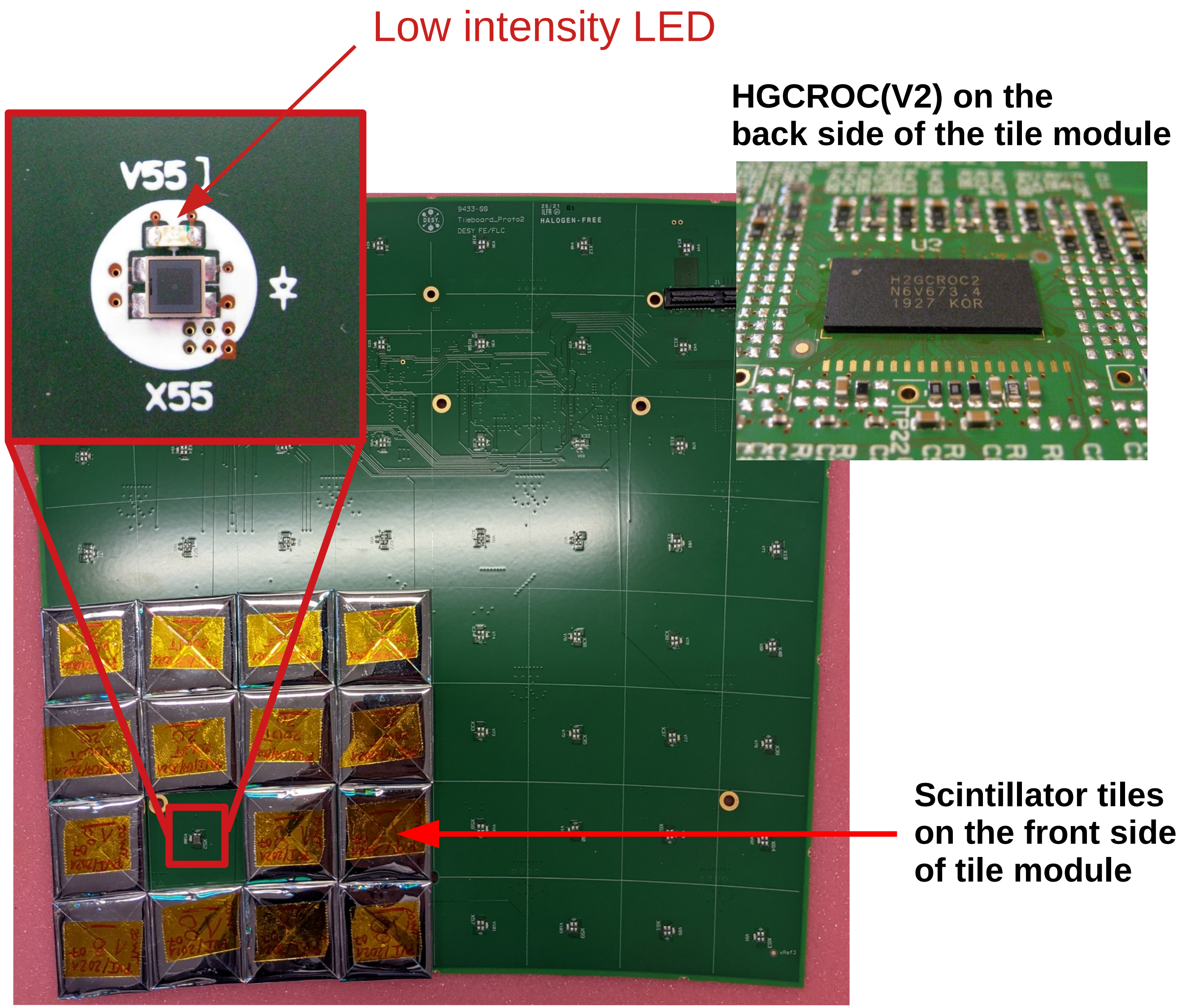
- The signals from SiPM-on-tiles are read out by the HGCROC front end electronic ASIC



CMS HGCAL Tile Module

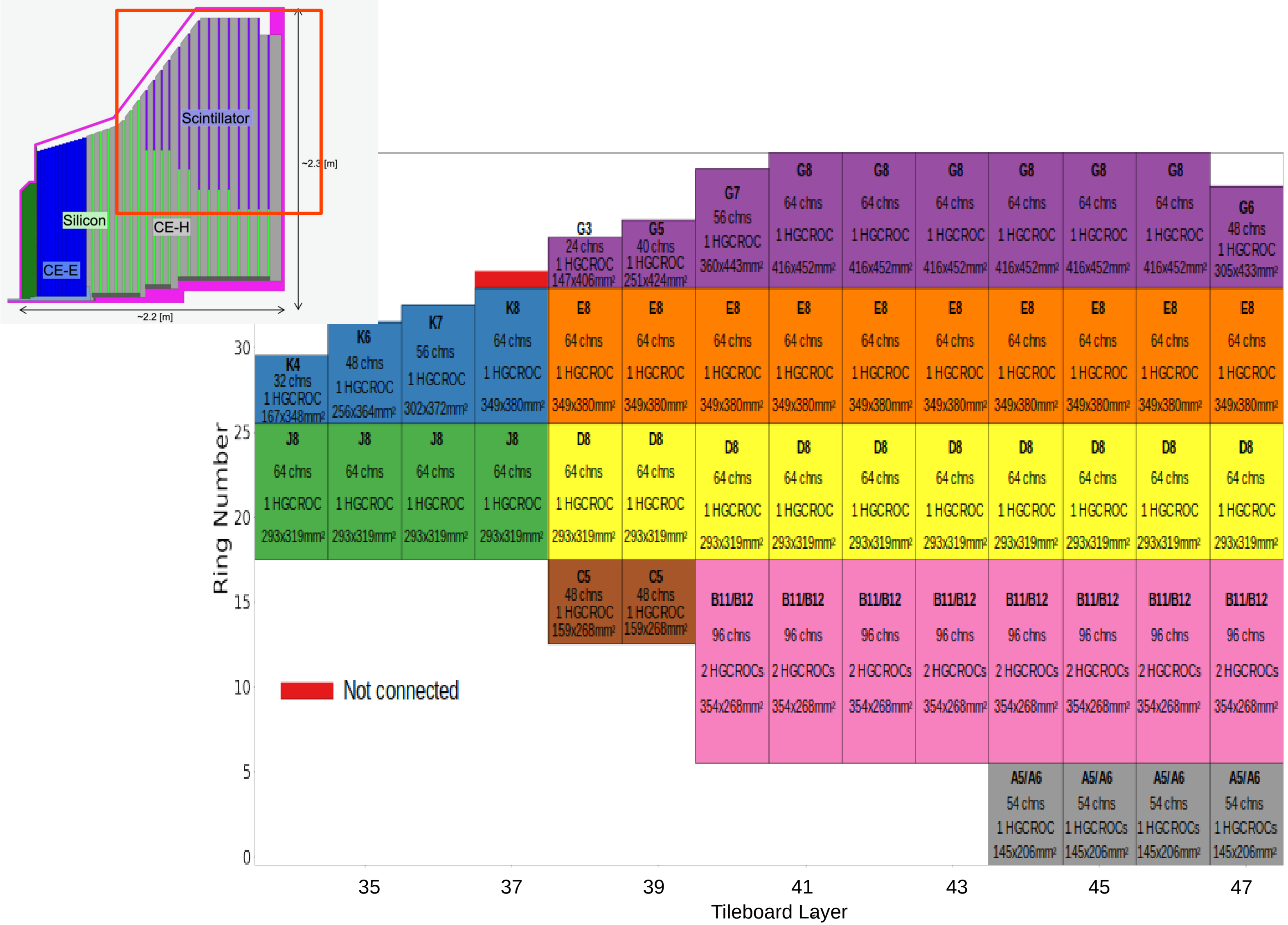
For the Scintillator Section of the CMS HGCAL

- 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 including the low intensity LED system.
- Most tile modules will hold one HGCROC
- HGCROC can read out up to 72 channels simultaneously.



