# Beam Tests of the First CMS HGCAL Tileboard Prototypes

## Analysis of DESY Test Beam Data from 2020

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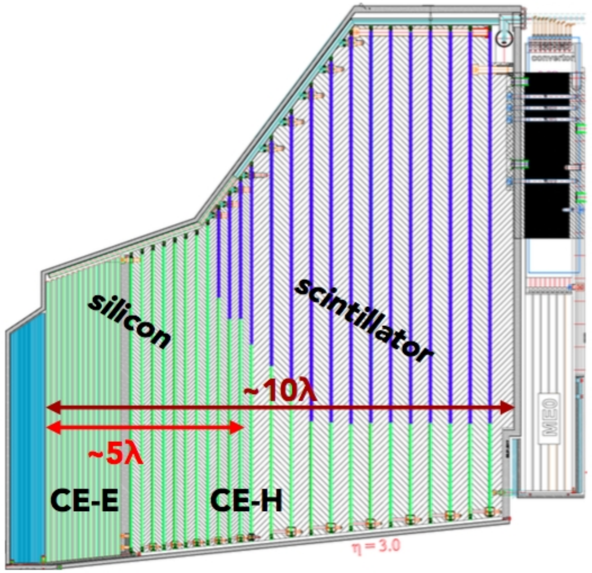
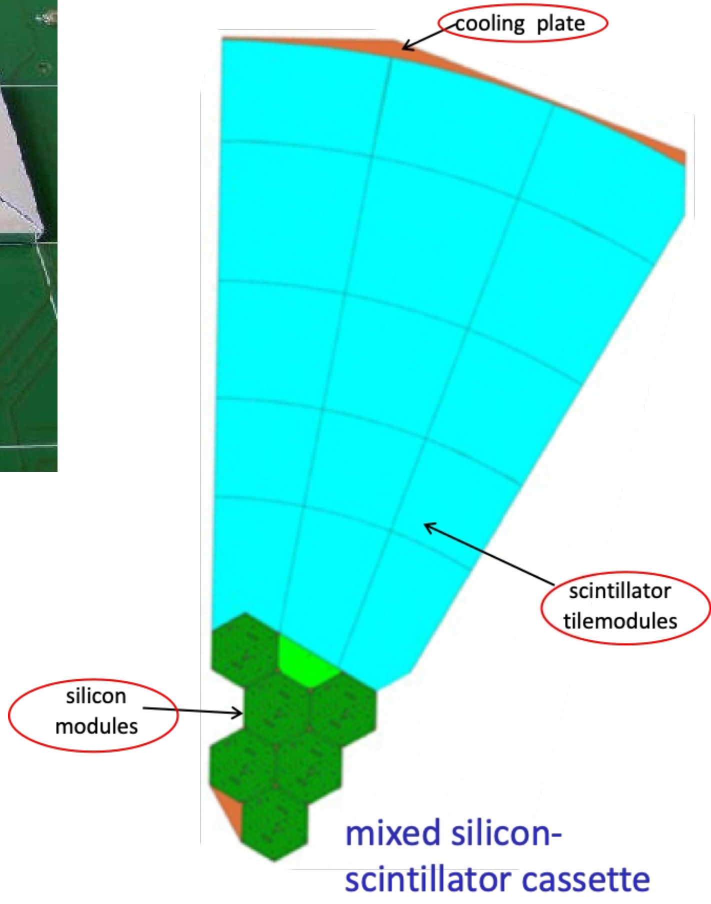
# Scintillator Component of the Hadronic Endcap Calorimeter

## SiPM-on-Tile Technology at CMS HGCAL

- The hadronic part of the endcap calorimeter (CE-H) will consist of
  - silicon detector component (CE-H-Si)
  - scintillator component (CE-H-Sc)
    - in areas where the expected radiation dose during the lifetime of the detector is up to $5 \times 10^{13}\ n_{eq}/cm^2$

- SiPM-on-Tile technology developed by the CALICE collaboration will be used as the active layers
  - Consist of individually wrapped plastic scintillator tiles placed on silicon photomultipliers (SiPM)
  - The tiles are trapezoidal shaped and increases in size as it moves away from the beamline.

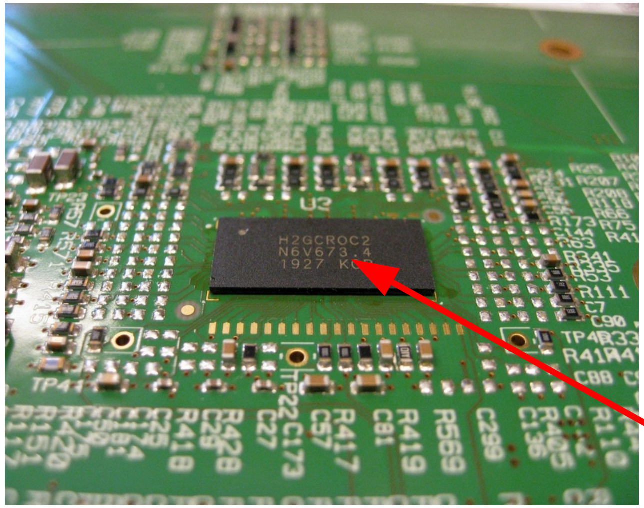



# Scintillator Component of the Hadronic Endcap Calorimeter

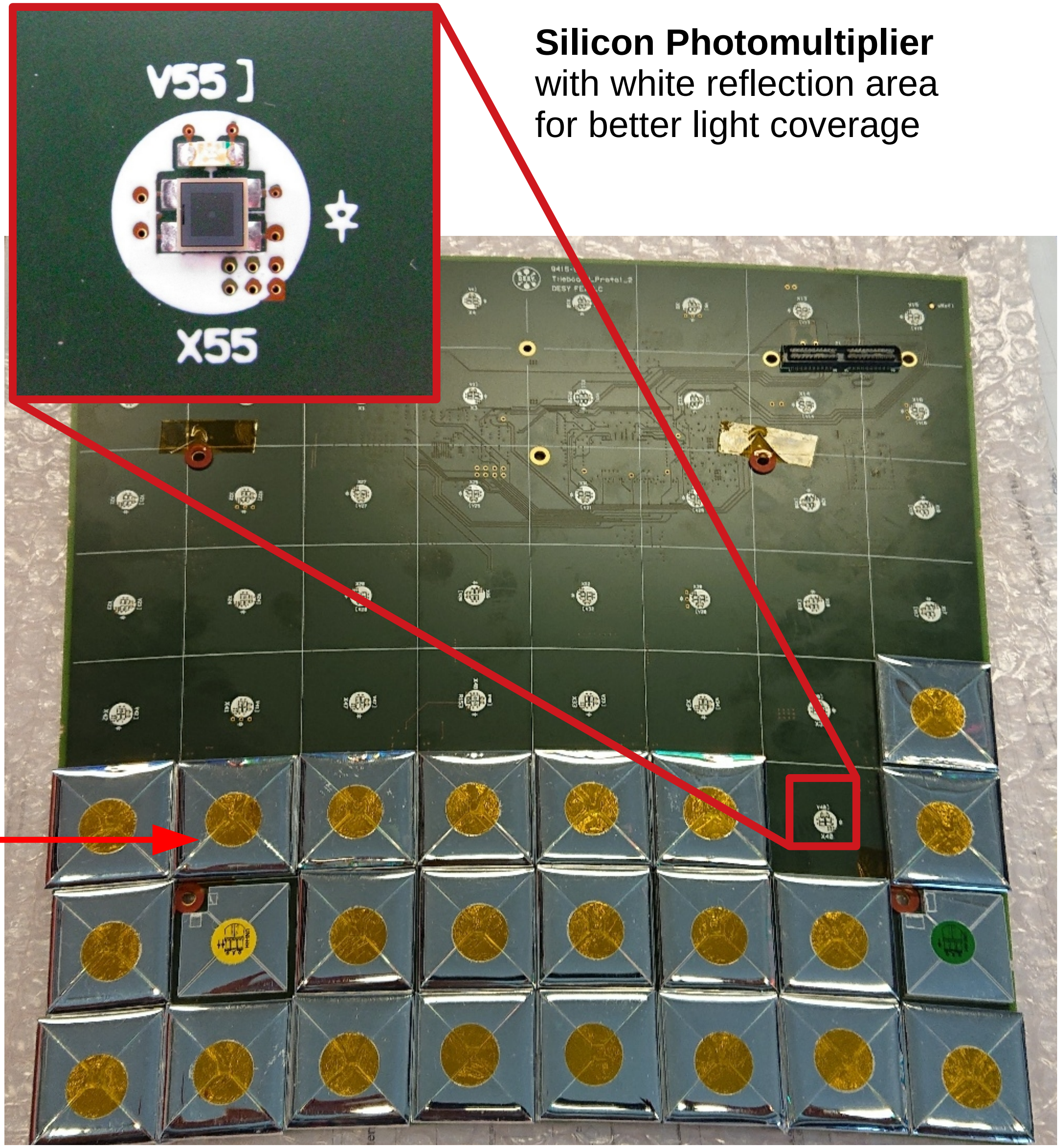
## Tileboard and Front End Electronics

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

- Tileboards hold the SiPMs, scintillators, on-board electronics and LED system.
  - Increases in size when going away from the beamline



