Beam Tests of the First CMS HGCAL Tileboard Prototypes

Analysis of DESY Test Beam Data from 2020

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On behalf of the CMS Collaboration
17th February 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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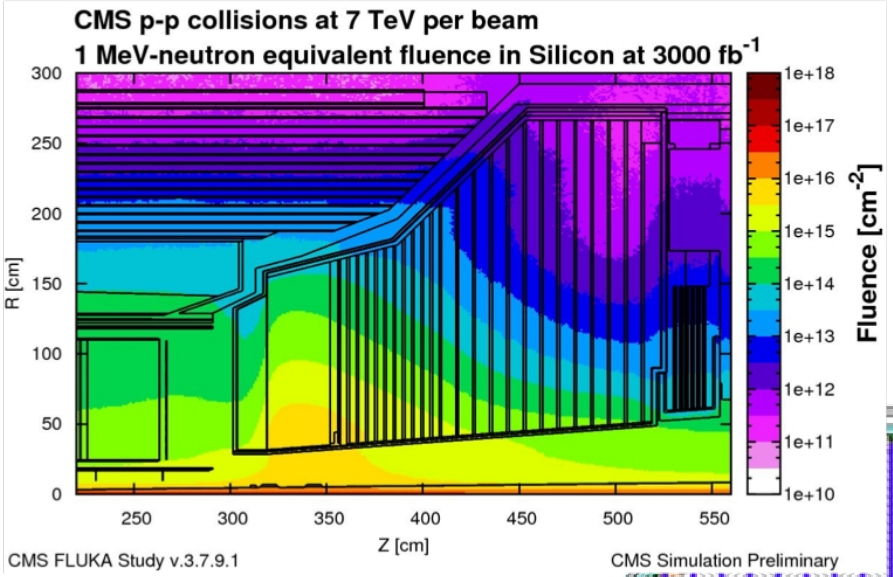
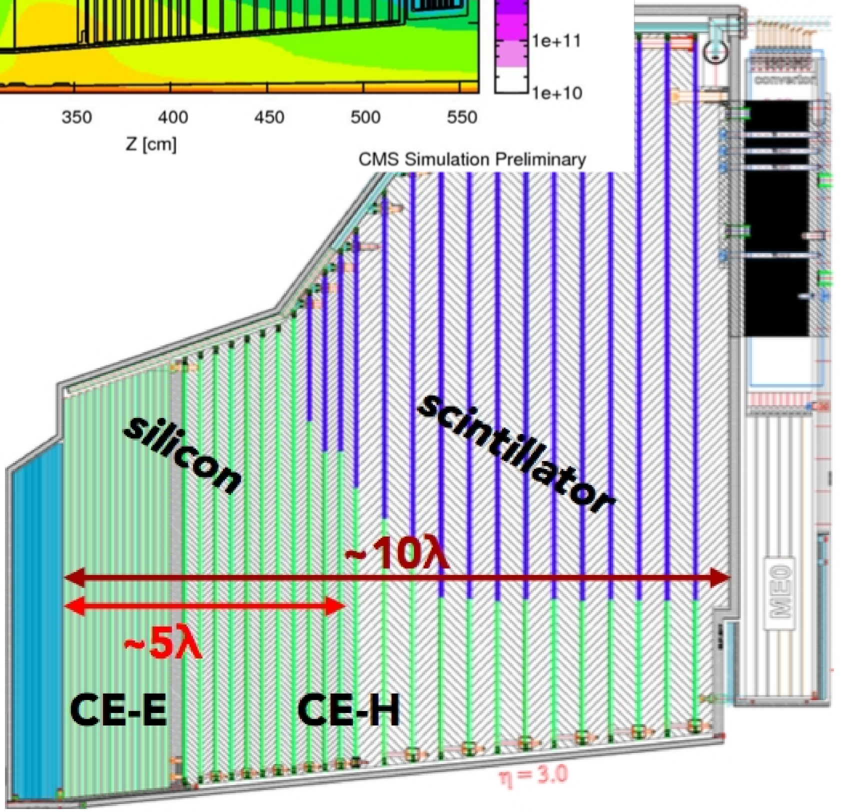
High Granularity for the High Luminosity LHC

Phase II Upgrade of the CMS End-Cap Calorimeter (HGCAL)

- 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 CMS end cap calorimeter
  - Need to replace the ECAL crystals and HCAL scintillators
- Proposed detector: a **5D (imaging) calorimeter using particle flow**
  - For high precision energy measurements
  - Fully utilise timing information
- The active area of CMS endcap calorimeter (HGCAL) will consist of:
  - silicon detector component
  - **scintillator component**
    - in areas where the expected radiation dose during the lifetime of the detector is below $5x10^{13}\ n_{eq}/cm^2$
- The Silicon and SiPM-on-Tile technology, originally developed for e+e- colliders by the CALICE collaboration

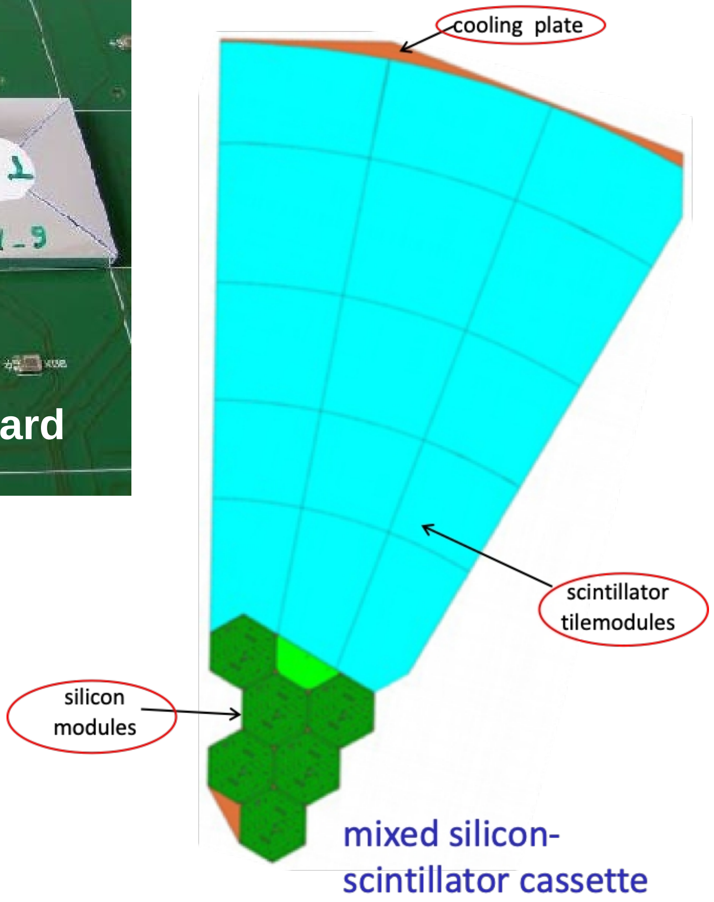




Scintillator Component of the Hadronic Endcap Calorimeter

CMS HGCAL Tileboard and Front-End Electronics

- SiPM-on-tiles:
  - Consist of individually wrapped plastic scintillator tiles placed on silicon photomultipliers (SiPM)
  - The tiles are shaped as trapezoids that increase in size towards larger radii

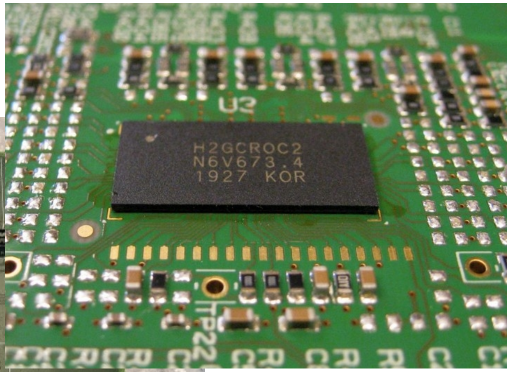


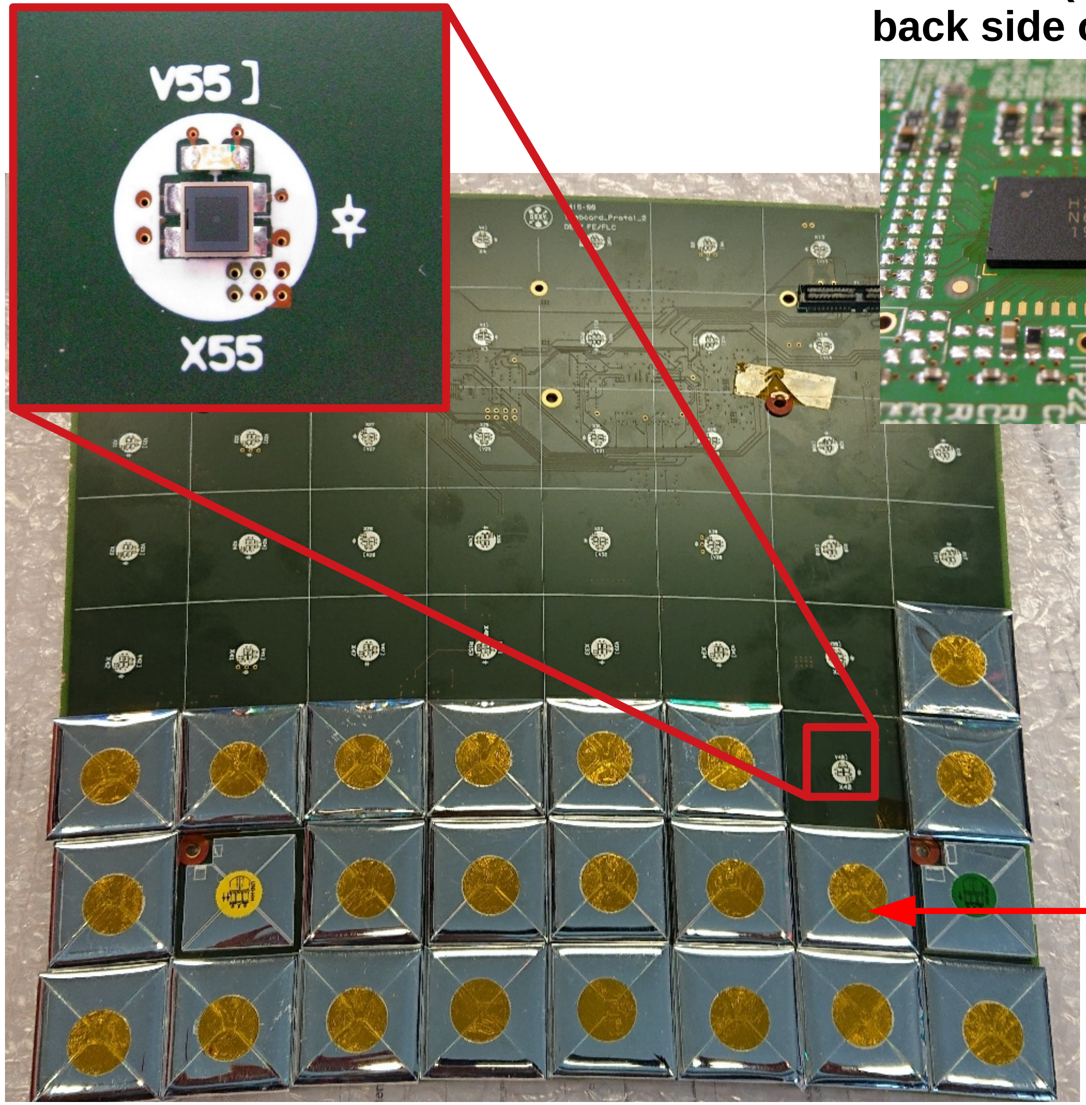
Scintillator Component of the Hadronic Endcap Calorimeter