Current Tile Module Plans For the HGCAL Scintillator Section

Tile Module Layout in r-z Direction



- **8 tileboard types cover both endcaps**
  - 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: more degradation than silicon sensors:
  - Will be used in areas where a **signal-to-noise ratio (SNR) > 3 for MIPs** can be maintained

$$SNR = \frac{MIP\ Signal}{Noise\ of\ Signal}$$

- **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 dose rate

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

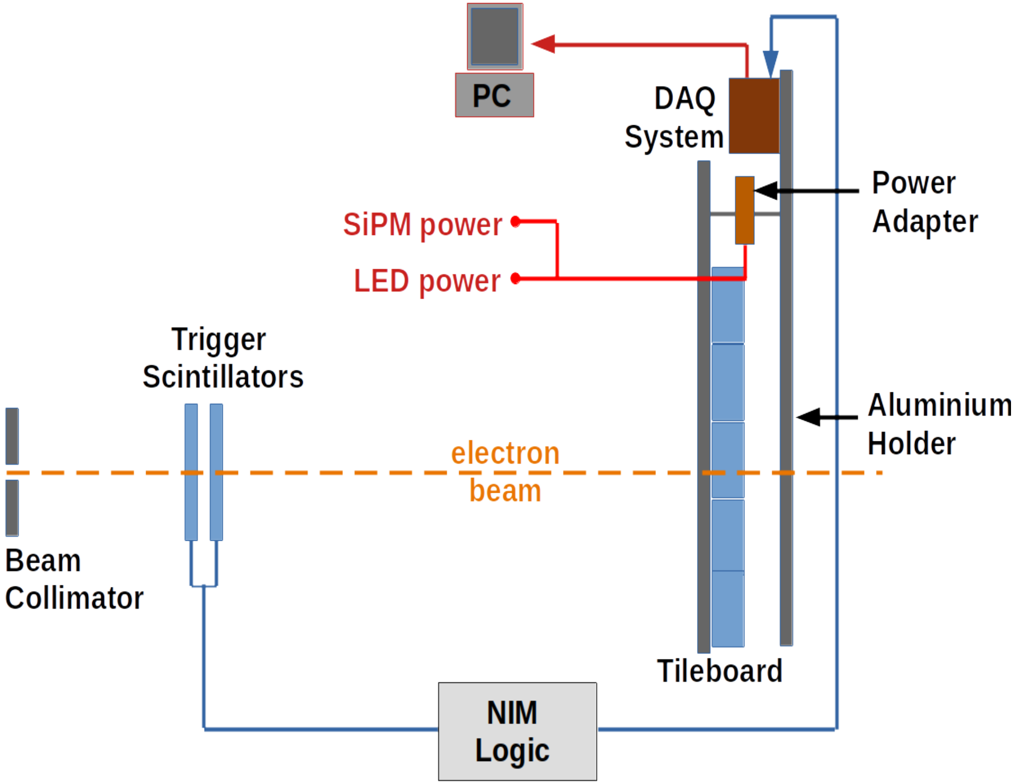
- SiPM-on-tile performance measured at DESY II test beam facility

  - 3 GeV electrons (has similar response to MIPs)

  - 30,000-100,000 events at a SiPM over-voltage of 2V (SiPM operation voltage at HGCAL)

$$Overvoltage = \begin{pmatrix} Bias \\ voltage \end{pmatrix} - \begin{pmatrix} Breakdown \\ voltage \end{pmatrix}$$

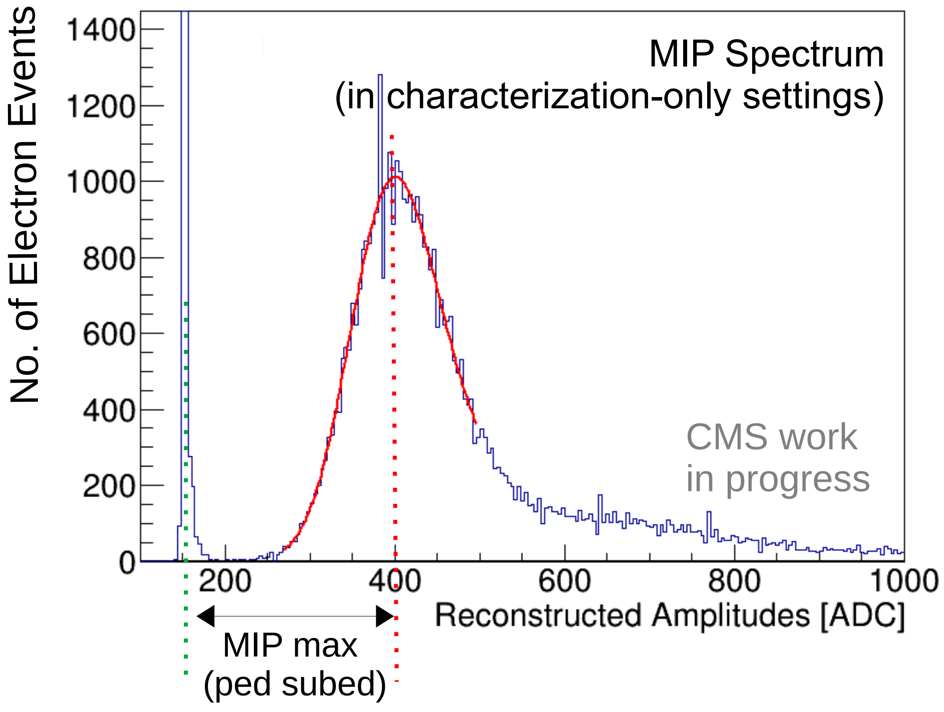
- 11 test beams to date since 2020



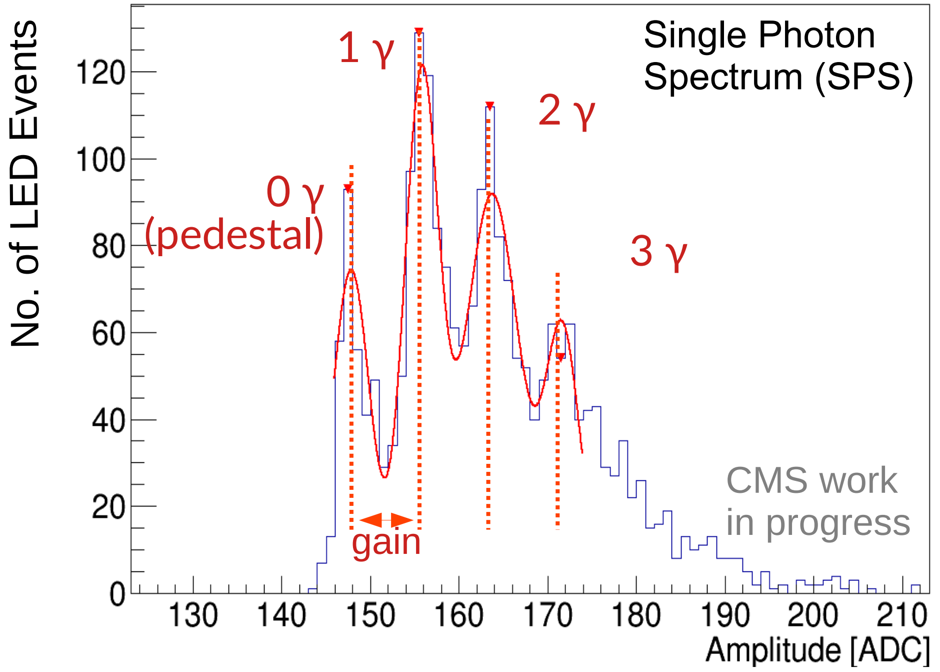
Quantifying SiPM-on-Tile Performance at Start Of Life