**HGCROC on the back side of the tileboard**



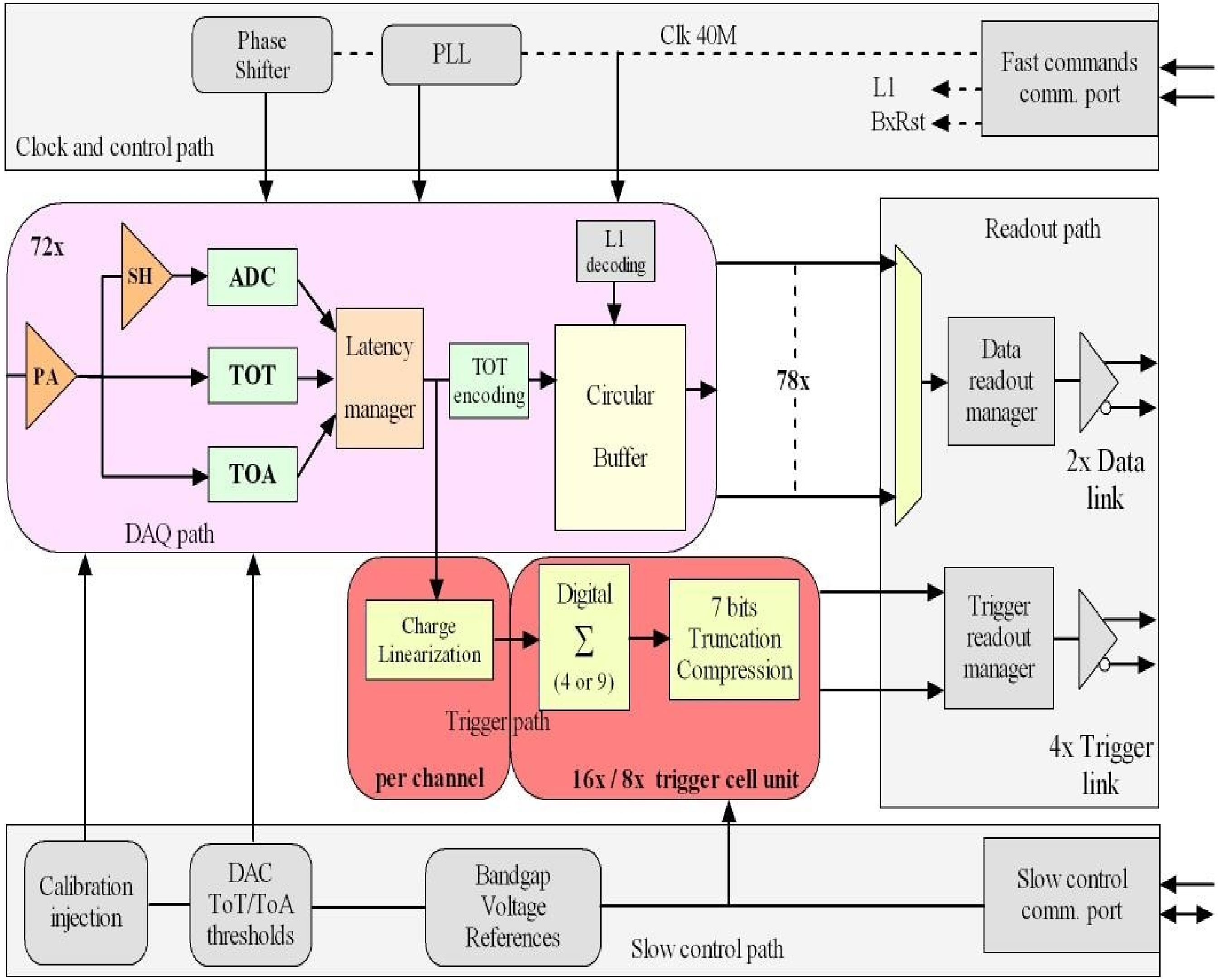

**Silicon Photomultiplier** with white reflection area for better light coverage

**Scintillator tiles on the front side of the tileboard**

# HGCROCv2 Front End Read Out ASIC

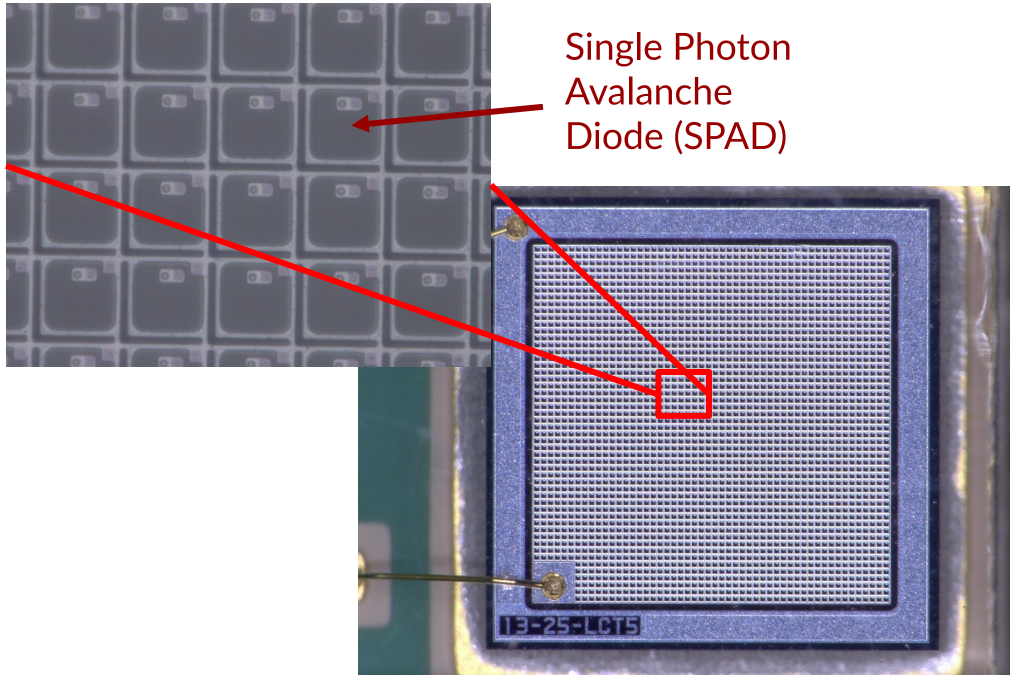
## Introduction

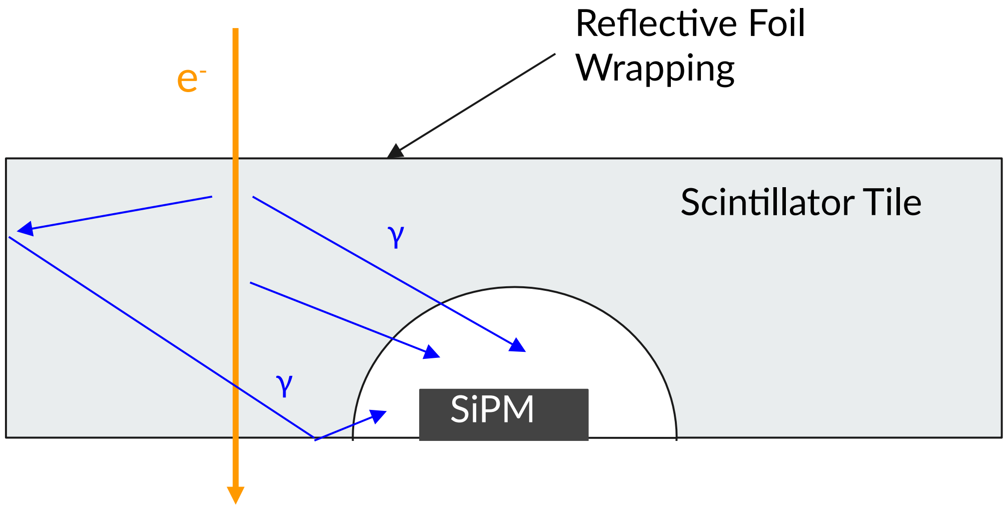
- HGCROCv2: Latest prototype of the front end read out ASIC to be used in the CMS HGCAL
  - CMOS 130 nm (TSMC) technology
- Two versions:
  - Silicon version: For CE-H-Si
  - **SiPM version:** For CE-H-Sc
    - Additional current conveyor for amplification
- Integrates 72 channels to read out
  - **With 64-ch configuration**
  - With 72-ch configuration
- Measurements:
  - 10 bit ADC: pulse amplitude
  - 10 bit time of arrival (TOA)
  - 12 bit time over threshold (TOT)



# SiPM-on-Tile technology

## Working Principle



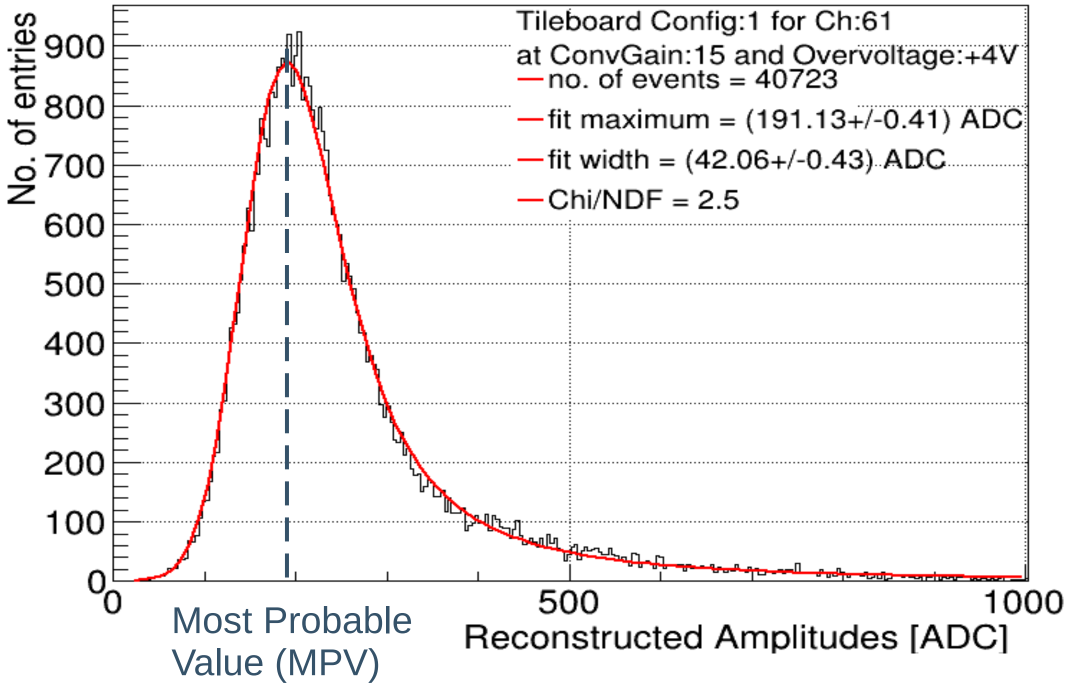

- Charged particles passing through the wrapped tiles scintillate producing scintillation photons.
- These photons are reflected back onto the SiPM with the help of the reflective foil wrapping
- On-board electronics converts the obtained charge into digital signals

- SiPMs consist of 1000s of single photon avalanche diodes (SPAD)
- Each diode is sensitive to single photons

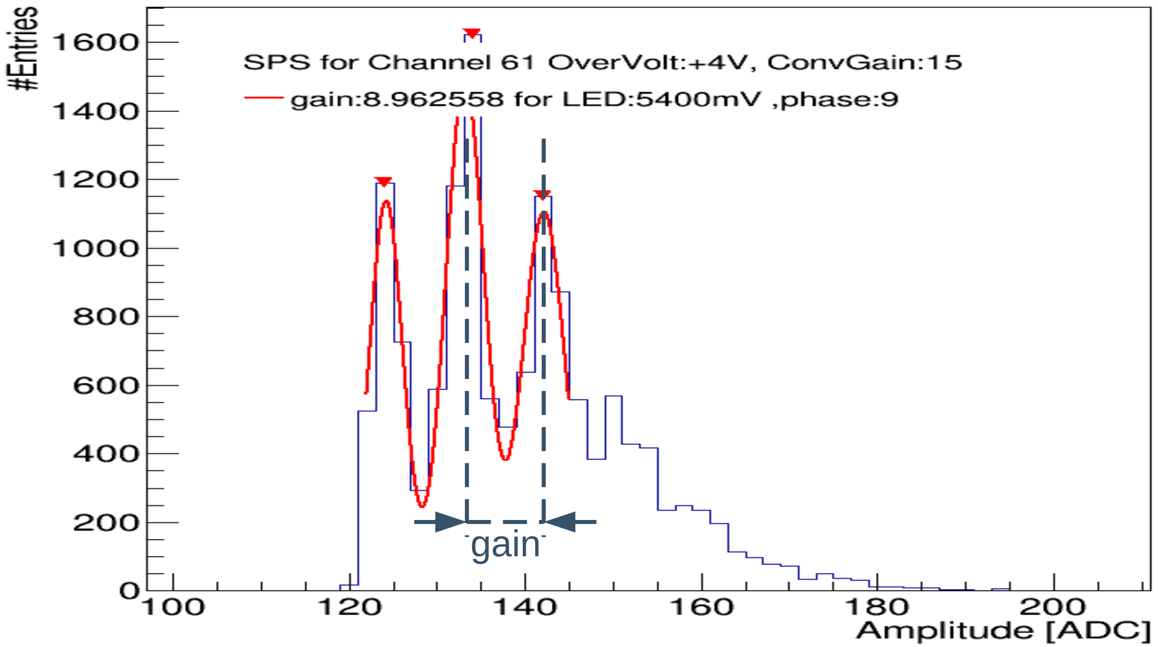
# SiPM-on-Tile technology

## Calculation of Light Yield

- MIP calibration from beam data:
  - Energy deposited in the scintillator tile follows a convoluted Landau-Gaussian function




- Single photon counts:
  - Using a low intensity LED to fire few individual cells of the SiPM.
  - Results in a single photon spectrum (SPS)
    - Can measure the separation between individual peaks → gain