CMS HGCAL Tileboard and Front-End Electronics

- SiPM-on-tiles:
  - Consist of individually wrapped plastic scintillator tiles placed on silicon photomultipliers (SiPM)
  - The tiles are shaped as trapezoids that increase in size towards larger radii
- The signals from SiPM-on-tiles are read out by the HGCROC front end electronic ASIC
  - Final version under development
  - Current version: HGCROC(V2)
- Tileboards hold the SiPMs, scintillators, on-board electronics and LED system.
  - Increases in size when going away from the beamline

HGCROC(V2) on the back side of the tileboard

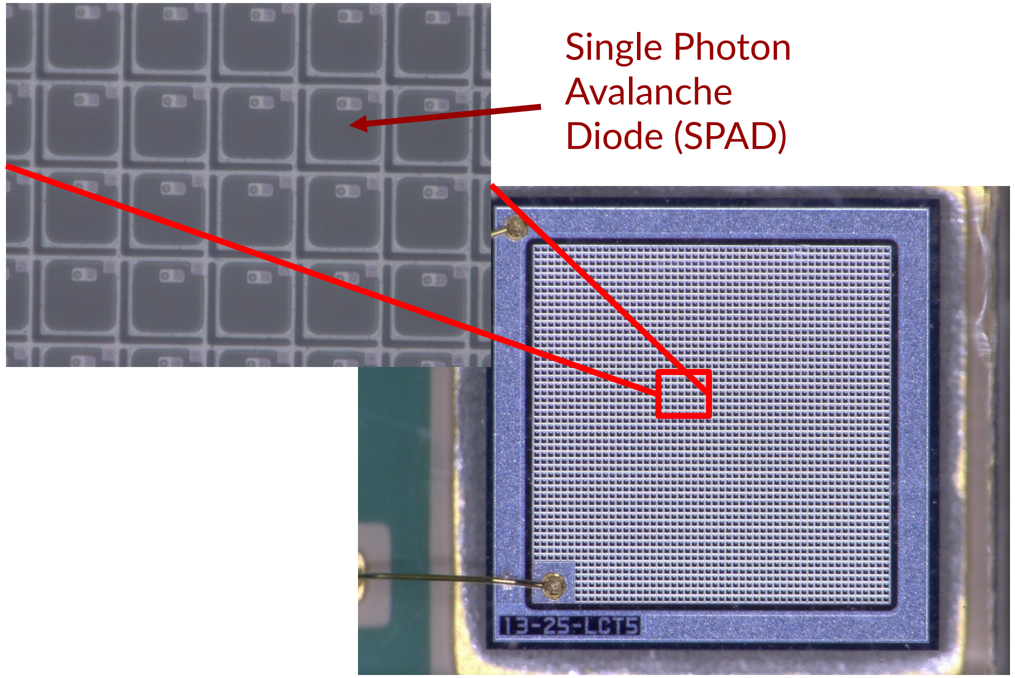




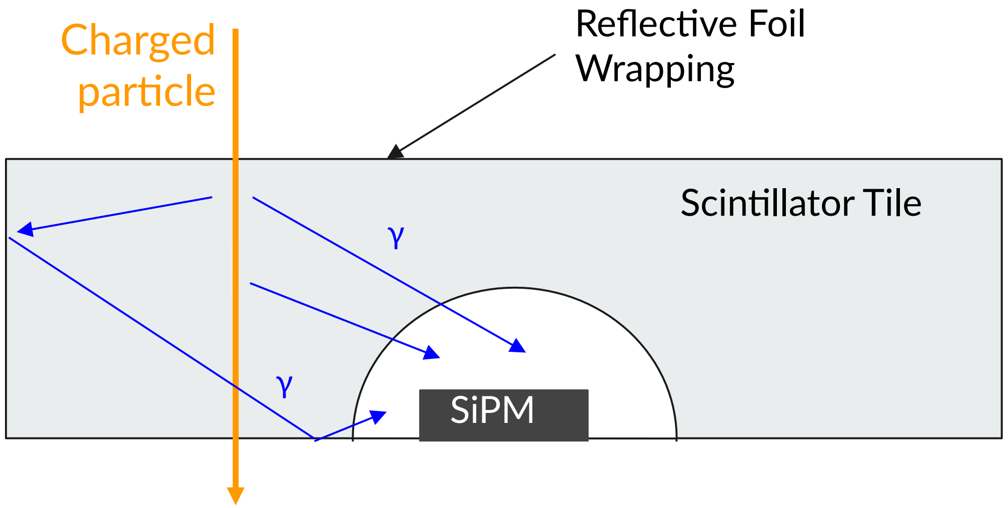
Scintillator tiles on the front side of the tileboard

SiPM-on-Tile technology

Working Principle



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

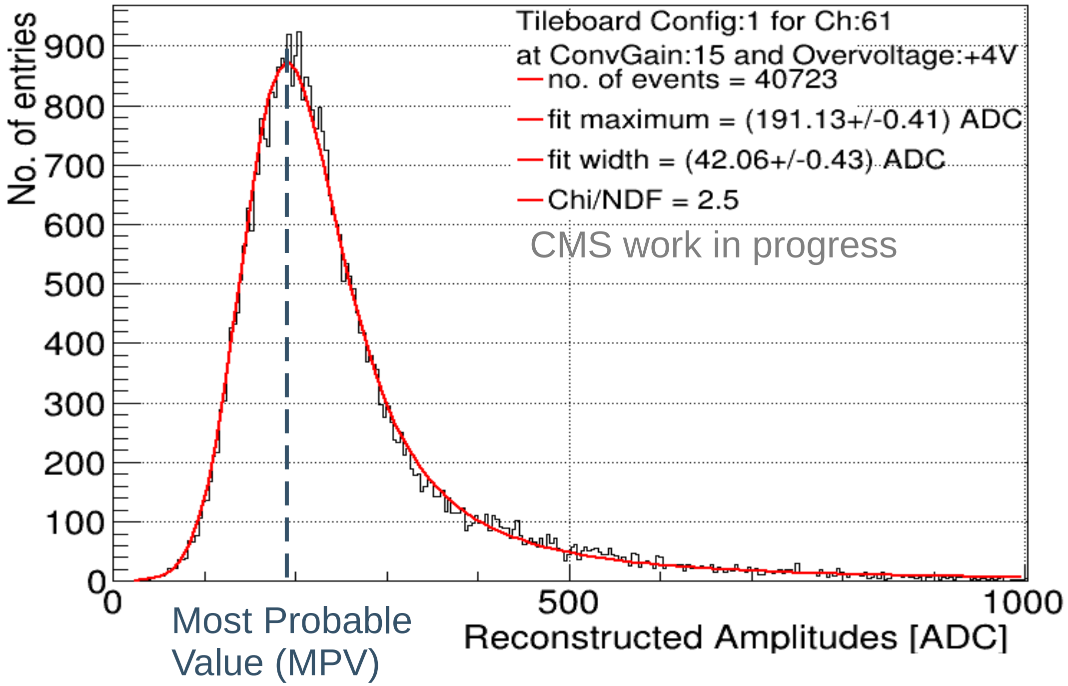


- Charged particles passing through the wrapped tiles scintillate producing scintillation photons.
- These photons are reflected back onto the SiPM with the help of the reflective foil wrapping
- On-board electronics (including the HGCROC's current conveyor) amplifies signal and converts the obtained charge into digital signals
  - **ADC scale for lower gains**
  - TOT for higher gains