At Beam Tests

- MIP extraction from beam data:



- SiPM gain extraction using low intensity LED:



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

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

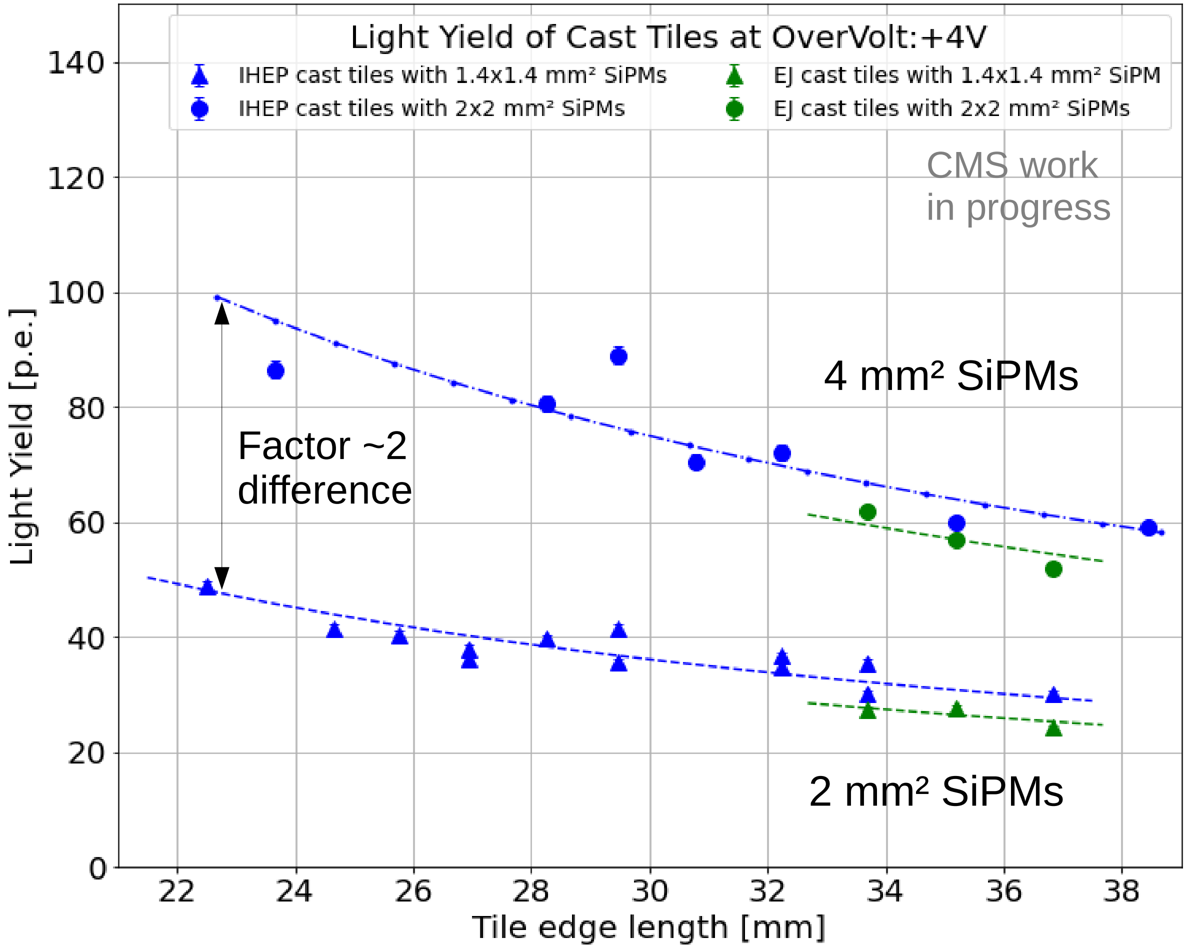
Light Yields of SiPM-on-Tiles

Using MIP and SiPM Gain measurements

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

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

- Detector can be optimised to maintain SNR>3 in highest irradiated area by:
  - Using smaller scintillator tiles
  - Using larger SiPMs
  - Using better performing scintillator materials



SiPM Noise Measurements with Irradiated SiPMs

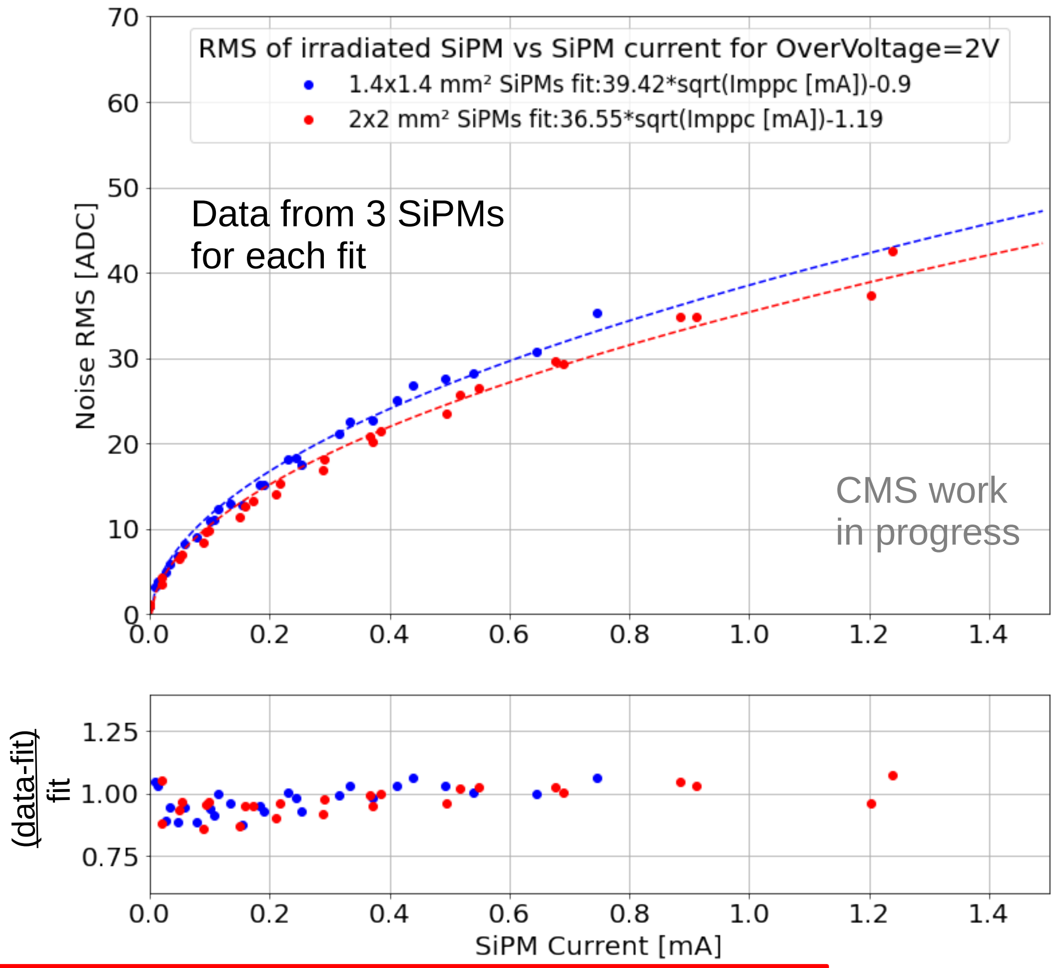
Results

- Leakage current passing through the SiPMs increases with fluence

- SiPM noise increases with leakage current:

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

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

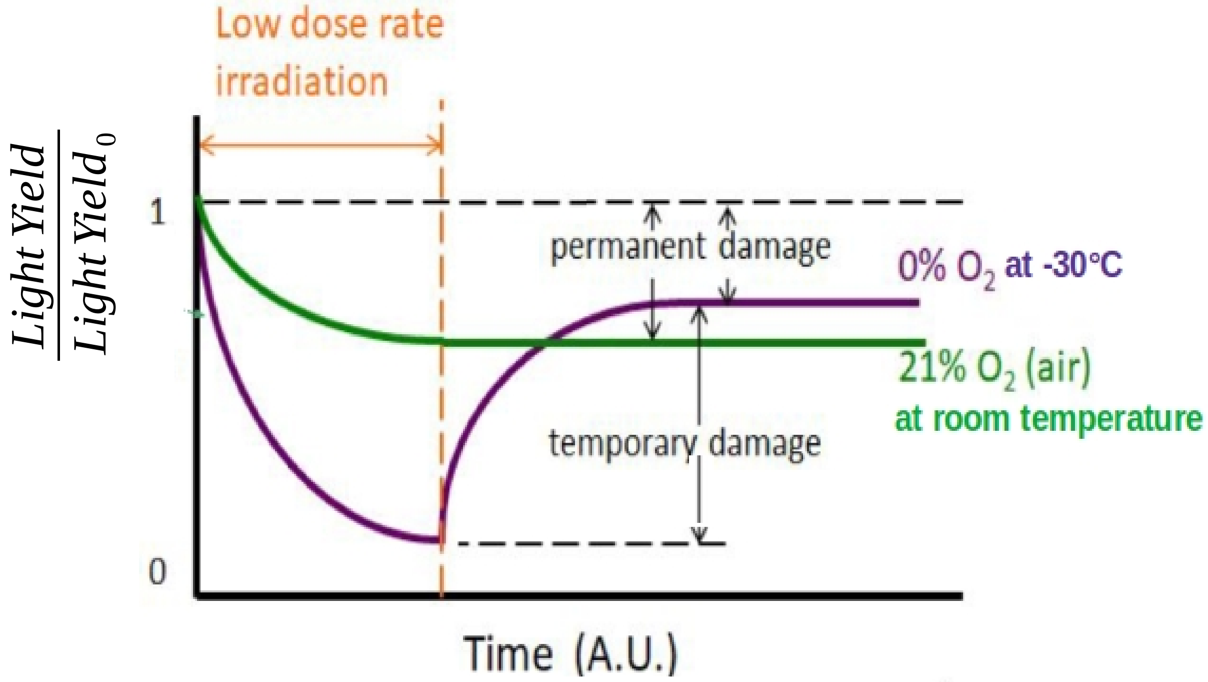


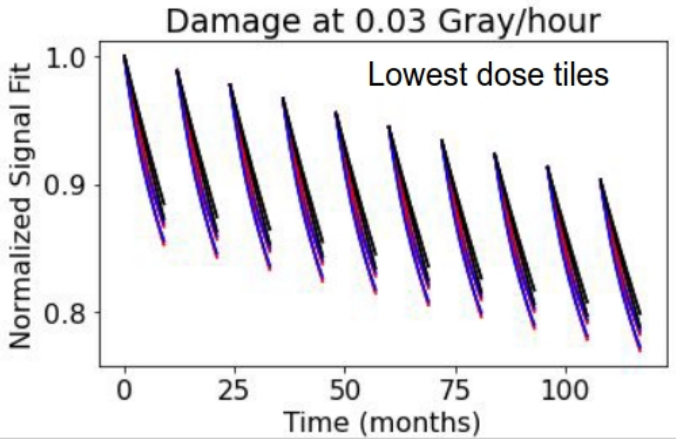
- The fit parameters can be used to re-scale the expected noise at any fluence and luminosity of all SiPMs of all sizes

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

Degradation of Scintillator Tile with Radiation

Permanent 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 per year of operation**
  - 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})

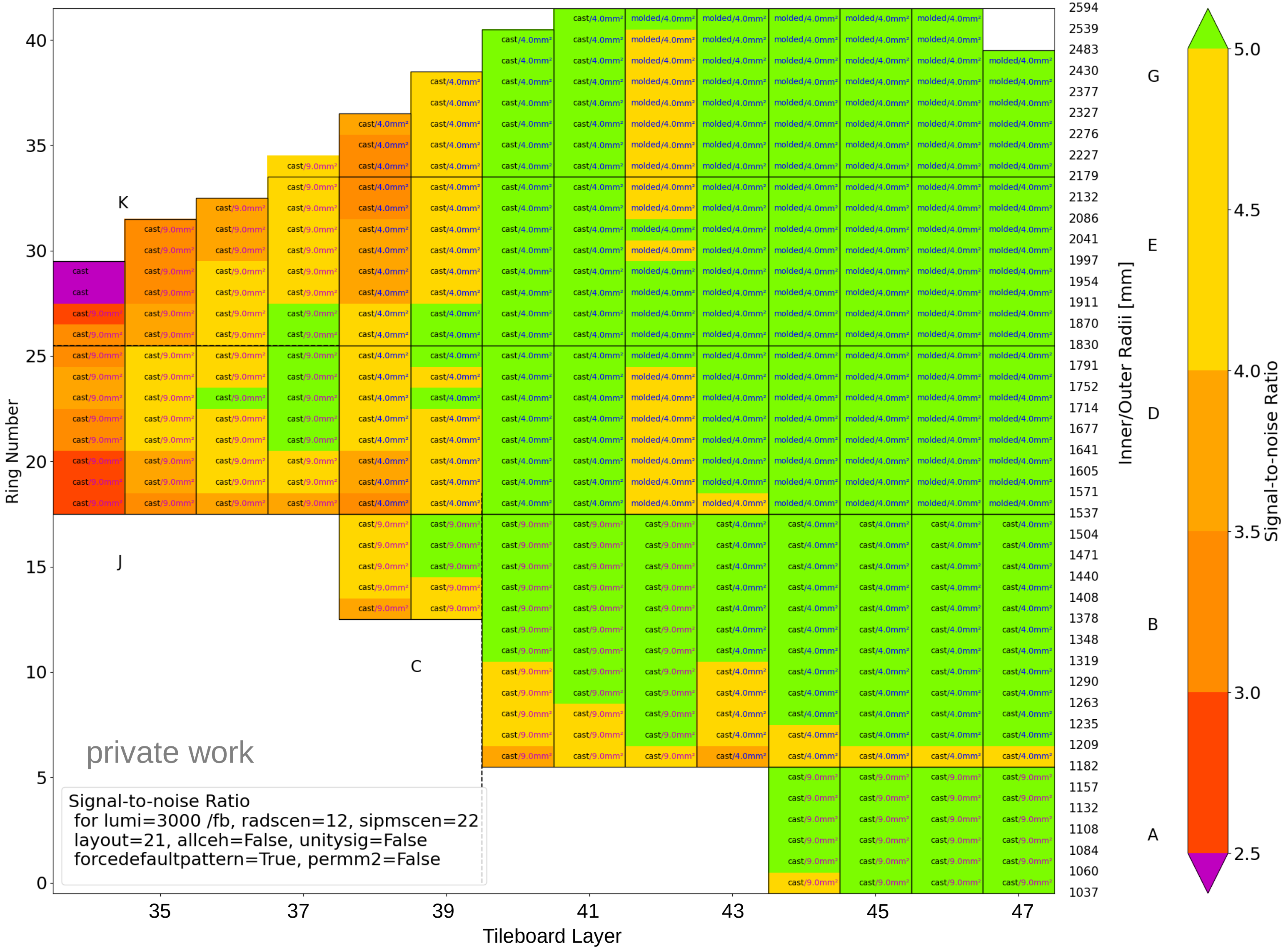
Of the scintillator section of the HGCAL