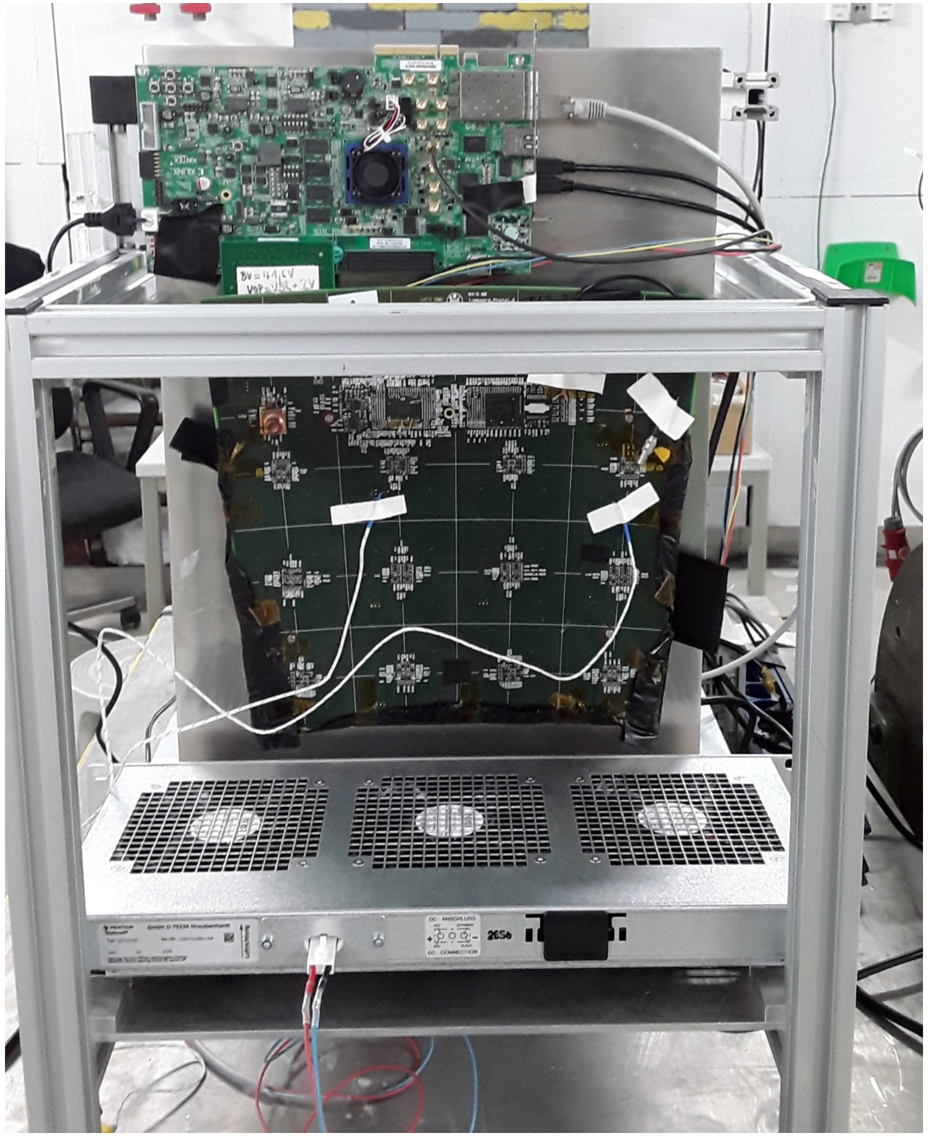



**No. of photons captured (Light Yield) is given by dividing the MPV of the signal by its SPS gain in photon equivalent units (p.e.).**

# Tileboard at the DESY Test Beams 2020

## Introduction

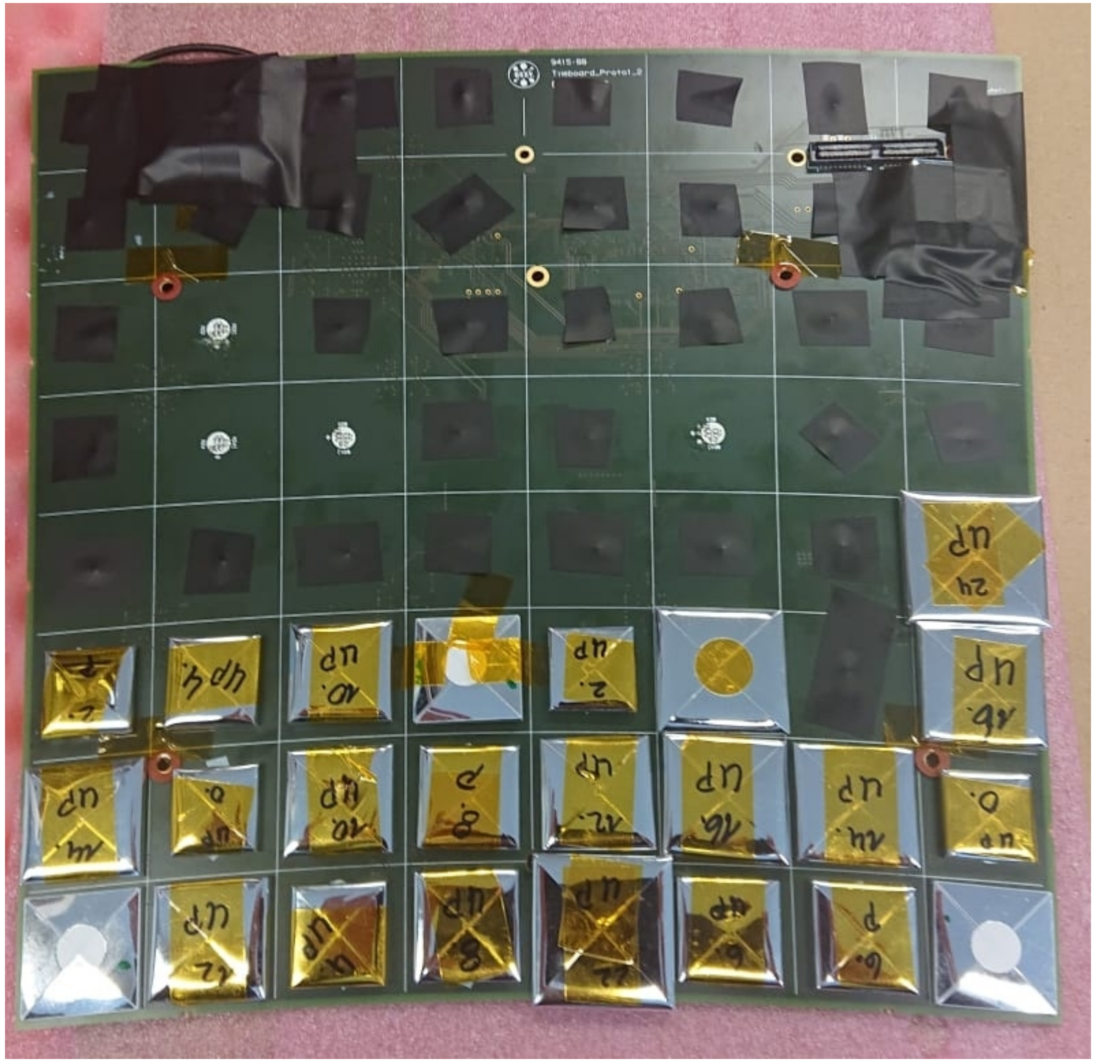
- The first prototype CMS HGCAL tileboard was tested at the DESY test beam facility between 17th to 23rd August and 19th and 25th October 2020.
- Objectives
  - Test the capabilities of the HGCROCv2
  - Establish triggered operation and multi-sample readout with beam
  - Test response to particles
  - If everything works: measure light yield with realistic electronics, SiPMs and tiles
    - **Scintillator material:** moulded and cast tile prototypes
    - **Reflector foil:** different wrapping cuts
    - **Tile sizes:** verify dependence for small cast tiles
    - **Irradiated SiPMs:** operate a noisy SiPM



# Tileboard at the DESY Test Beams 2020

## Tileboard Setup

- The lower half of tileboard is equipped with:
  - **SiPMs** used were Hamamatsu HDR-2 type photomultipliers custom made for the HGCAL upgrade
    - 12 x unirradiated 15 µm pitch, **2 mm² area** SiPMs
    - 12 x unirradiated 15 µm pitch, **4 mm² area** SiPMs
    - 2 irradiated SiPMs one each from above
      ($2x10^{12}$ n/cm$^2$ at room temperature
      ~$5x10^{13}$ n/cm$^2$ at -30$^o$ C)
  - **Scintillator tiles**
    - MEPHI produced injection-moulded tiles
    - IHEP cast tiles (BC-408)
      - Of varying sizes
    - CALICE reference tiles
      - Injection moulded tiles produced for AHCAL prototype of 2018
        *(see talk by J. Kvasnicka, L. Emberger)*



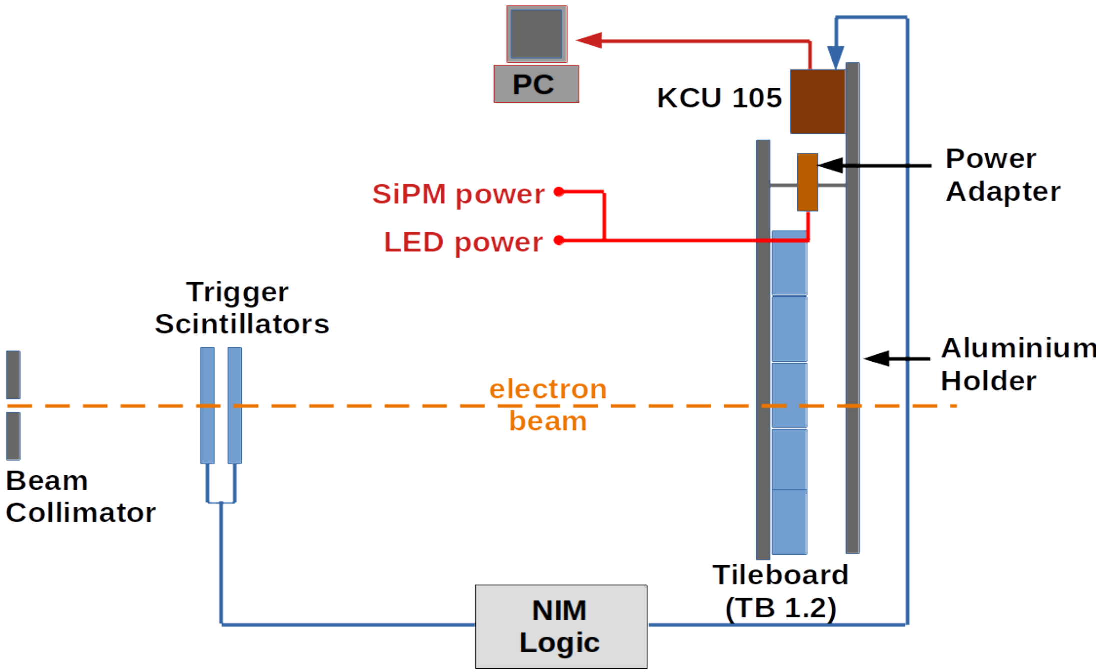
# From the Test Beams

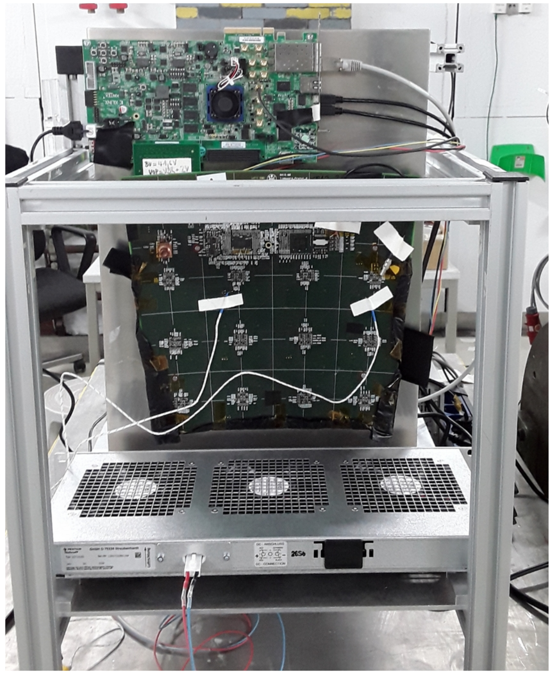
## Measurements

- **Single Photon Spectral data** using LED system (~7,000 events per run for different LED voltages)
  - For over-voltages : 2V, 4V, 6V
  - Conveyor gain : 12, 15