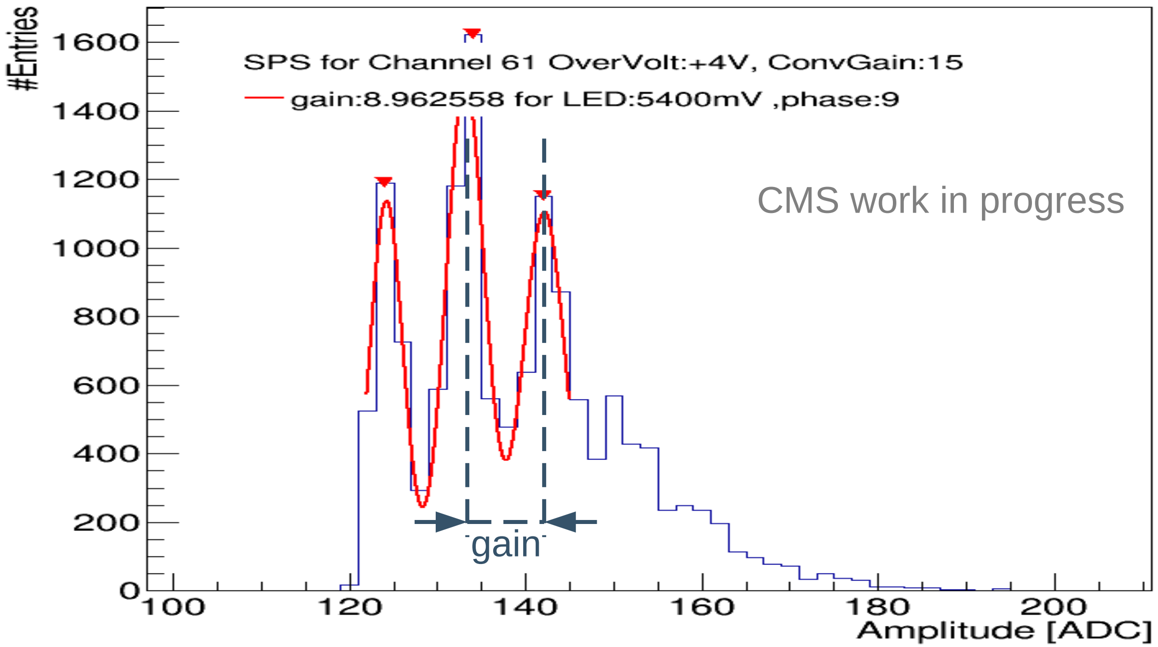
SiPM-on-Tile technology

Calibration of Light Yield

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



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

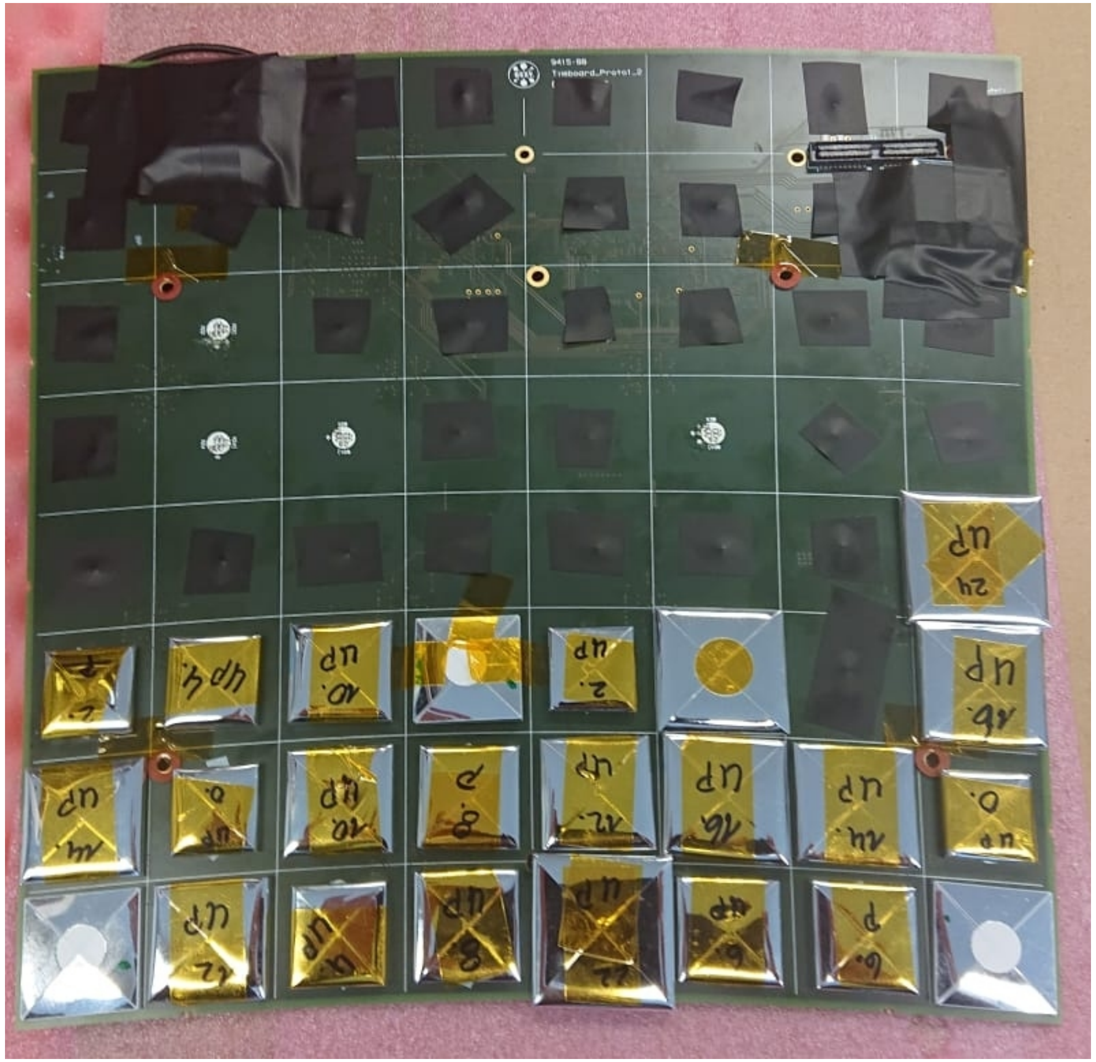


No. of photons captured (Light Yield) is given by dividing the MPV of the signal by its SPS gain in photon equivalent units (p.e.).

Tileboard at the DESY Test Beams 2020

The First Prototype of the CMS HGCAL Tileboard

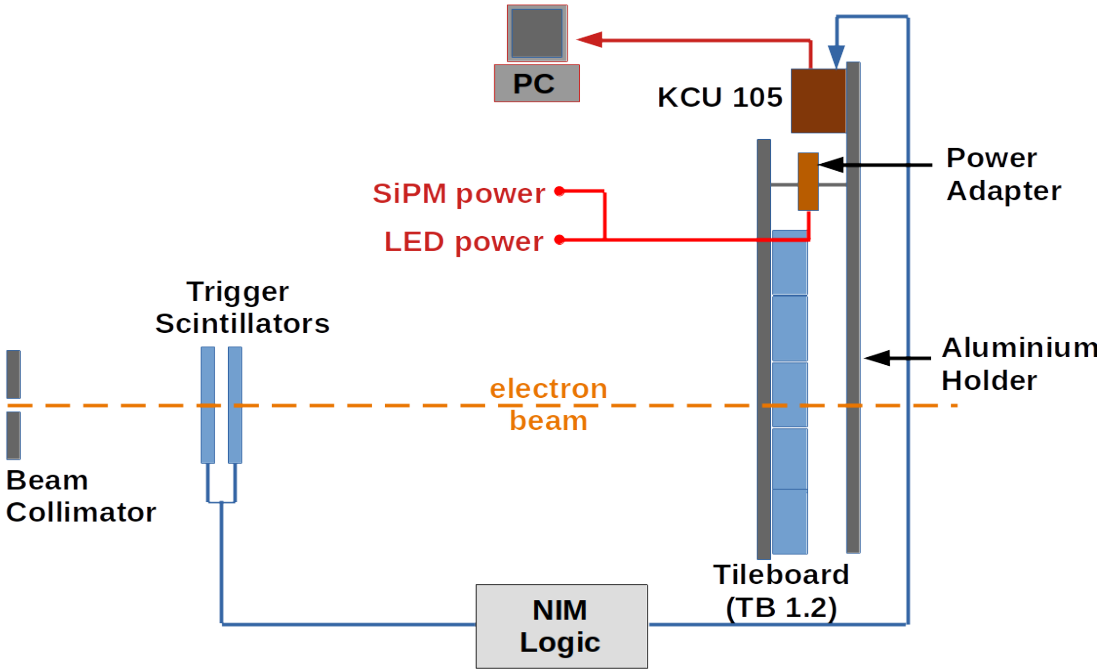
- Tileboard (TB 1.2) was tested at the DESY test beam facility in 2020
- The lower half of tileboard is equipped with:
  - **SiPMs** used were Hamamatsu HDR-2 type photomultipliers custom made for the HGCAL upgrade
    - 12 x unirradiated 15 µm pitch, **2 mm² area** SiPMs
    - 12 x unirradiated 15 µm 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)
    - CALICE reference tiles



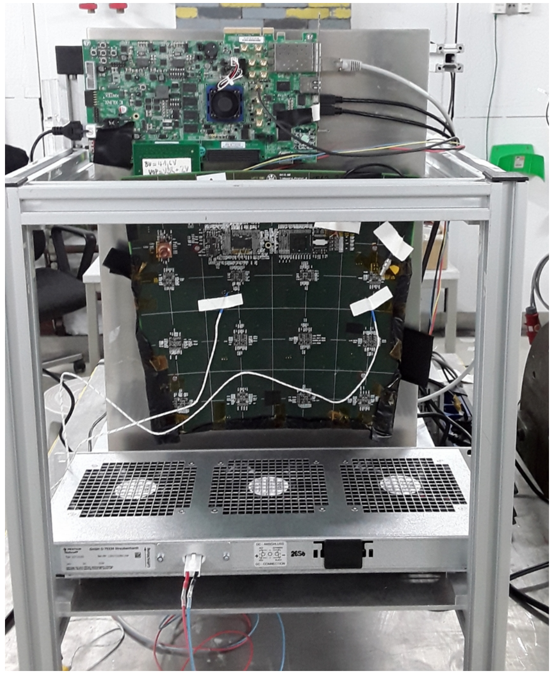
Tileboard at the DESY Test Beams 2020

Beam Test Setup

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



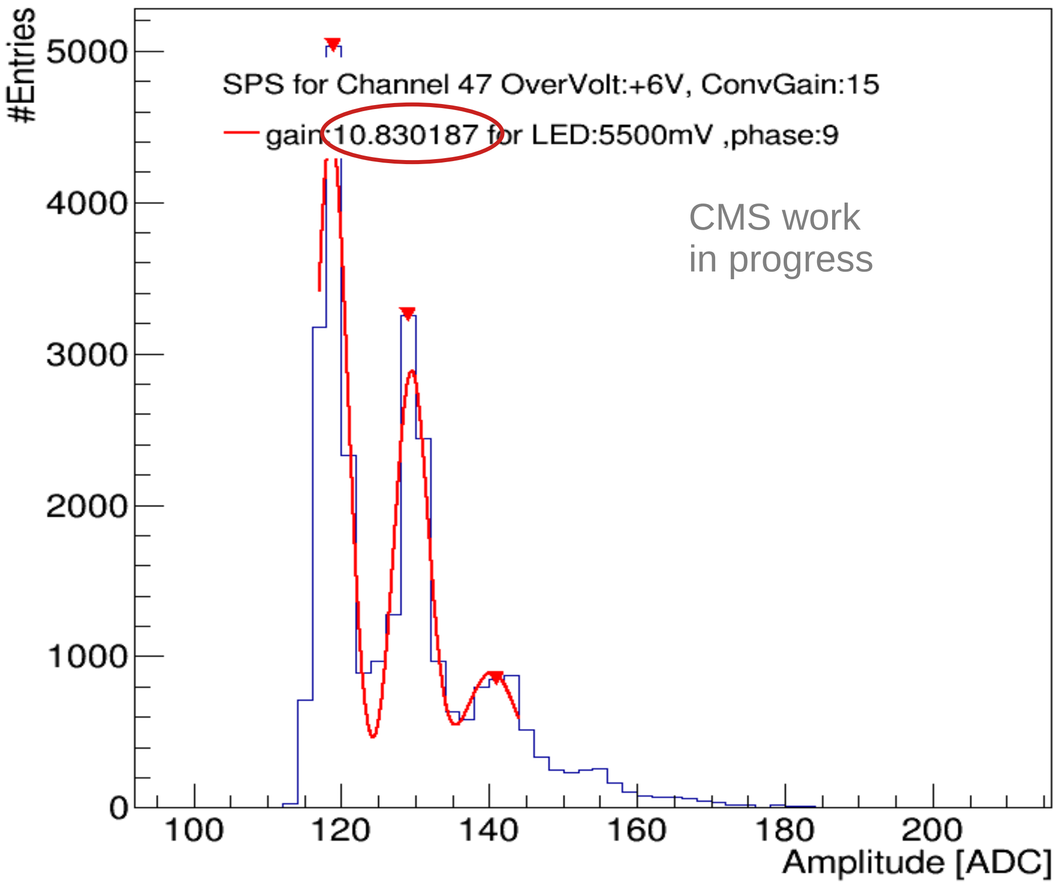
- Measurements:
  For different over-voltages and conveyor gains
  - **SPS data using LED system** (7000 events per channel)
  - **Beam data with 3 GeV electrons** hitting each channel (10,000 events per channel)