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

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

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

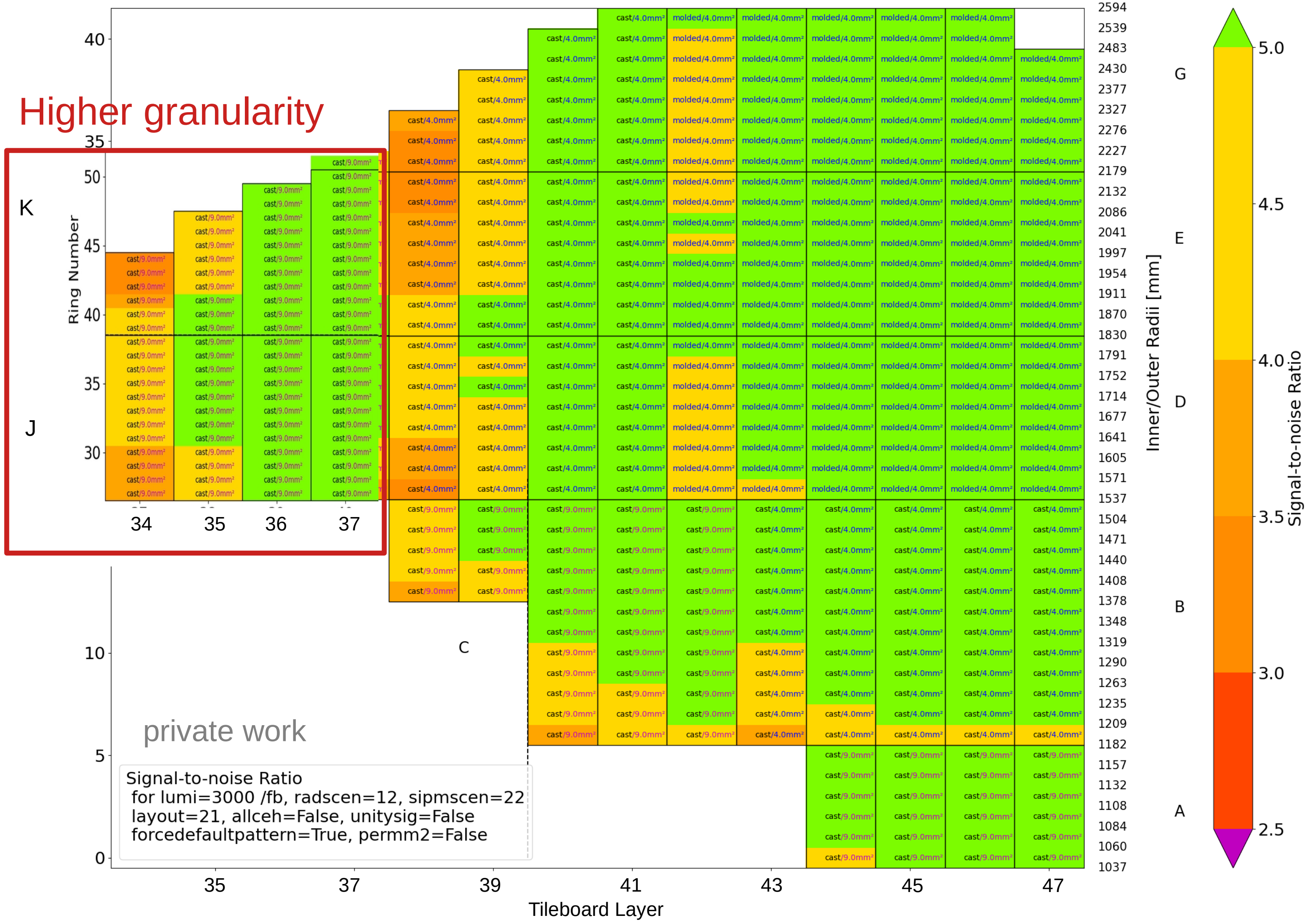
- Most SiPM-on-tile channels maintains SNR>3 at end of life (3000 fb^{-1})
  - Front layer are the only exception



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
  - Increase granularity in first 4 layers: Have 3x3 channels in an area that previously had 2x2 channels
  - Will require the change in hardware design of tileboard types J and K



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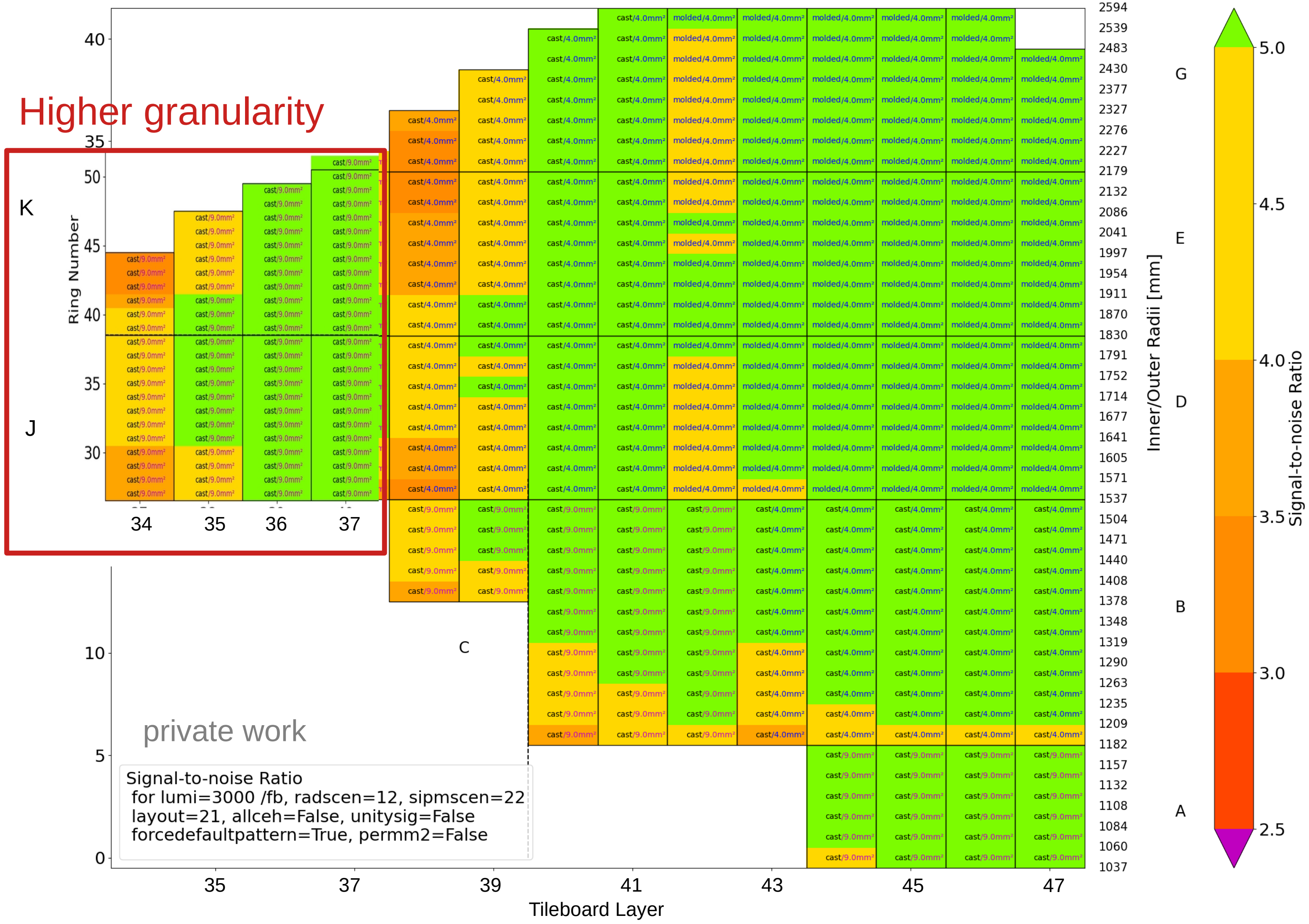