- **Beam Data** with the 3 GeV electron beam hitting each channel (~10,000 events per channel + few long scans with over 100,000 events)
  - For over-voltages : 2V, 4V, 6V
  - Conveyor gain : 1, 2, 4, 8, 12, 15

- KCU105 module is used for data acquisition
  - Commercially available FPGA evaluation board

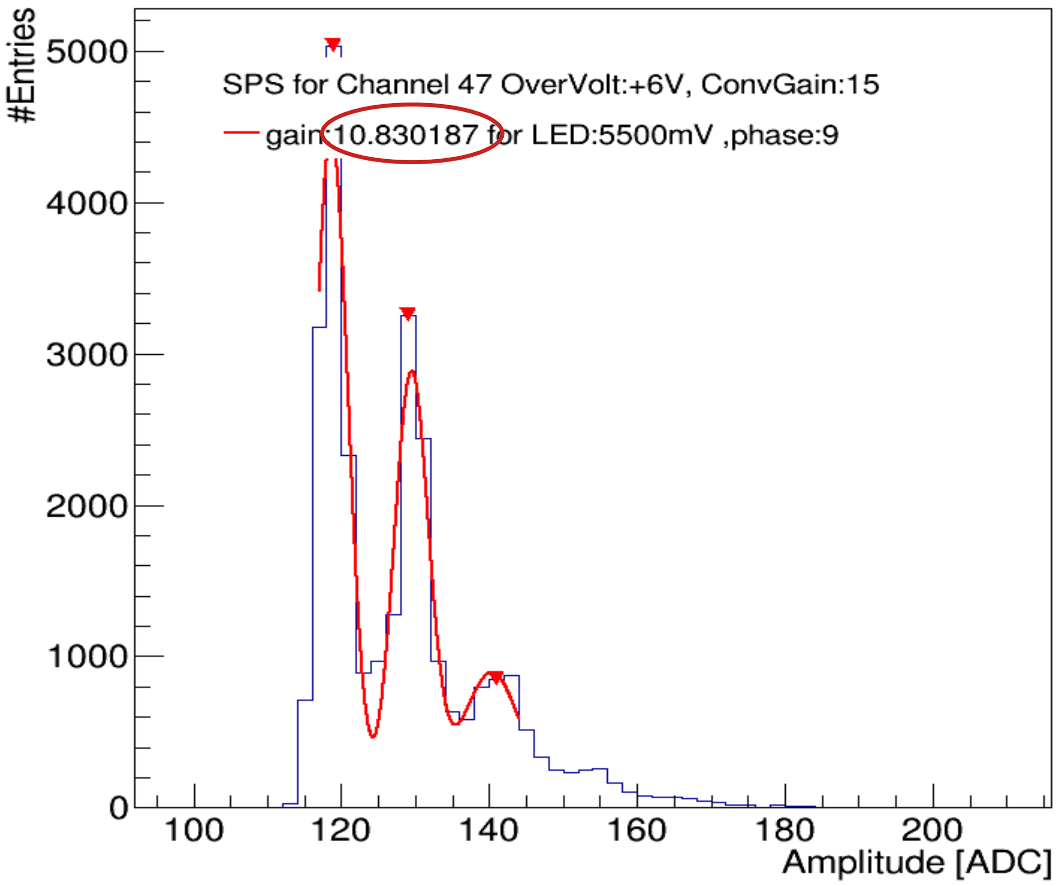


# Calibration Data from the October Testbeam

## Using LED system

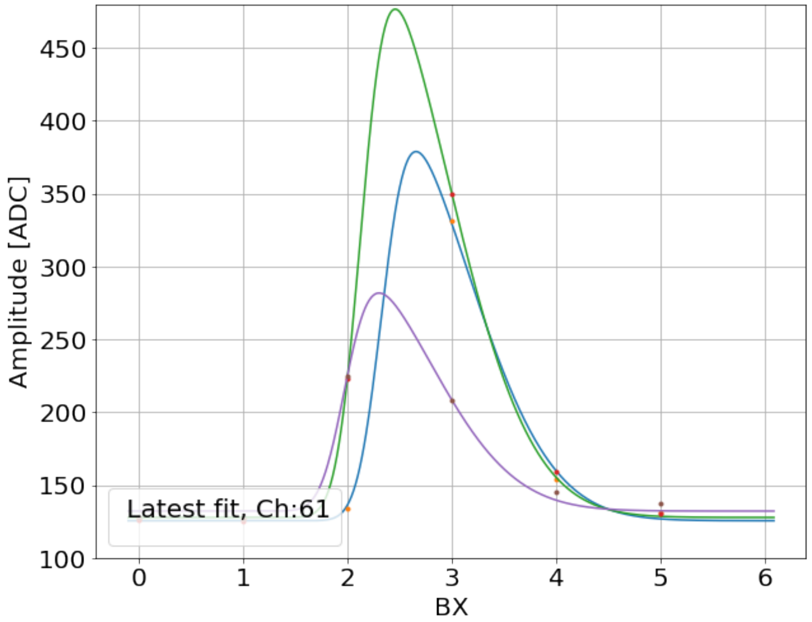
- SPS is visible at **over-voltages +4V and above** in most channels for **conveyor gain = 15** (highest possible)
  - A differential non-linearity in the HGCROC prevents from getting a visible spectra for lower over-voltages and conveyor gains.
  - Correction at higher over voltages possible by rebinning
- Final version of the tileboard to be installed at CERN is expected to run at conveyor gain = 4 and over-voltage = 2V
  - **Requires further research and development to obtain estimates of SPS from lower conveyor gains at over-voltage 2V**
    - Work in progress

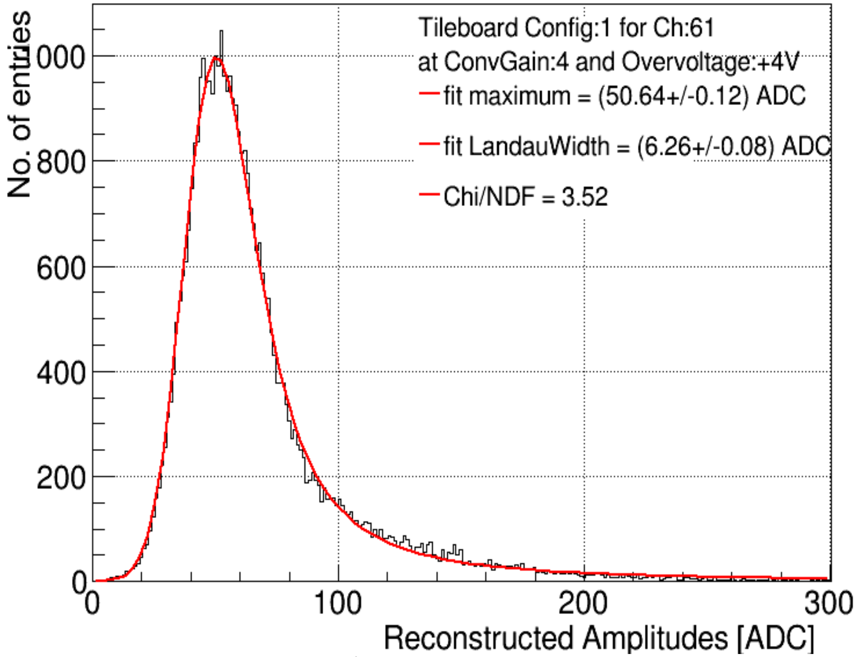


# Pulse Fit Correction

## Optimization of Fit Parameters

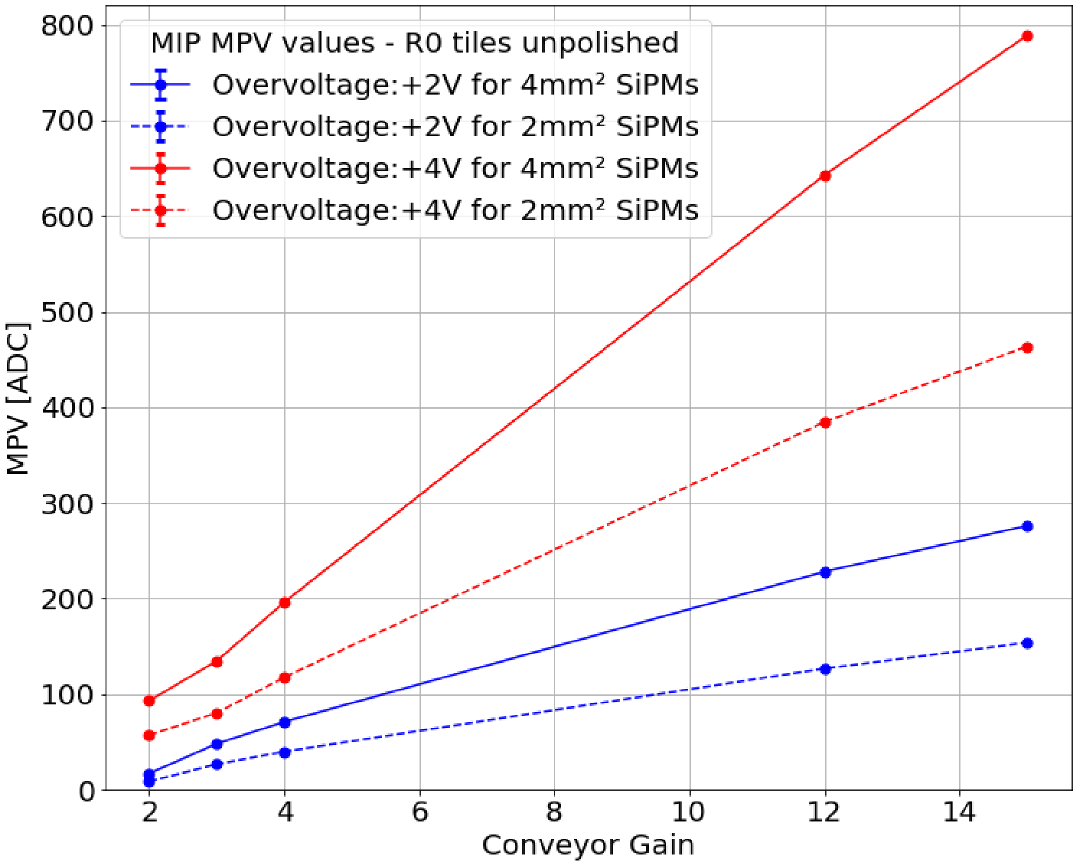
- HGCROC samples the signal at 40 MHz corresponding to the collision frequency
- DESY beam is **non-synchronous to the system**. Therefore pulse maxima needs to be extracted offline
- Pulse amplitude is reconstructed from the maxima of a multi-sample event-by-event template fit
  - 6 points sampled at 25 ns rate per event is fitted using a skewed-Gaussian fit with fixed std. dev and skewness.
  - Based on pulses from sampling scan using the LED system
- We see physics signals with our pulse reconstruction
  - **First ever beam particle signal observed using the HGCROC**