Calibration Data from the October Testbeam

Using LED system

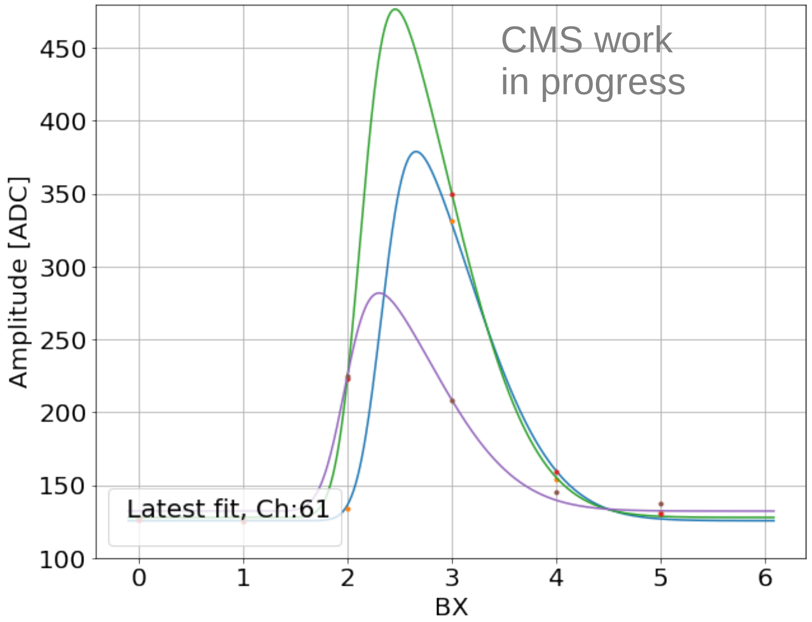
- SPS gain measured using CALICE fit
- SPS is visible at **over-voltages +4V and above** in most channels for **conveyor gain = 15** (highest possible)
  - DNL presently prevents from calculating gains at lower over-voltages and conveyor gains
- Final version of the tileboard to be installed in HGCAL is expected to run at conveyor gain = 4 and over-voltage = 2V
  - Best S/N ratio at end of life expected at these values
  - **Requires further research and development to obtain estimates of SPS from lower conveyor gains at over-voltage 2V**
    - Work in progress

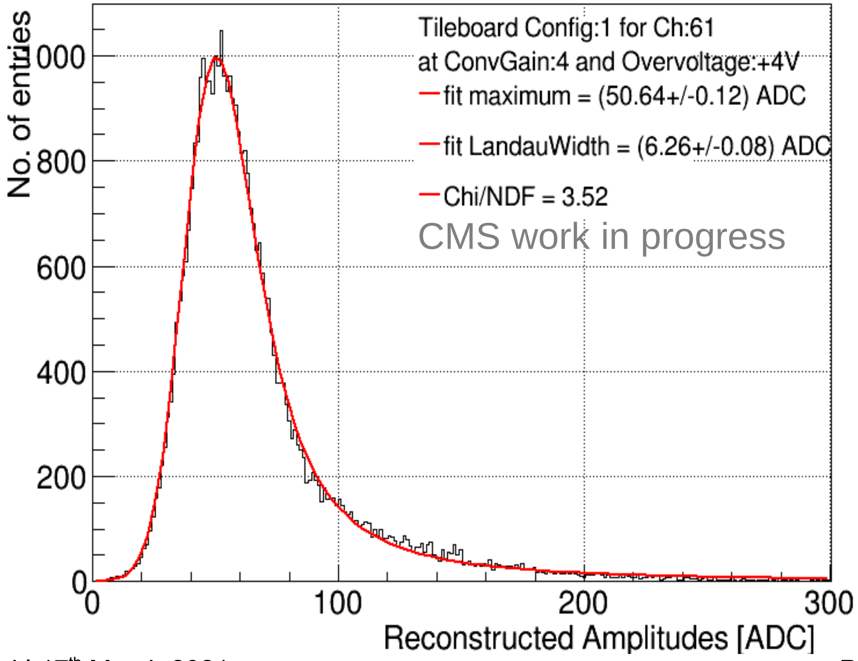


Pulse Fit Correction

Optimization of Fit Parameters

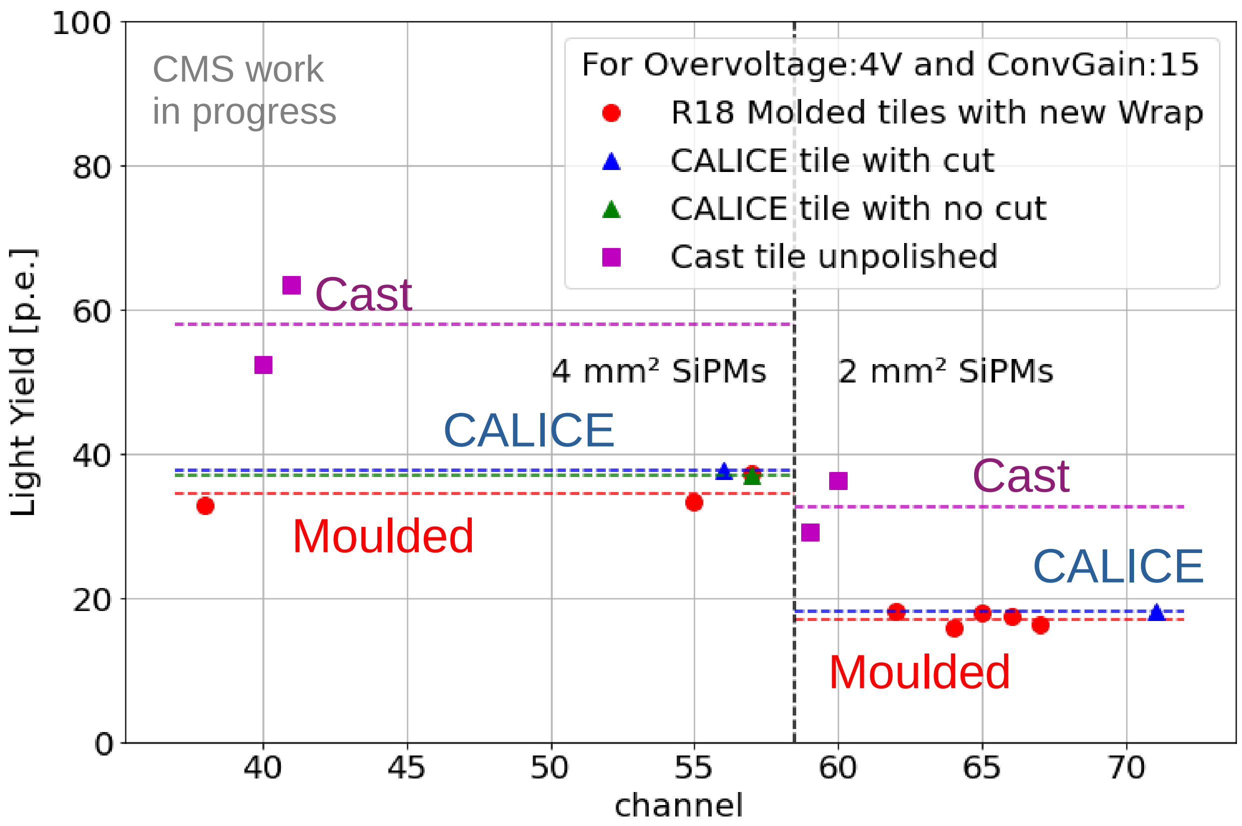
- HGCROC samples the signal at 40 MHz corresponding to the collision frequency
- DESY beam is **non-synchronous to the system**. Therefore pulse maxima needs to be extracted offline
- Pulse amplitude is reconstructed from the maxima of a multi-sample event-by-event template fit
    - 6 points sampled at 25 ns rate per event are fitted using a skewed-Gaussian fit with fixed std. dev. and skewness.
    - Fixed parameters 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**