- **Irradiation and component results are not final and work in progress**
- **Decisions on potential reconfigurations are still to be made**

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

Overview

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

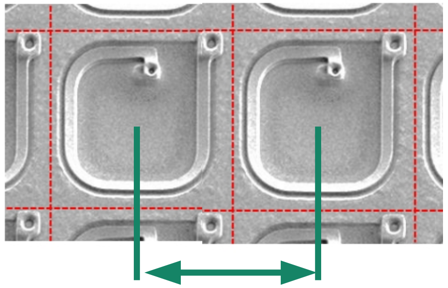
- Introduction to the CMS HGCAL Upgrade
  - Scintillator Section of the HGCAL Upgrade
- Signal-to-Noise Requirement for the Scintillator Section
- Model, Data Acquisition and Results used for SNR Extrapolations
- Updated Signal-to-Noise Ratios at end of life
- Summary

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) :**

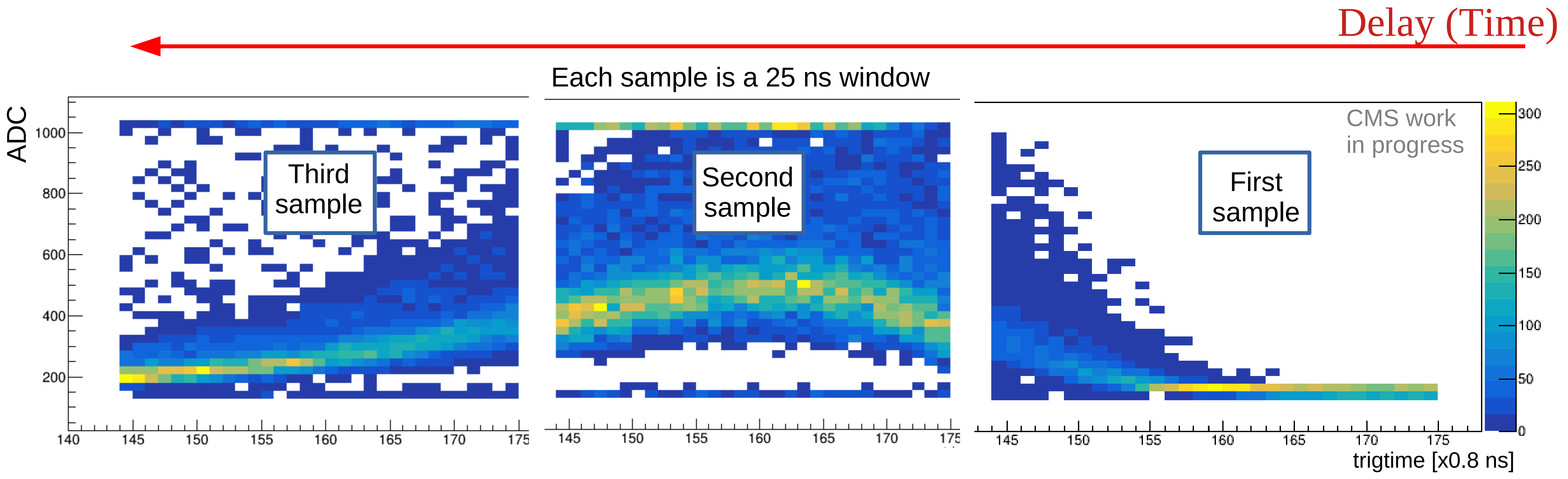
  Efficiency at which SiPMs can detect photons

- Both SiPM gain and PDE depend on the overvoltage

Data Analysis with Trigger Time Readout

Pulse Shape of 3GeV Electron Events

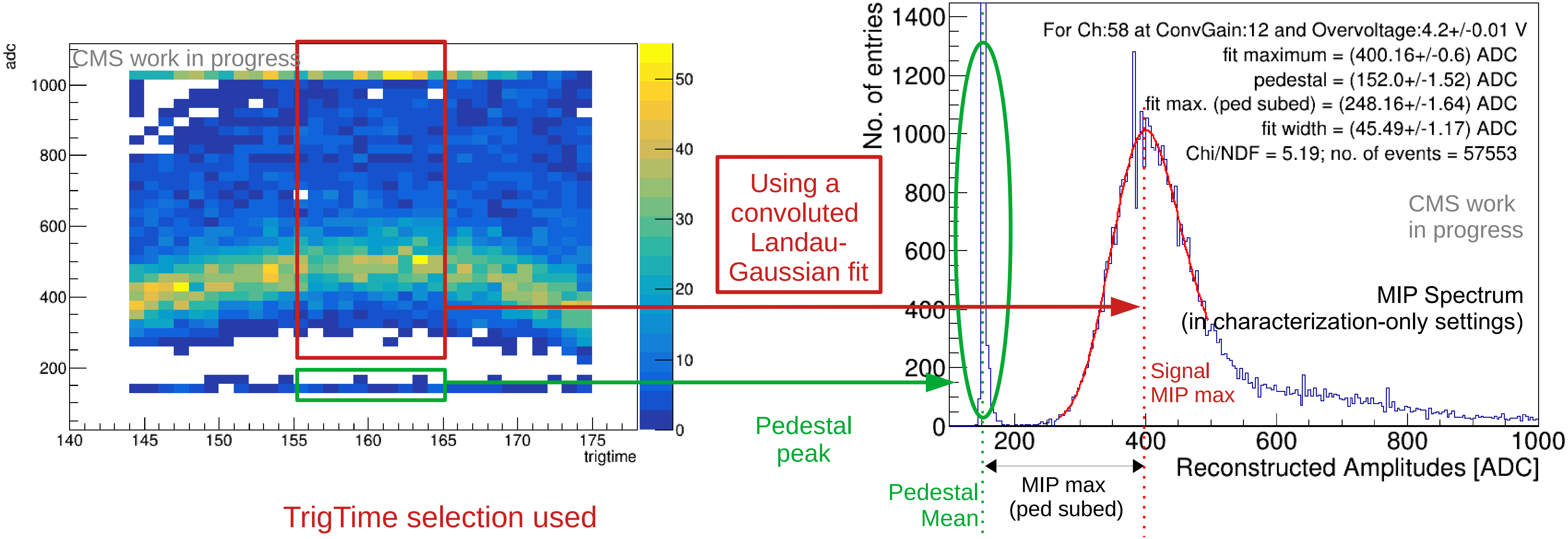
- DESY II beam is asynchronous to the HGCROC clock.
  - Introduces a 25 ns uncertainty to the pulse amplitude position
- The TB-tester DAQ used, saves the time stamp of trigger with ~0.8 ns resolution