# Dependence of MIP MPV with Current Conveyor Gain

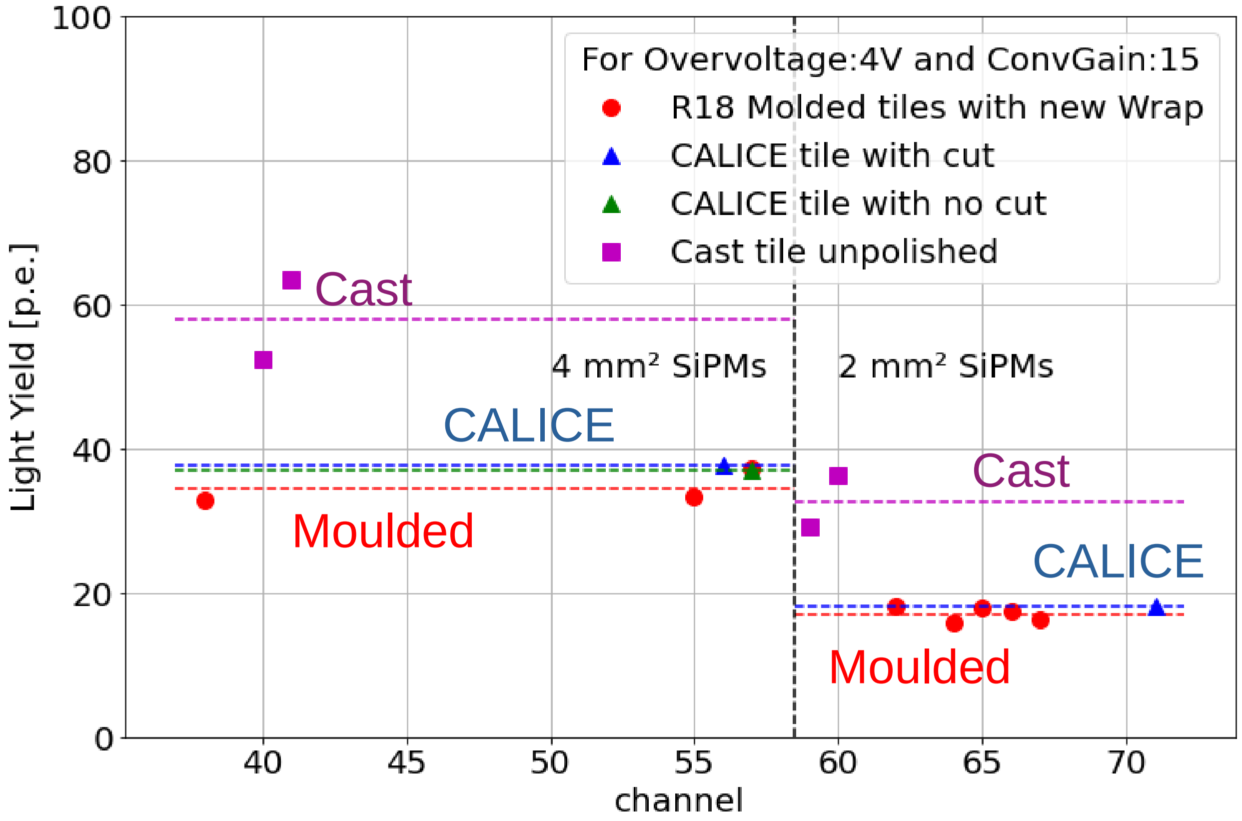
## From October Testbeam




- MPV appears to increase linearly with conveyor gain for all channels.
- **Light yield analysis is not possible for conveyor gain < 15** as SPS is only observable for conveyor gain = 15 at over voltage = 4 V and above.

# Light Yield Comparison

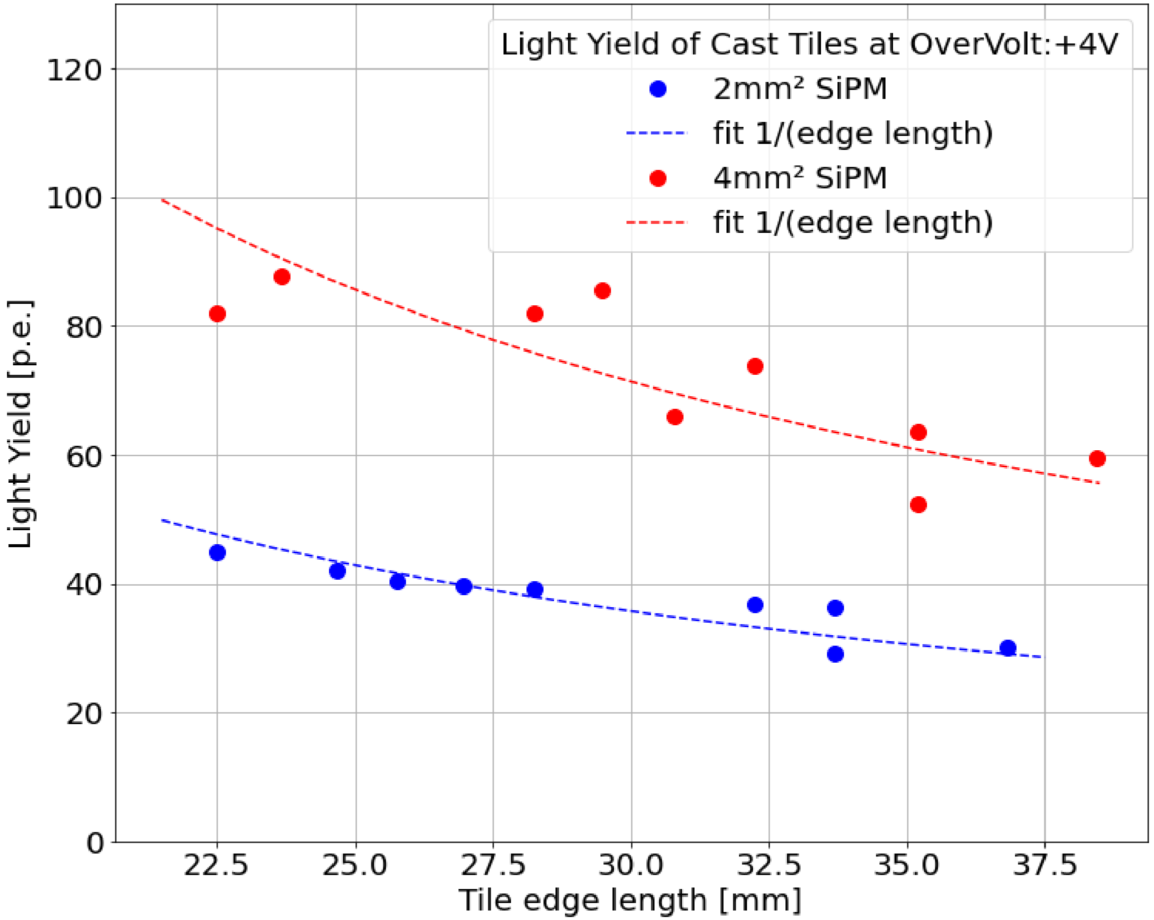
## Envelope-type Foil Wraps – Molded, Cast and CALICE tiles




- Light yield comparison for different SiPMs **looks consistent with scaling by active area** for most tiles
  - (i.e. LY_4mmSiPM = ~2*LY_2mmSiPM)
- Cast tiles appear to have a **factor 2 higher light yield** than molded tiles as expected
- Small discrepancy for cast tiles on 4mm2 SiPMs
  - Due to large scatter of measurements and small statistics

# Light Yield Comparison

## Cast Tiles – Different Sizes




- Light yield (LY) decreases as a function of tile size (A) as:

$$LY \sim \frac{1}{\sqrt{A}} \sim \frac{1}{tile\ edge\ length}$$

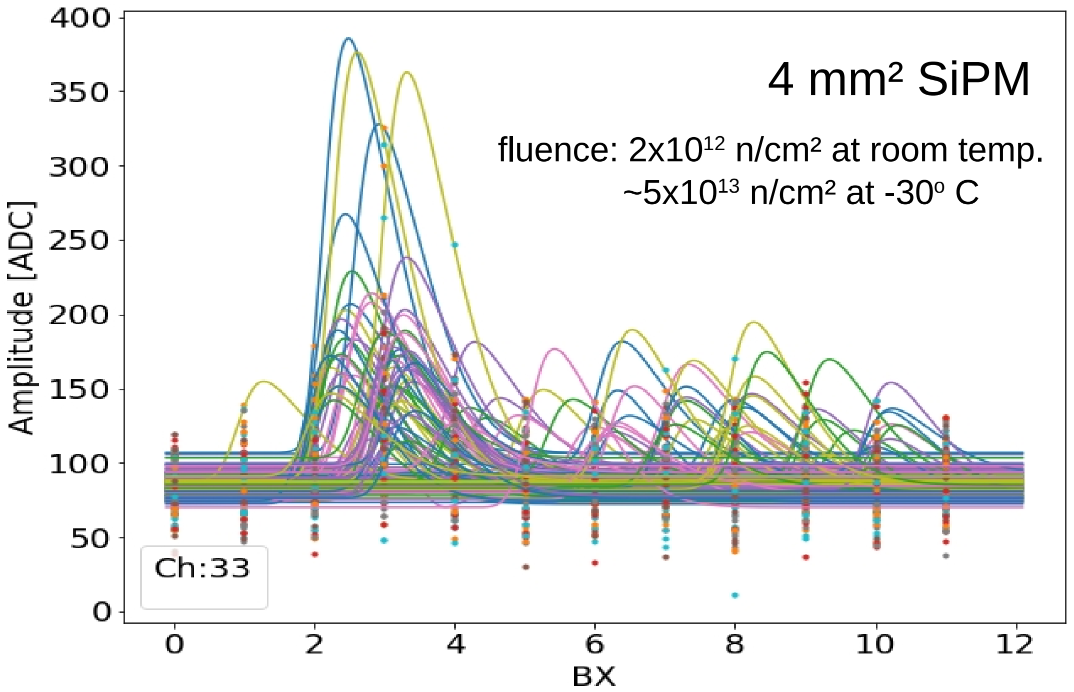
  - Consistent with results

- Fits show that the ratio between 4mm² and 2mm² tiles is ~2 as expected.