Light Yield Comparison

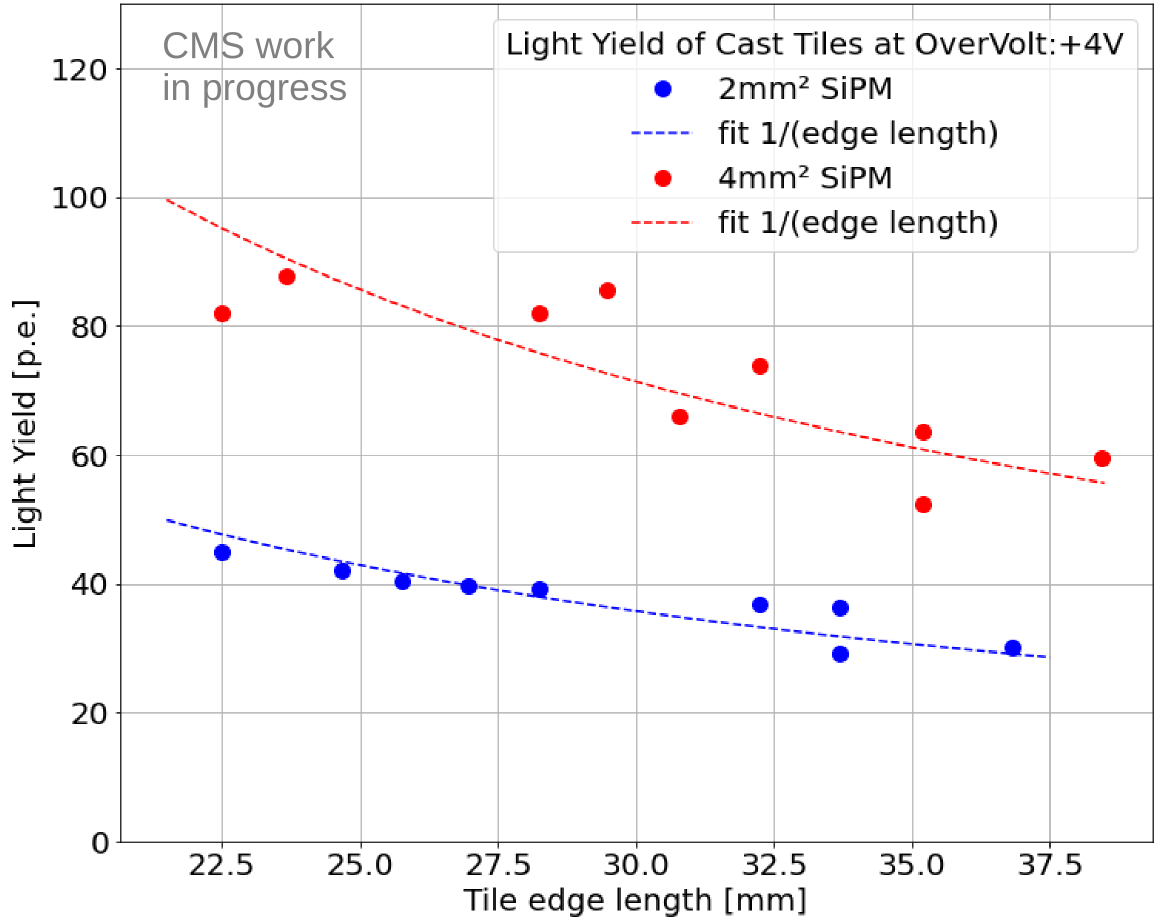
Envelope-type Foil Wraps – Molded, Cast and CALICE tiles



- 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:

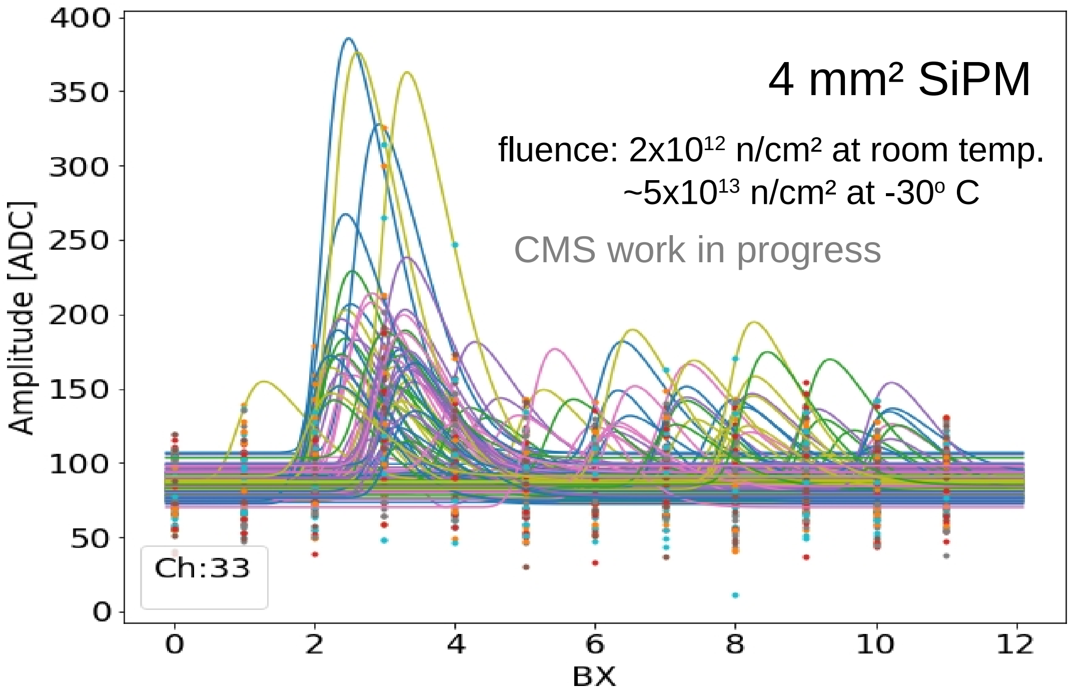
$$LY \sim \frac{1}{\sqrt{A}} \sim \frac{1}{tile\ edge\ length}$$

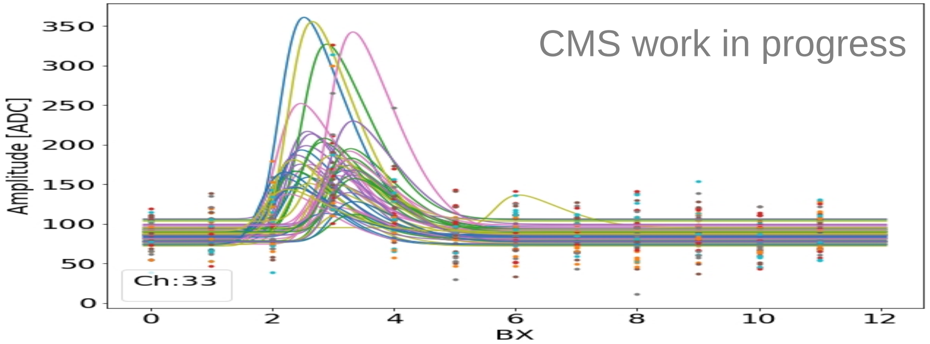
  - Consistent with results

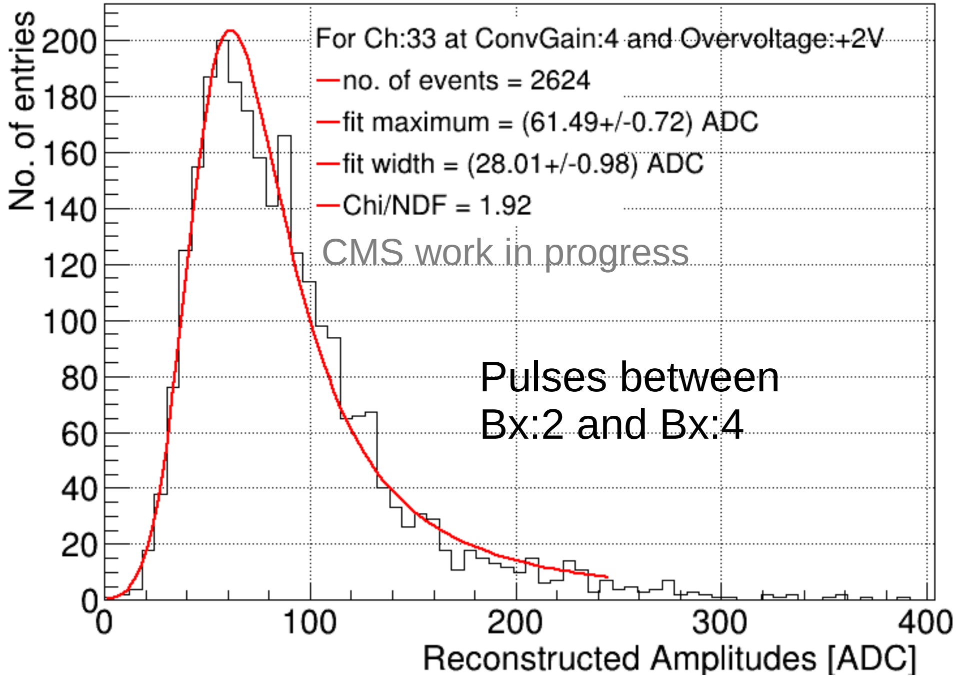
- Fits show that the ratio between 4mm² and 2mm² tiles is ~2 as expected.

Irradiated SiPM pulses

Basic Pulses from both channels







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

- Pulse width is roughly consistent with the width of the unirradiated signal and the noise after irradiation