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

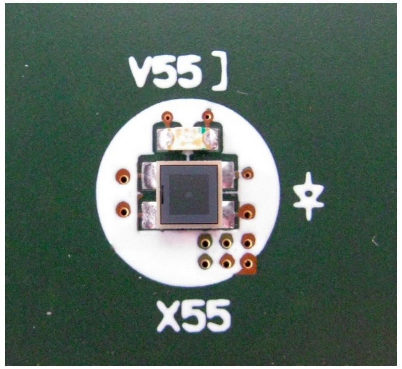


(Pedestal subtracted MIP max.) = (MIP max. of signal) – (Pedestal mean)

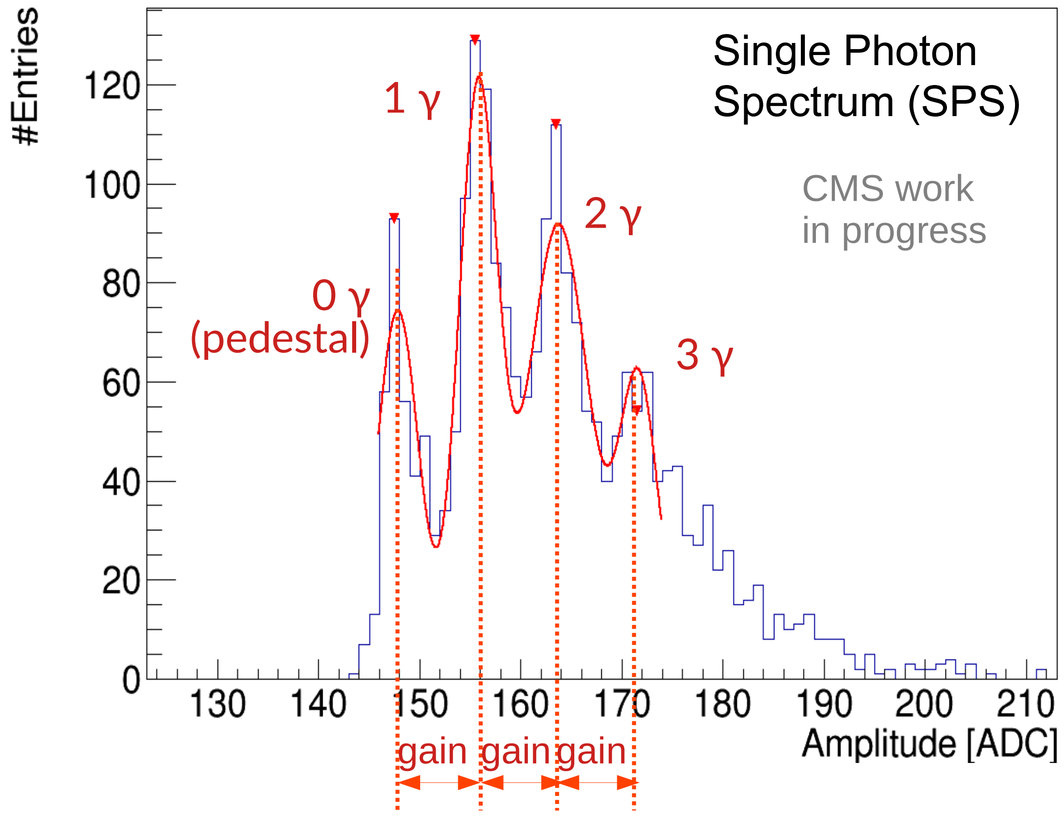
Overview of SiPM Gain Analysis

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

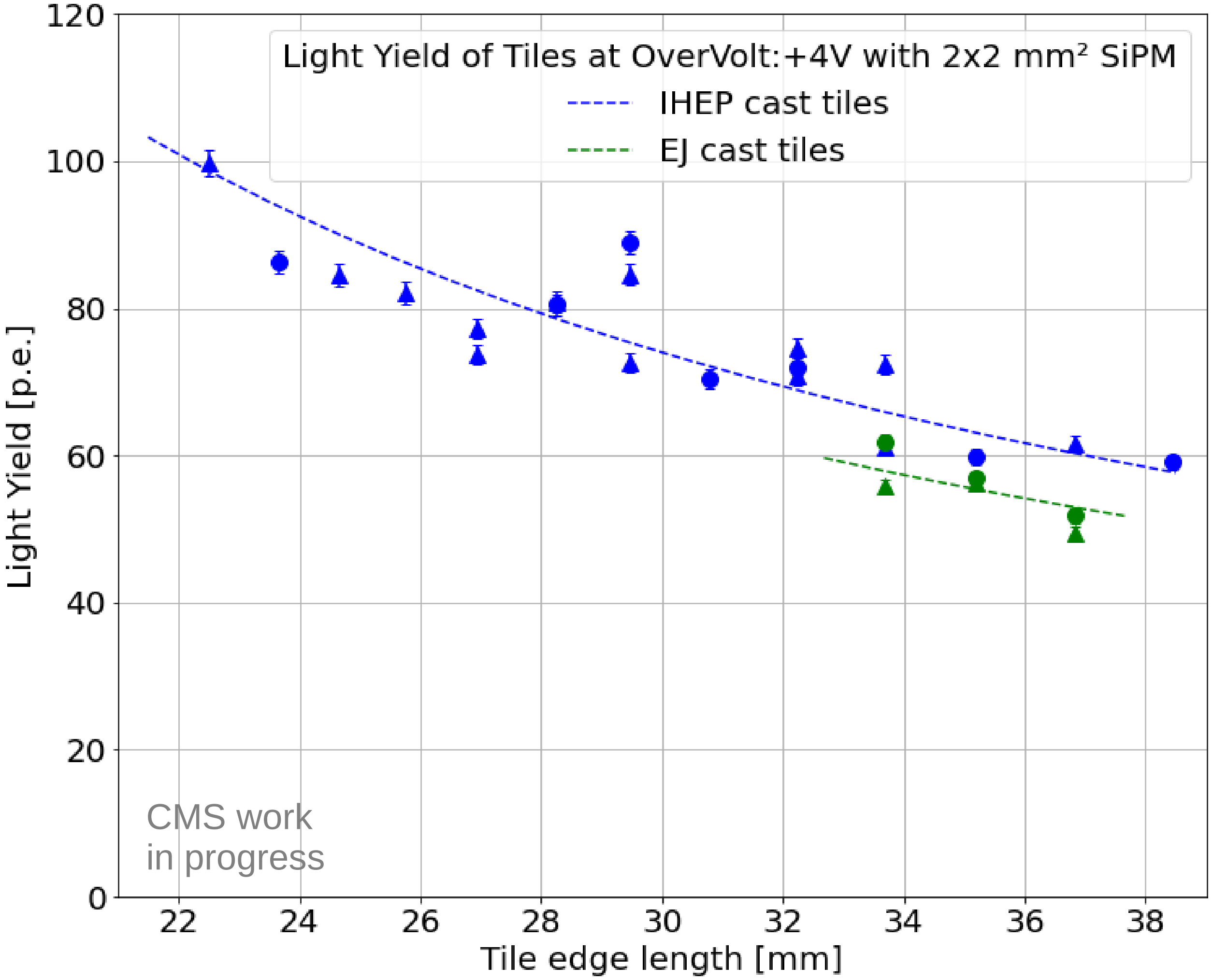
$$\boxed{\mathit{Light\ Yield}[p.e.] = \frac{\mathit{MIP\ maxima}[ADC]}{\mathit{SiPM\ gain}[ADC]}}$$