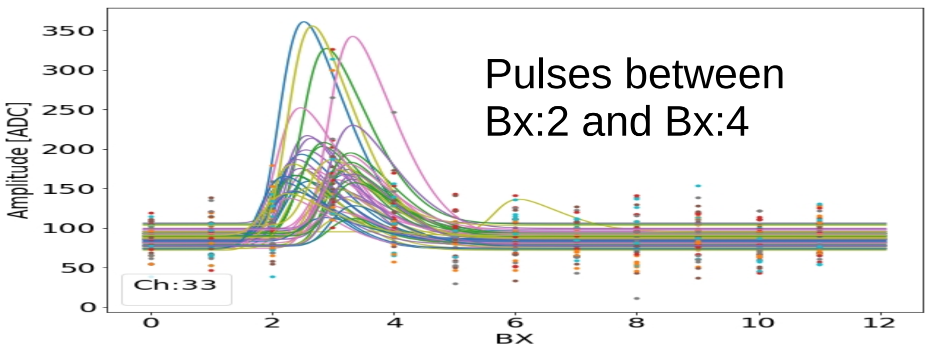
- Need more statistics to reduce the uncertainties

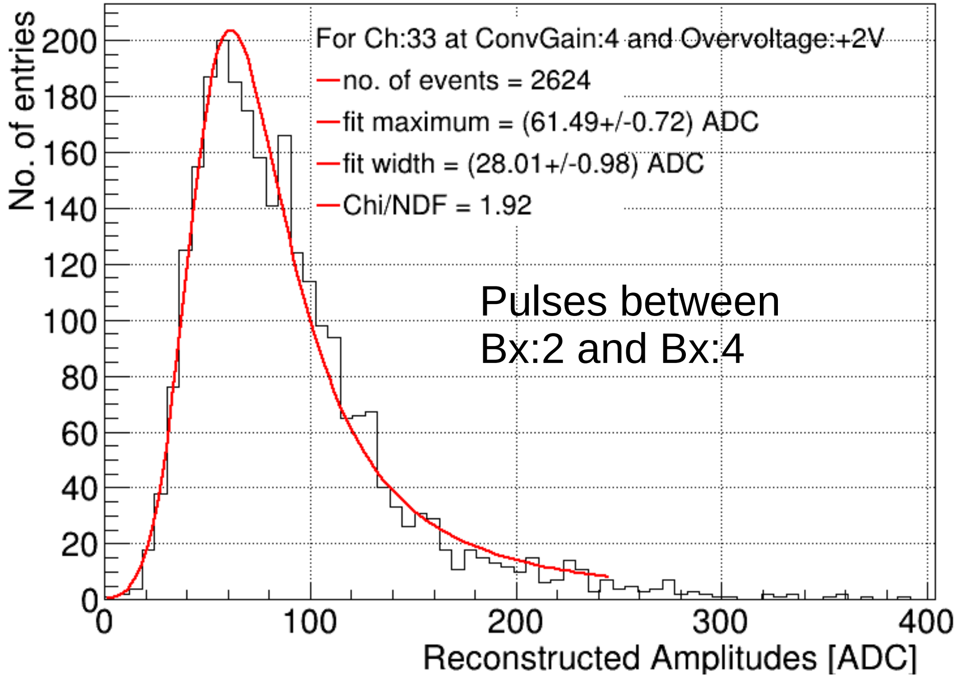
# Irradiated SiPM pulses

## Basic Pulses from both channels




- 12 samples were taken for irradiated channels
- Pulse max should be between Bx:2 and Bx:4
  - Seen in results
  - Other Bx: Pedestal fluctuations
- **It is possible to extract a signal from irradiated SiPMs**




**Analysis still on-going**

# Summary and Outlook

## CMS HGCAL Test Beams

- SiPM-on-Tile technology developed by the CALICE collaboration is being applied as a solution for the high pileup expected at the high-lumi LHC upgrade

- The test beams at DESY gave the **first beam particle results from the front-end electronics to be used at the HGCAL**

- The test beam also compared many SiPMs, tiles of different sizes, wrappings and 2 irradiated SiPMs

- **Light Yield:**
  - Cast tiles produce much more light than molded tiles. Close to a factor of 2.
    - Need higher statistics to confirm with certainty
  - Different sizes of cast tiles tested follow the expected distribution

- **Irradiated SiPMs:** Preliminary results show that it is possible to extract a signal from irradiated SiPMs

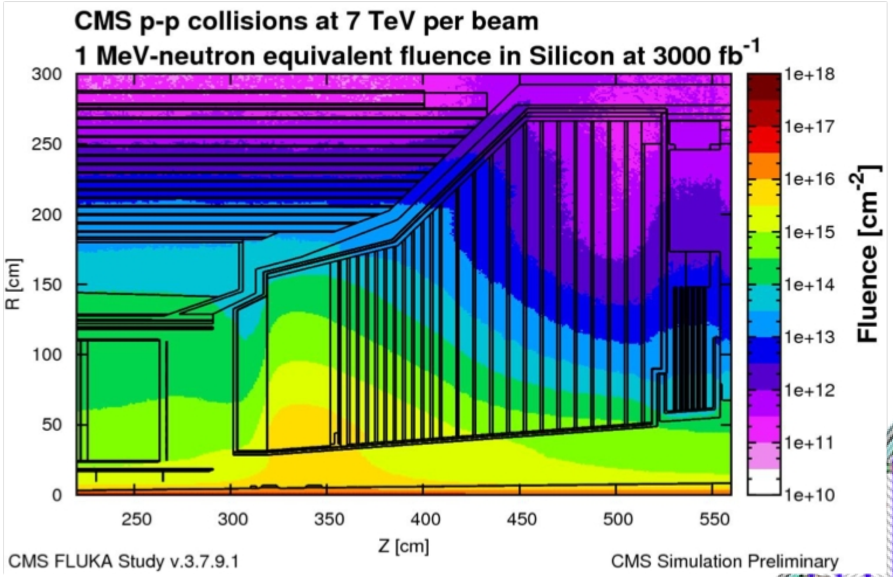
# High Granularity for the High Luminosity LHC

## Phase II Upgrade of the End-Cap Calorimeter

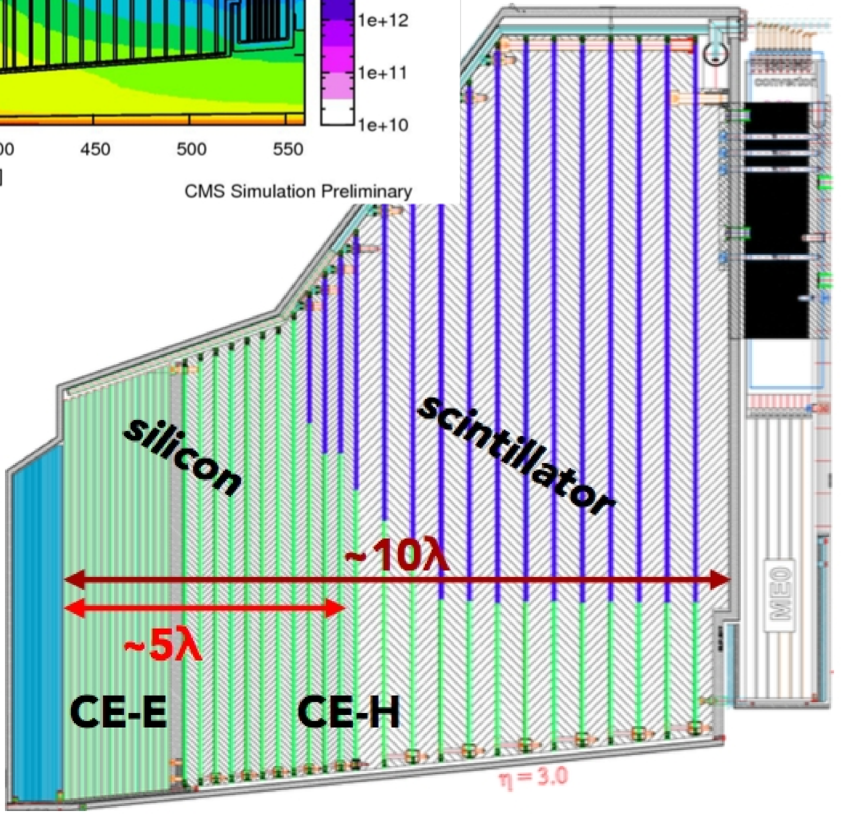
- HL-LHC will integrate ten times more luminosity than the LHC

- This poses significant challenges for radiation tolerance and event pileup on detectors, especially on the end cap calorimeter

- The Silicon and SiPM-on-Tile technology, originally developed for e+e- colliders (CALICE), are also among the very few possible choices for the radiation conditions at the upgraded LHC.



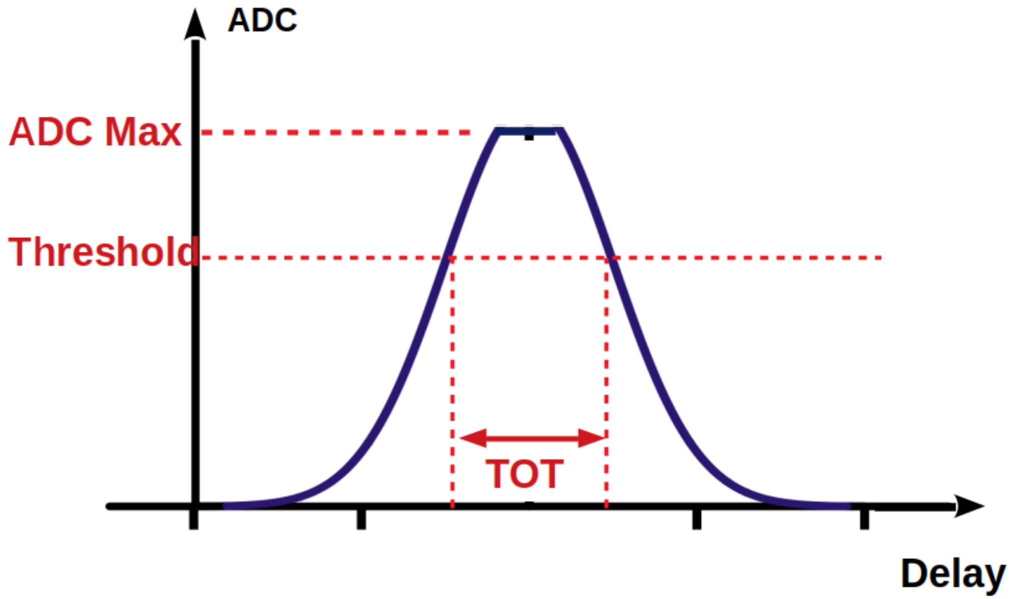

- **CE-E (electromagnetic part):**
  - stack up of lead absorber alternated with active layers of silicon sensors
- **CE-H (hadronic part):**
  - made of steel absorber with insertable cassettes.
  - Where radiation fields allow, the CE-H is instrumented with SiPM-on-tile sharing mixed cassettes with silicon sensors nearer to the beam pipe.

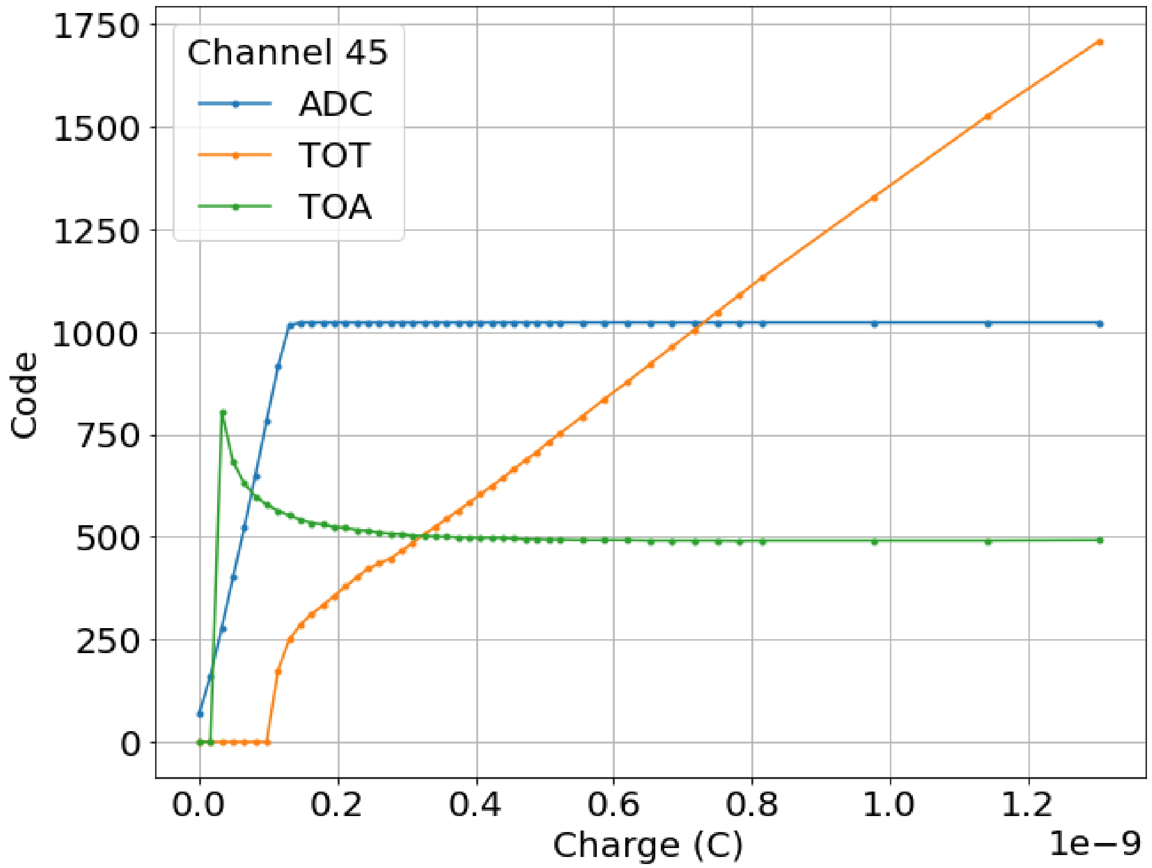


# Charge Measurement with HGCROCv2

## Low and High Gain Modes

- Pulse amplitude before saturation: ADC measurement
- Pulse amplitude after saturation : TOT measurement