Summary and Outlook

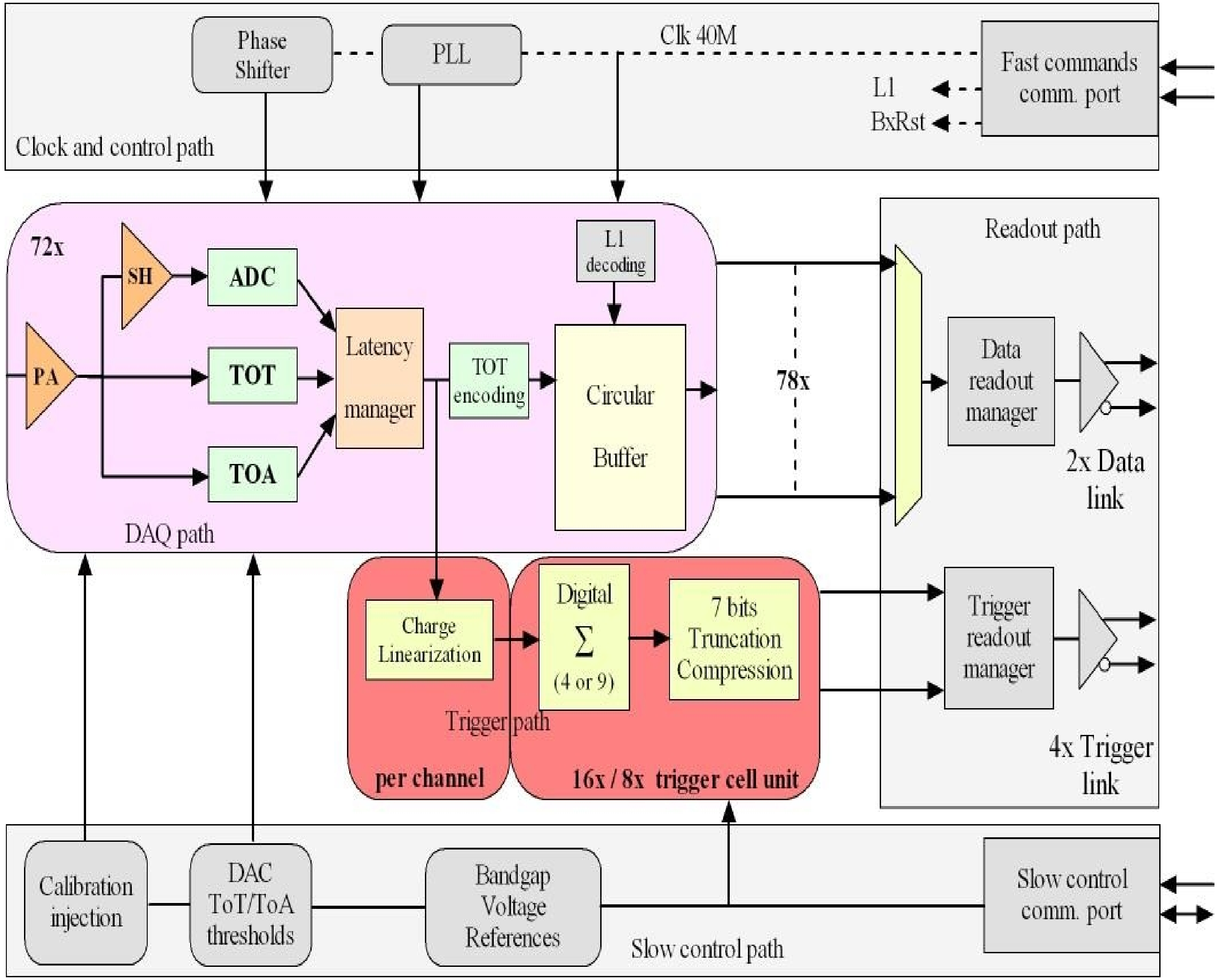
CMS HGCAL Test Beams

- SiPM-on-Tile technology developed by the CALICE collaboration is being applied as part of the HGCAL upgrade
- The test beams at DESY gave the **first beam particle results from the front-end electronics to be used at the HGCAL**
- The template fit method used to extract the pulse amplitude can be applied to other asynchronous particle sources, like cosmic rays
- The test beam also compared many SiPMs, tiles of different sizes, wrappings and 2 irradiated SiPMs
- **Light Yield:**
  - Cast tiles produce about 2x more light than molded tiles
  - 4mm² SiPMs produce about 2x more light than 2mm² SiPMs
  - More data needed to confirm scaling factors
- **Irradiated SiPMs:** Preliminary results show that it is possible to extract a signal from irradiated SiPMs

HGCROC(v2) Front End Read Out ASIC

Introduction

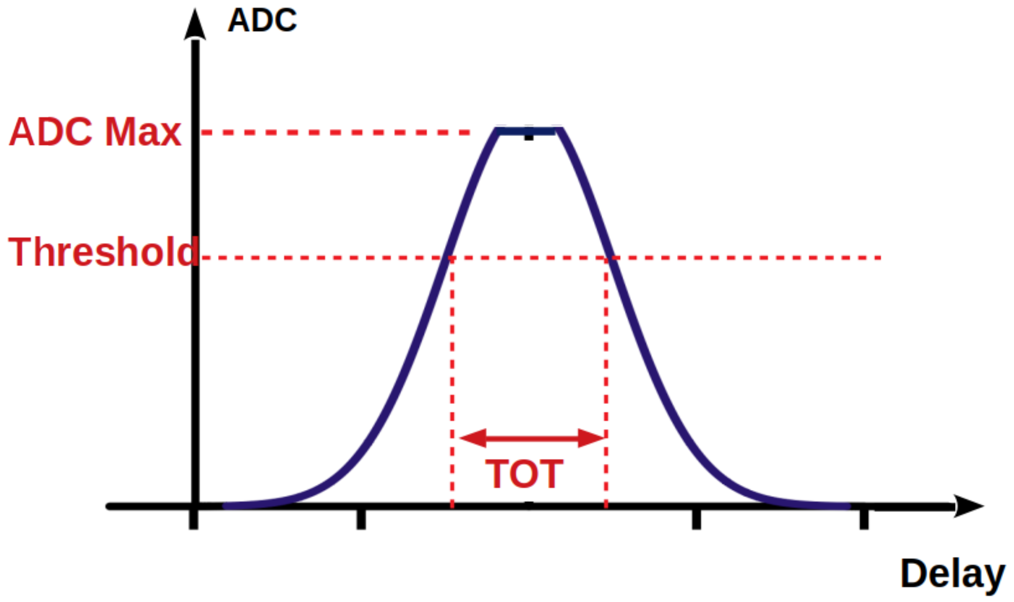
- HGCROC(v2): Latest prototype of the front end read out ASIC to be used in the CMS HGCAL
  - CMOS 130 nm (TSMC) technology
- Two versions:
  - Silicon version: HGCROC
  - **SiPM version:** H2GCROC
    - Additional current conveyor for amplification
- Integrates up to 72 channels to read out
- Measurements:
  - Charge:
    - **ADC (Pulse Amplitude)**
    - Time over Threshold (TOT)
  - Timing:
    - Time of Arrival (TOA)