- Light yield scales with the scintillator tile are and SiPM's active area as:

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

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:

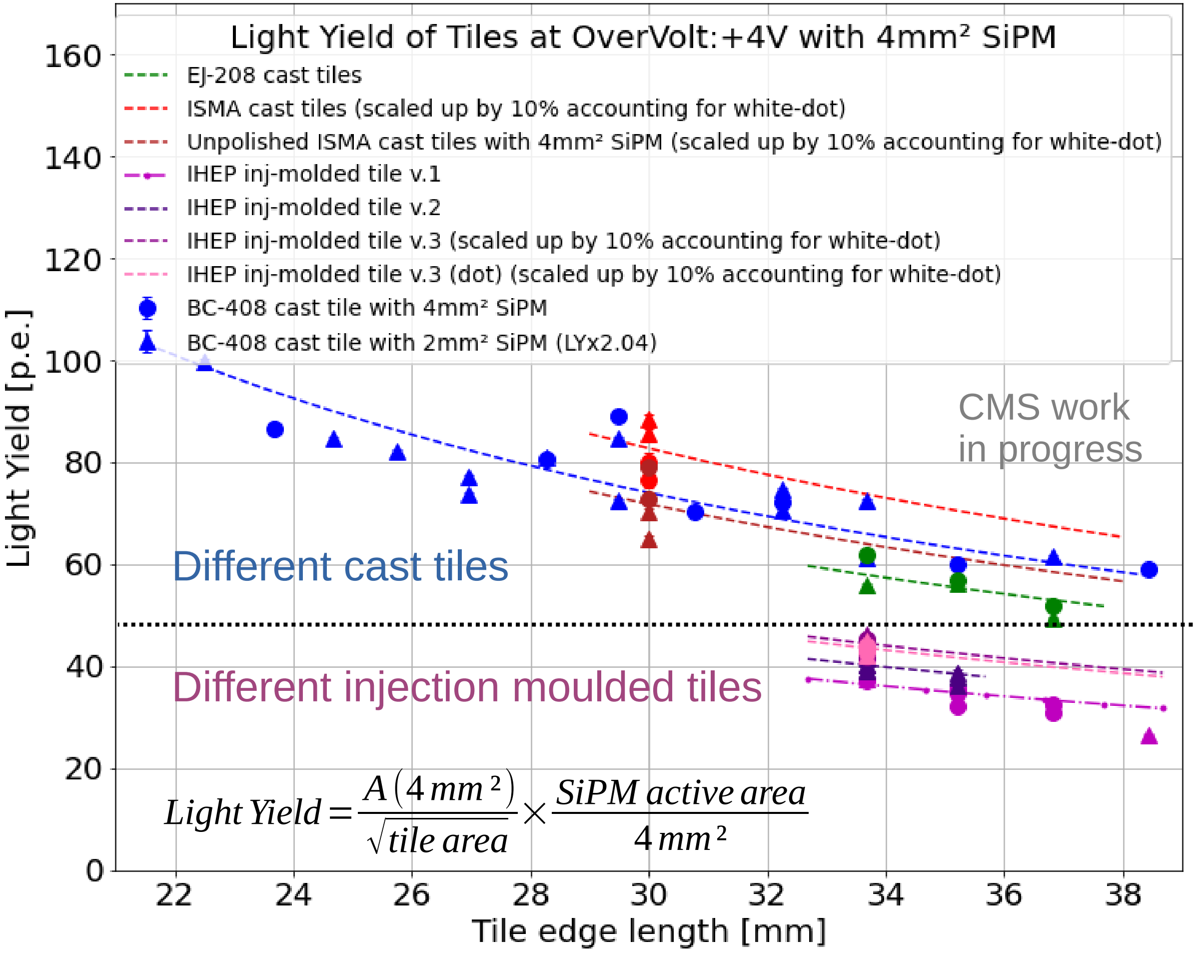
$$\boxed{Light\ Yield = \frac{A(4\,mm^2)}{\sqrt{tile\ area}} \times \frac{SiPM\ active\ area}{4\,mm^2}}$$

- 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



SiPM Noise Measurements with Irradiated SiPMs

Methodology

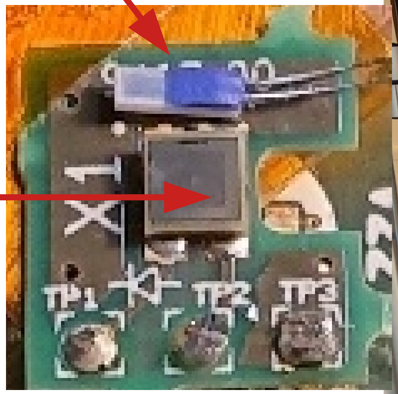
- Fluence increases the leakage current passing through of SiPMs
- SiPM noise is an ADC measurement of the fluctuation of leakage current:

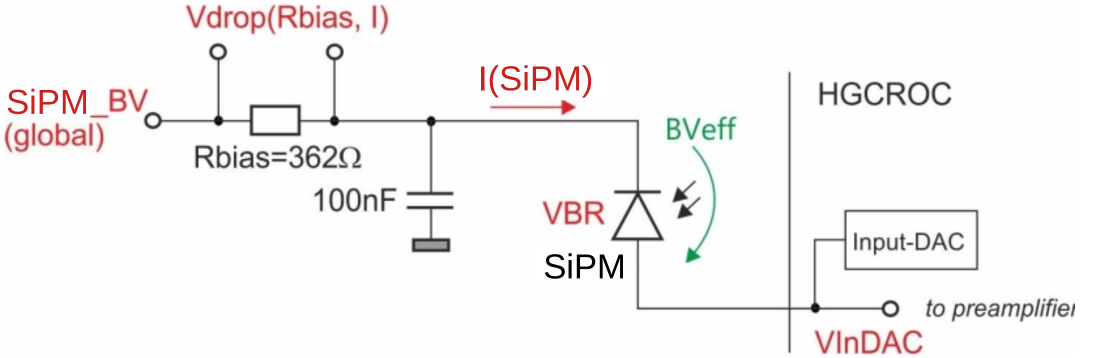
$$\boxed{\textit{Pedestal noise} = \left(A \times \sqrt{\textit{SiPM current}} + B\right)}$$

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

PT1000 temperature sensor

Irradiated SiPM





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

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

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

- $\boxed{Q = \int I \cdot dt = N \cdot G \cdot e}$ where Q = charge collected by SiPM

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

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

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

High Granularity Solution

For Tileboard Type J and K (with 20% less signal to include a safety margin)

- J, K tileboards has the worst SNR in the detector
- Plots below accounts for a possible longer run period and for an additional 20% less light loss
  - Higher granularity will solve this problem