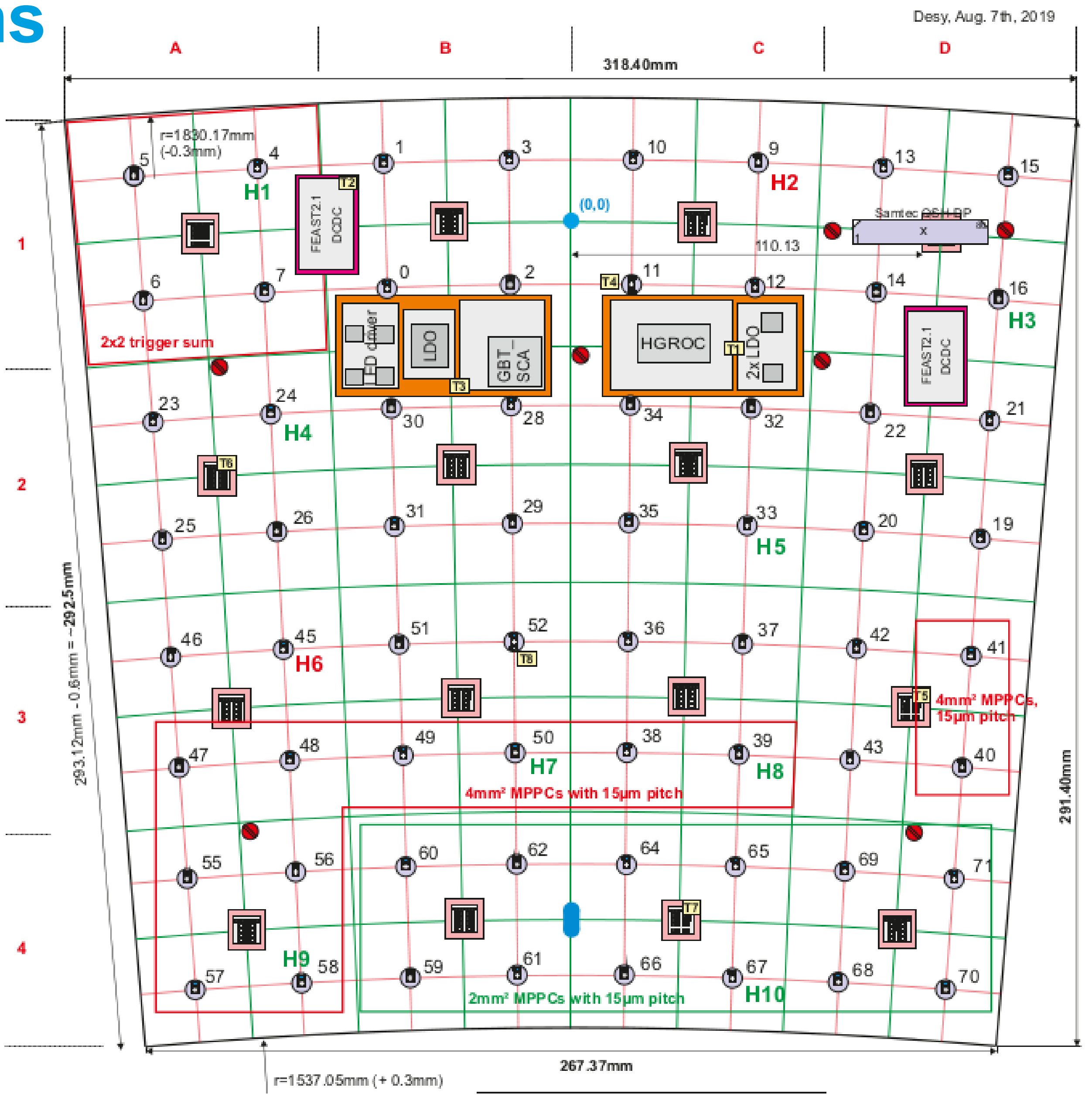




Measurement using external charge injection into the HGCROC channel 45

# Tileboard at the two test beams

## SiPMs

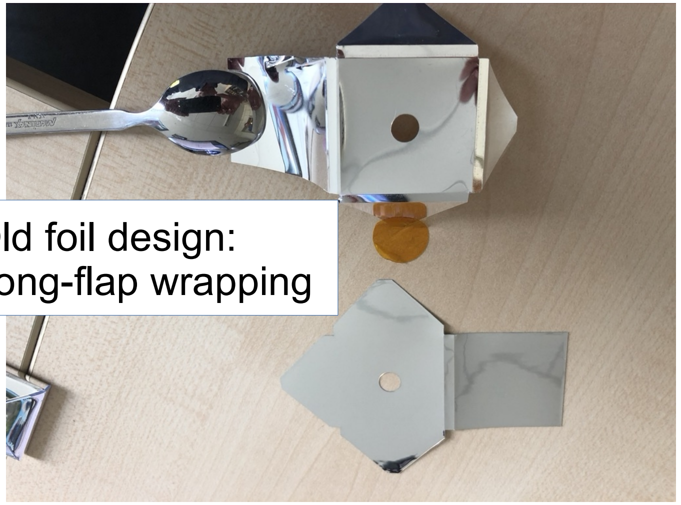
- Bottom half of tileboard was equipped with Hamamatsu S14160 series SiPMs in both testbeams:
  - Custom made SiPMs for HGCAL with improved radiation hardness
    - 12 cells with 15 µm, **2 mm²** SiPMs
    - 12 cells with 15 µm, **4 mm²** SiPMs
- SiPMs in 5 positions replaced in October testbeam with holder PCBs containing a SiPM (H1,H3,H4,H5,H7)
  - **Irradiated SiPMs** (fluence: $2\times10^{12}$ n/cm² at room temp: JSI Ljubliana)
    - 2 mm² and 4 mm² – one from each size
  - Un-irradiated SiPMs (for reference)
    - 2 mm² and 4 mm² – one from each size
  - One new 2 mm² SiPM **with WB package**



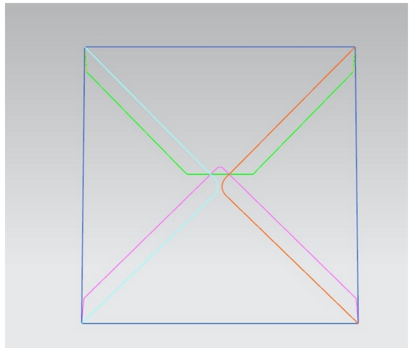
# Tileboard at the October test beam

## Scintillator Tiles in Configuration 1

- The lower half of tileboard is equipped with:
  - **MEPHI moulded tiles with envelope style wrapping**
    - R18, R20 Tiles
  - **MEPHI moulded tiles with long flap wrapping**
    - from previous beam test for reproducibility study
    - R18, R20 Tiles
  - **CALICE reference tiles**
    - With mechanical cut-out
    - Without mechanical cut-out
      - On SiPMs on holder PCBs
  - **IHEP cast tiles with envelope style wrapping**
    - Unpolished (Tiles marked UP)
    - R18, R20 Tiles



Old foil design:
Long-flap wrapping



New foil design:
Letter Envelope Inspired

# Foil Optimisation

## Tests with small series (Felix Sefkow, Sept 2020)

**Wrapping tests with long flap design**

- Original idea: overlap limits light leakage

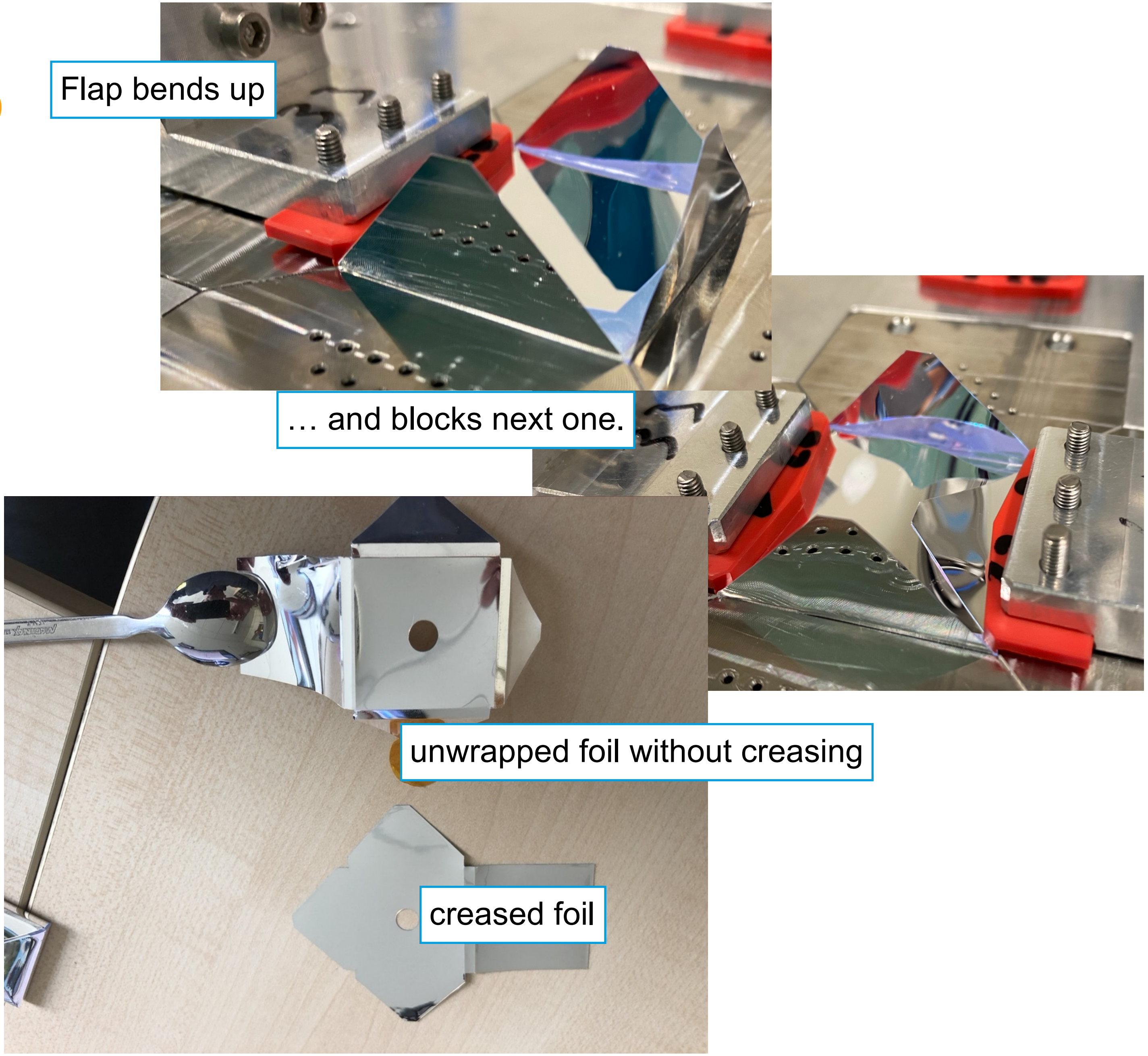
**Long flap causes frequent problems at wrapping step**