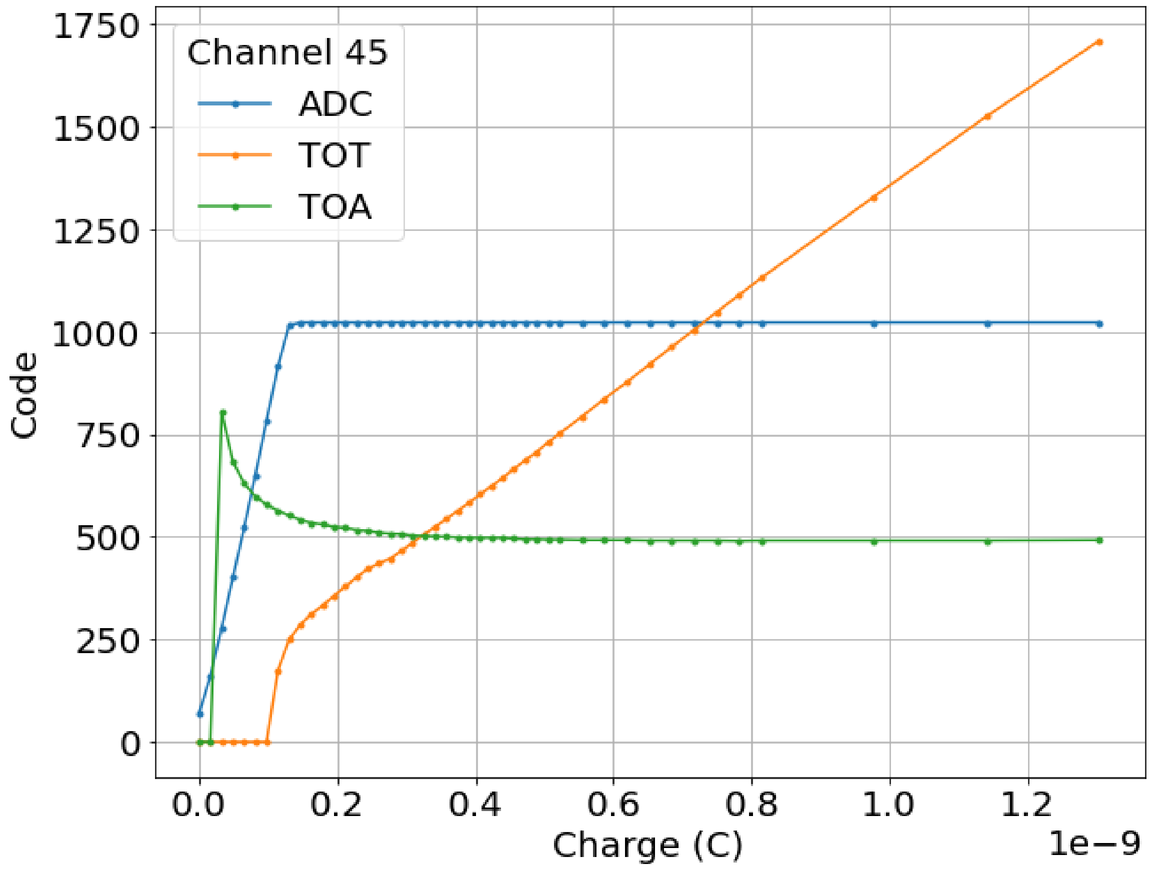


Charge Measurement with HGCROCv2

Low and High Gain Modes

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



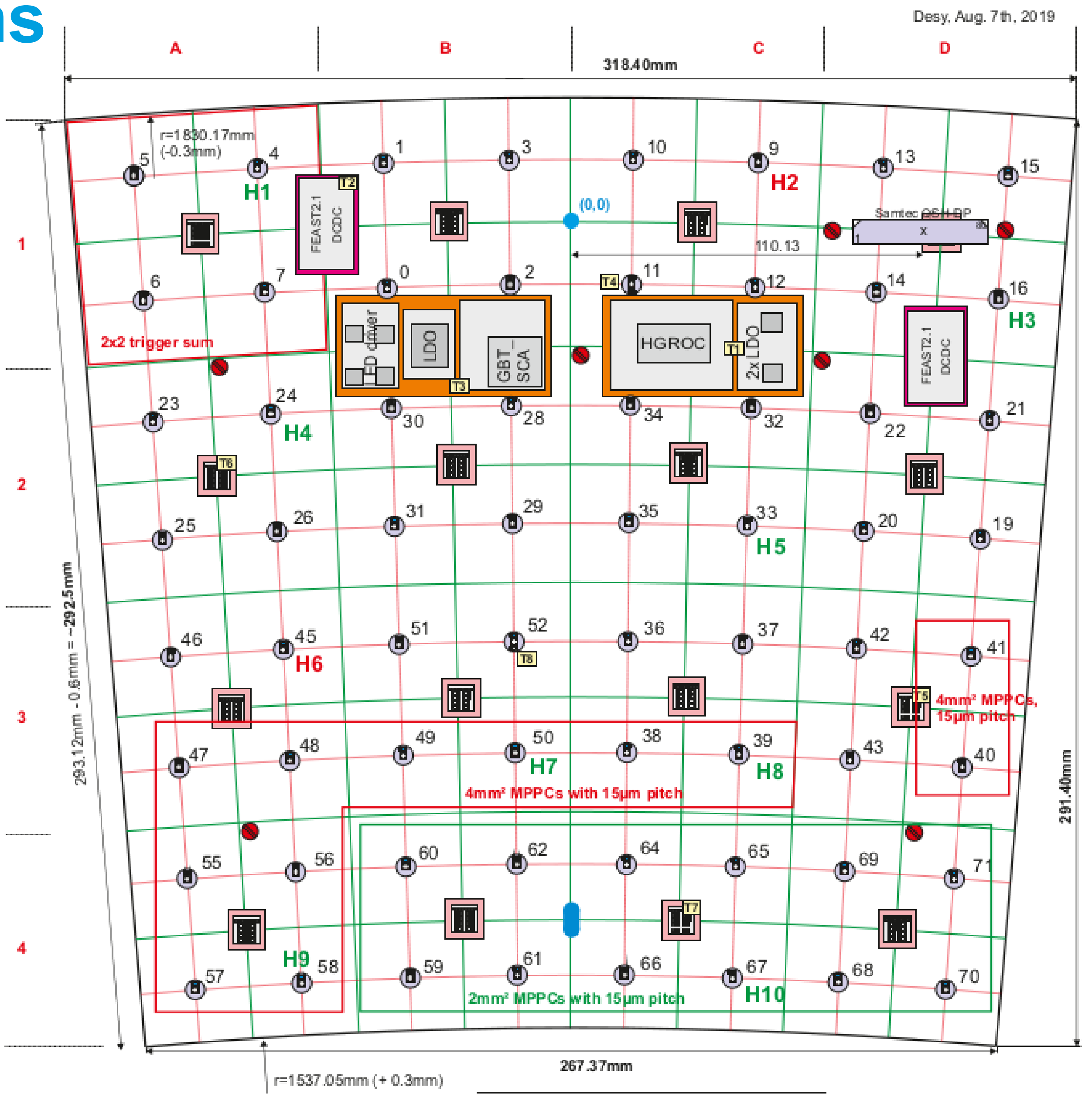


Measurement using external charge injection into the HGCROC channel 45

Tileboard at the two test beams

SiPMs

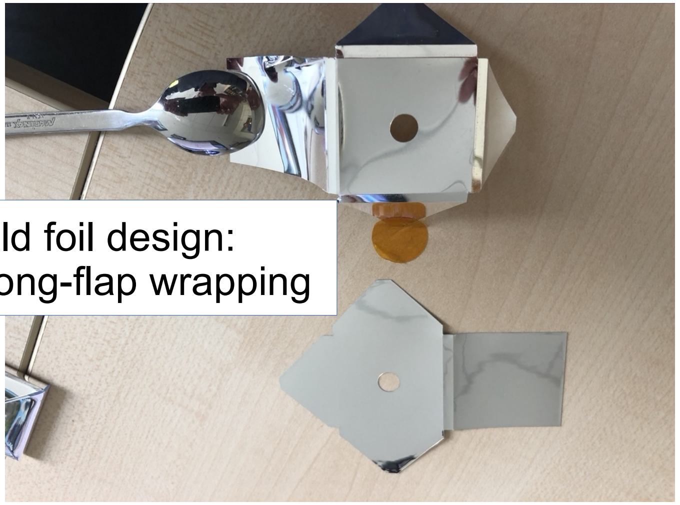
- Bottom half of tileboard was equipped with Hamamatsu S14160 series SiPMs in both testbeams:
  - Custom made SiPMs for HGCAL with improved radiation hardness
    - 12 cells with 15 µm, **2 mm²** SiPMs
    - 12 cells with 15 µm, **4 mm²** SiPMs
- SiPMs in 5 positions replaced in October testbeam with holder PCBs containing a SiPM (H1,H3,H4,H5,H7)
  - **Irradiated SiPMs** (fluence: $2x10^{12}$ 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**



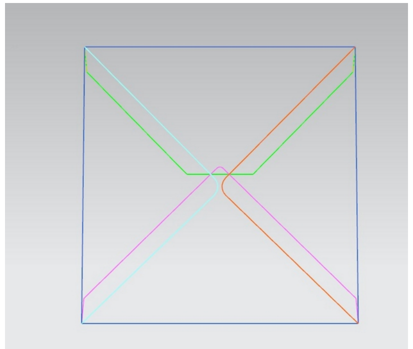
Tileboard at the October test beam

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

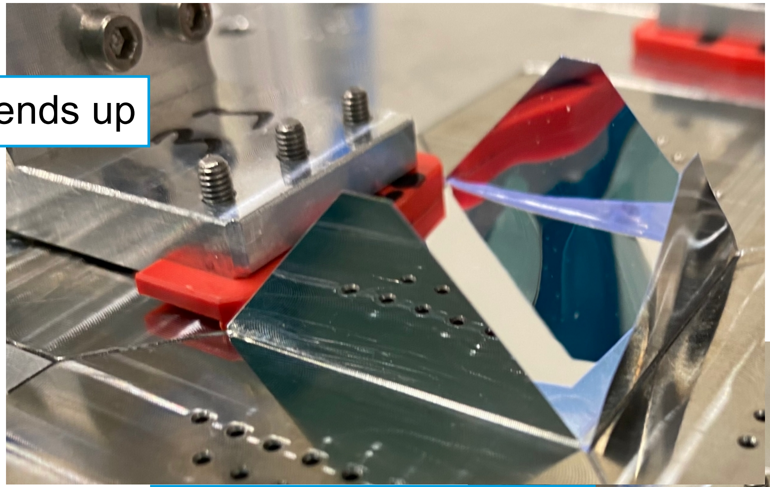
Long flap causes frequent problems at wrapping step

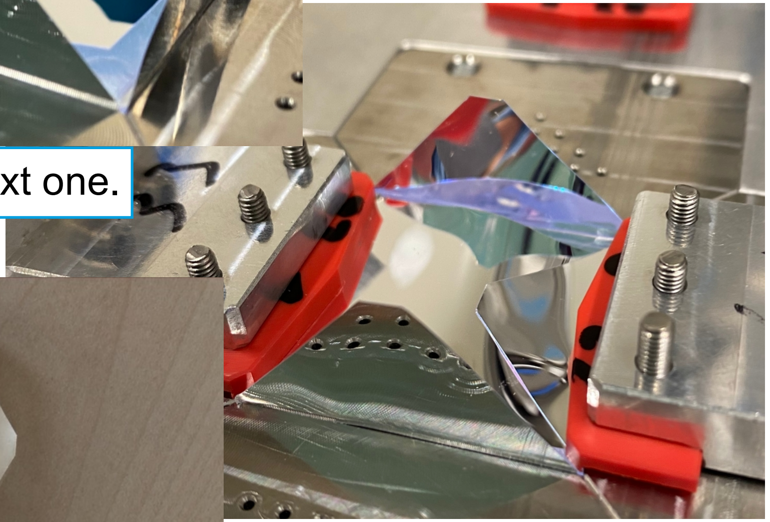
- does not occur in manual wrapping tests
- persists also with somewhat shorter or narrower flaps

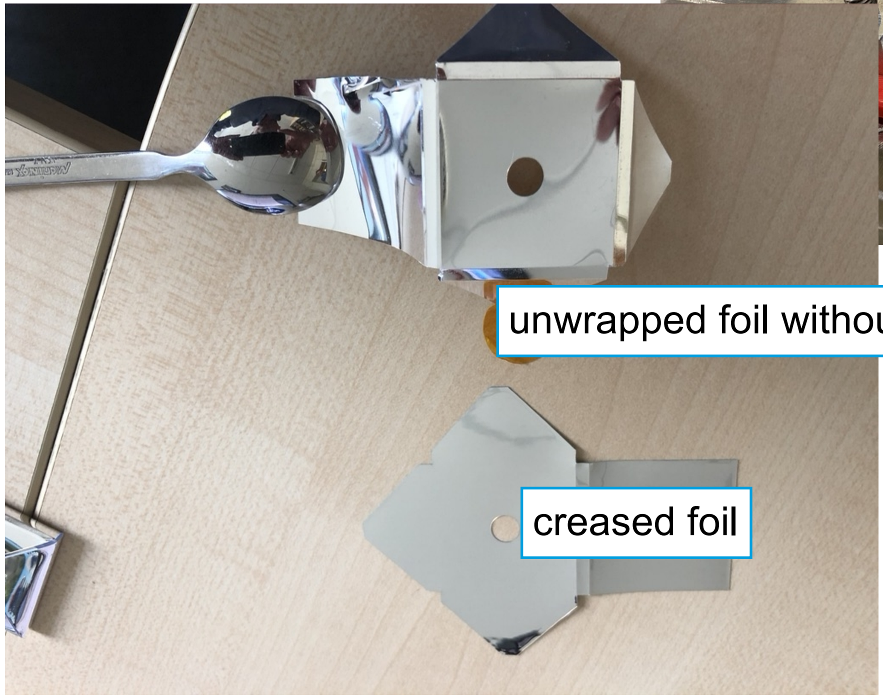
Re-introduce creasing in foil preparation