- does not occur in manual wrapping tests
- persists also with somewhat shorter or narrower flaps

**Re-introduce creasing in foil preparation**

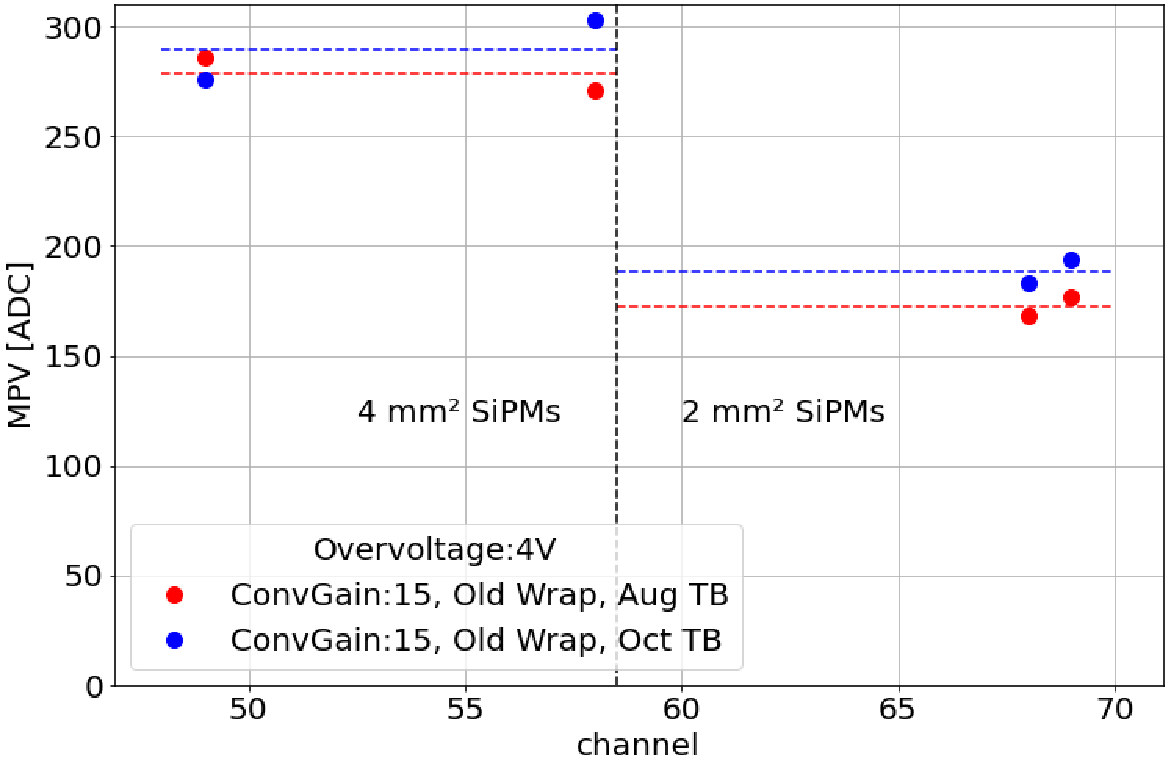
- no noticeable difference
- wrapping tool produced sharp edges, too

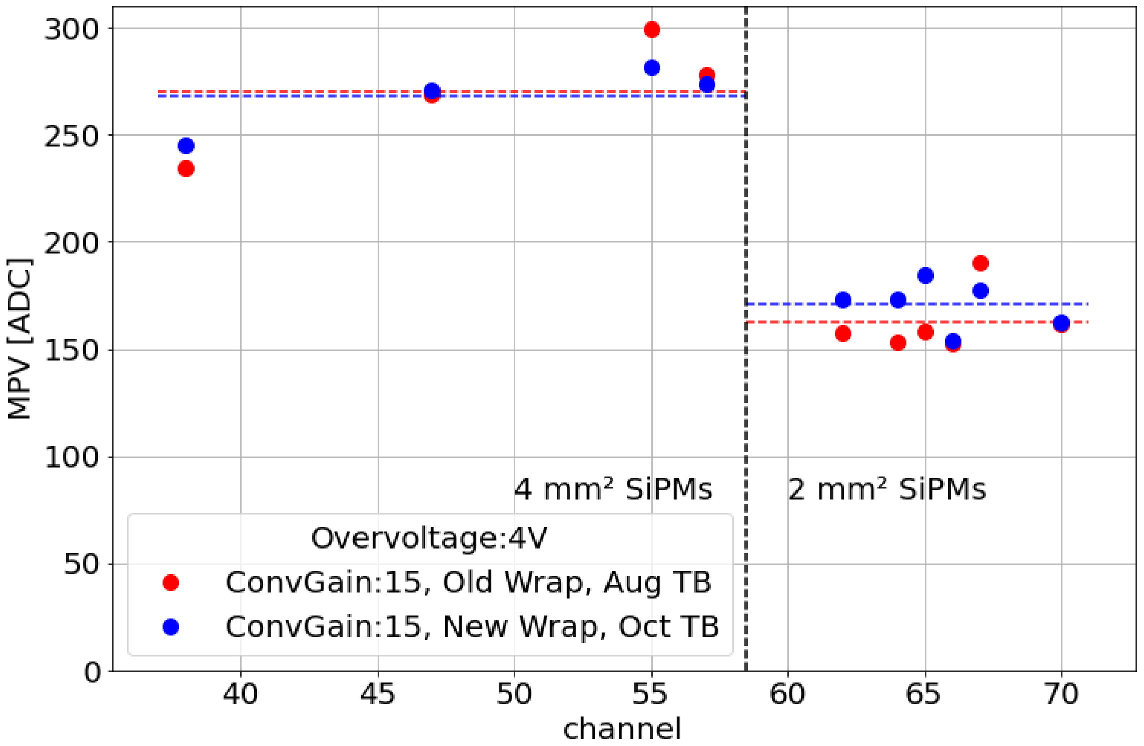
**Conclusion: need to withdraw our premature “green light” for long flap design**



# MIP MPV Comparison of Two Testbeams

## Reproducibility Test and Comparison of Old and New Wrappings

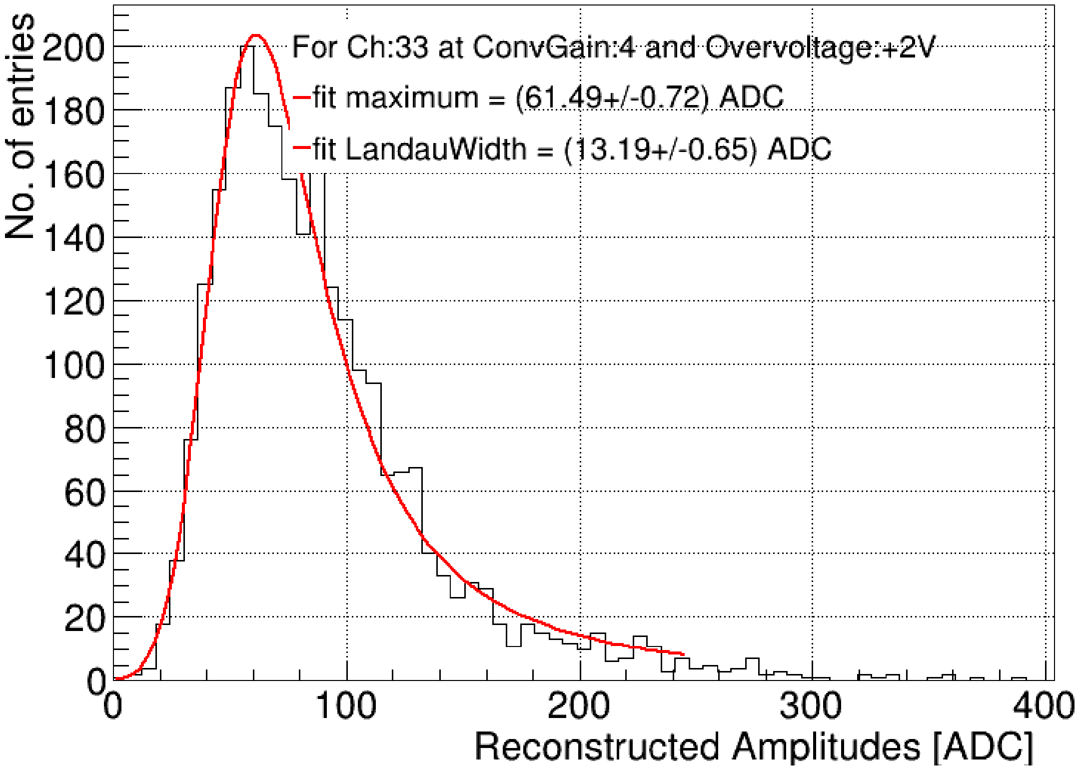



- Left plot:
  - Direct comparison of long arm wrap (old wrap) between the two testbeams
  - Results reproducible between two testbeams
    - 4-9 % difference in results
- Right plot:
  - August testbeam: Consists of long arm wrap (old wrap)
  - October testbeam: Same tileboard, envelope-type wrap
  - Within uncertainties, no difference between two wrappings

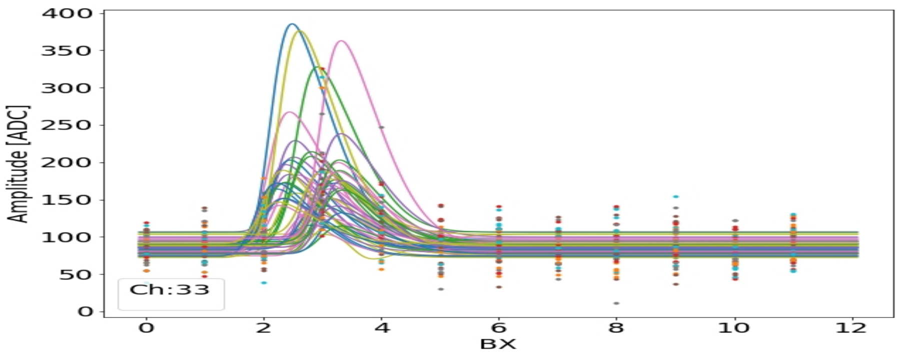
# Irradiated SiPM pulses

## MIP MPV for Channel 33 for ConvGain:4 (4mm² SiPM)




- Data plots with max between Bx:2 and Bx:4

**Analysis still on-going**




$$w_{irr} = \sqrt{w_{pedestal,irr}^2 + w_{signal}^2} \qquad w_{noirr} = \sqrt{w_{pedestal,noirr}^2 + w_{signal}^2}$$

Where $w_{signal}$ denotes the “genuine” width from the signal formation (Landau distribution and photo-electron statistics).

Since $w_{signal}$ should be same for irradiated and non-irradiated SiPMs, and if we neglect $w_{pedestal,noirr}$:

$$w_{irr} = \sqrt{w_{pedestal,irr}^2 + w_{nonirr}^2}$$

**For irradiated Ch:33 SiPM (4 mm² SiPM):**

$w_{irr}$ = 28.01 ADC

$\sqrt{w_{pedestal,irr}^2 + w_{nonirr}^2}$ = 26.33 ADC

**For irradiated Ch:24 SiPM (2 mm² SiPM):**

$w_{irr}$ = 20.64 ADC

$\sqrt{w_{pedestal,irr}^2 + w_{nonirr}^2}$ = 18.14 ADC