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

Conclusion: need to withdraw our premature "green light" for long flap design

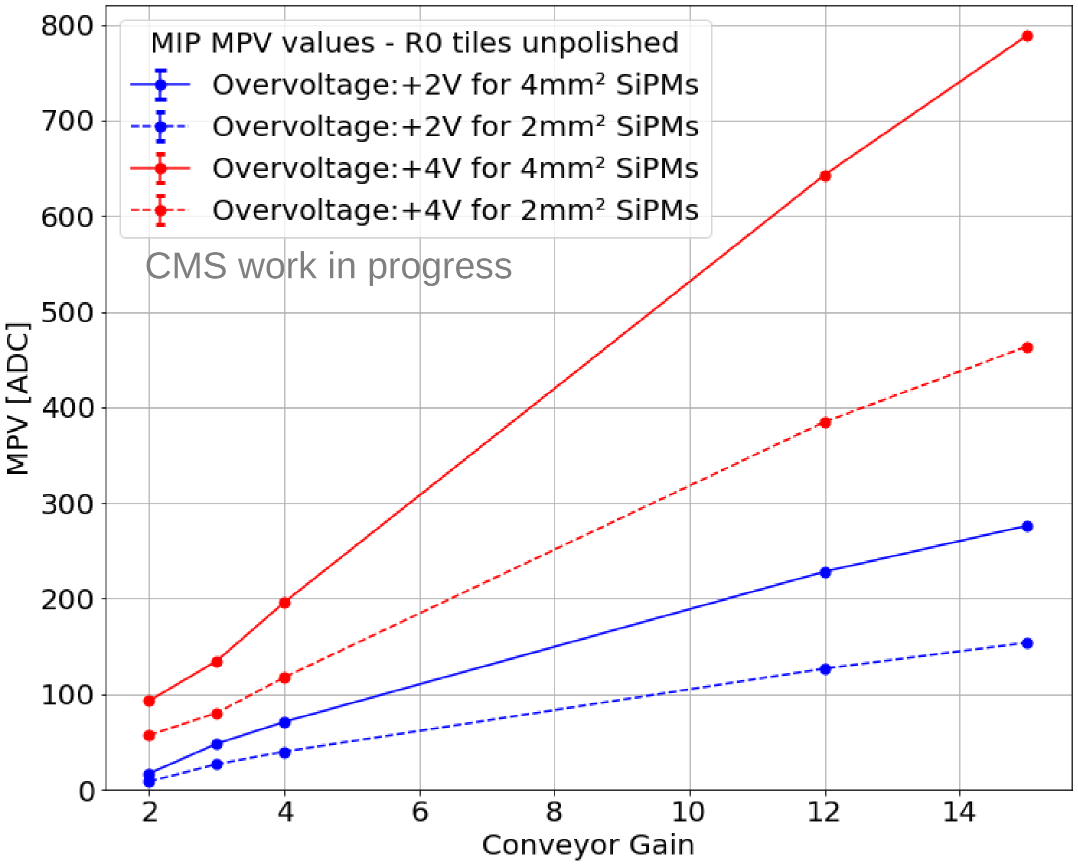






Dependence of MIP MPV with Current Conveyor Gain

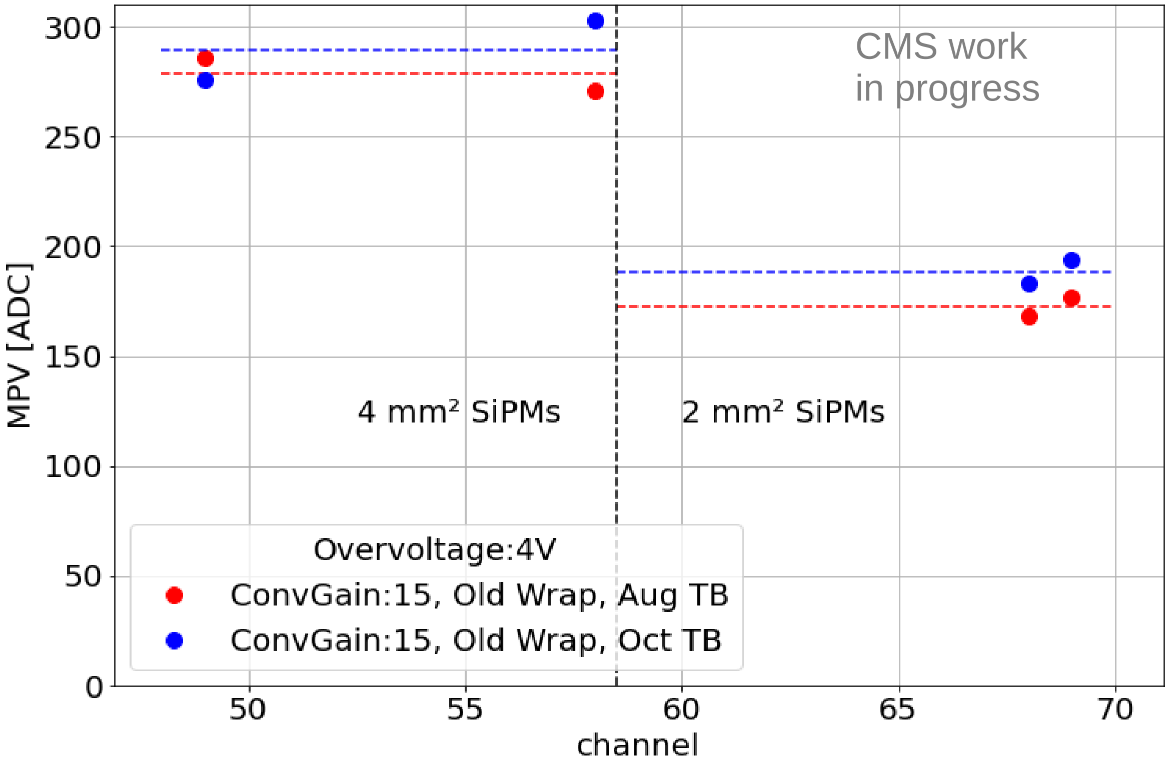
From October Testbeam

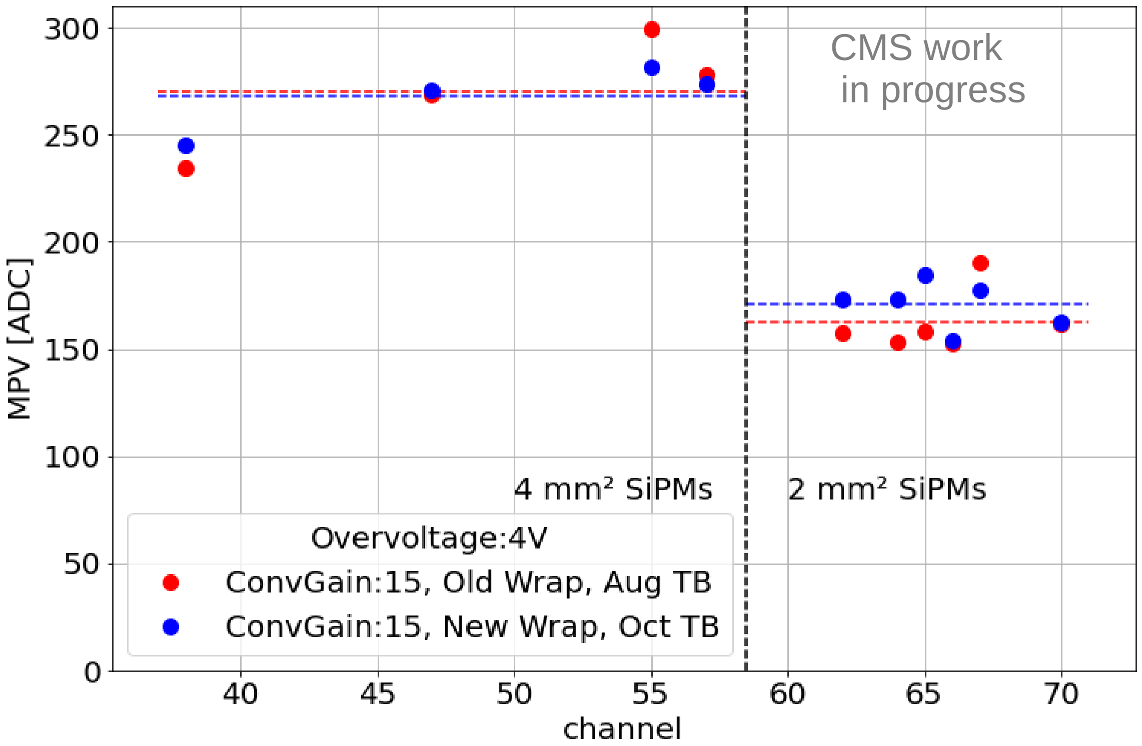


- MPV appears to increase linearly with conveyor gain for all channels.
- **Light yield analysis is not presently possible for conveyor gain < 15** as SPS is only observable for conveyor gain = 15 at over voltage = 4 V and above.

MIP MPV Comparison of Two Testbeams

Reproducibility Test and Comparison of Old and New Wrappings

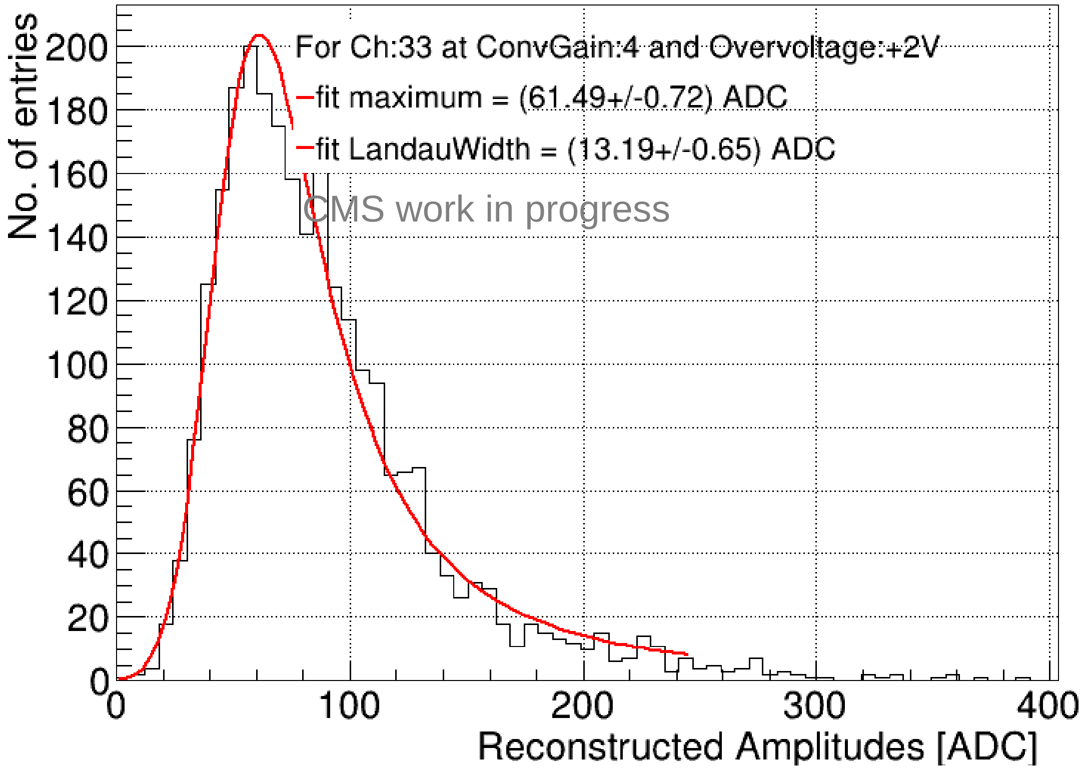




- Left plot:
  - Direct comparison of long arm wrap (old wrap) between the two testbeams
  - Results reproducible between two testbeams
    - 4-9 % difference in results
- Right plot:
  - August testbeam: Consists of long arm wrap (old wrap)
  - October testbeam: Same tileboard, envelope-type wrap
 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

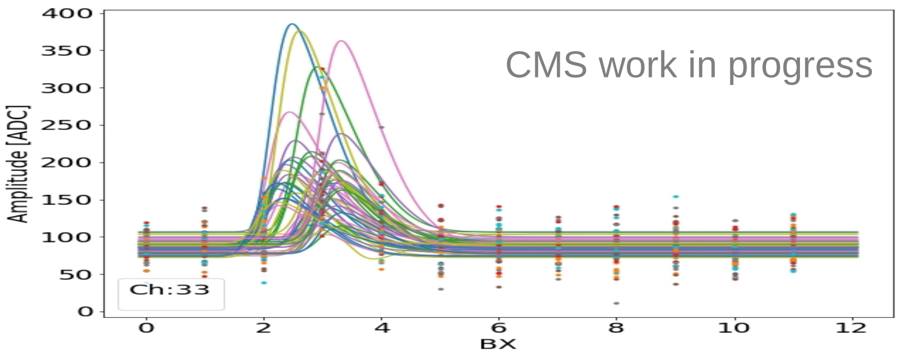
Irradiated SiPM pulses

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



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

Need More Data



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

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