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Federal Ministry of Research, Technology and Space

# Hadron calorimeter prototype for future circular collider without power pulsing

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Bad Honnef

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

HIGH-D-CALO
Consortium

# Motivation

**LHC:**

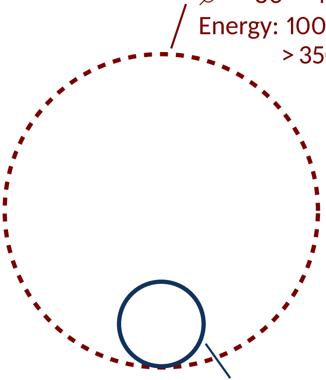
- Last data taking period has ended, upgrade to High-Luminosity LHC started

➤ **What is coming afterwards?**

**FCC-ee**

- Precision instrument for studying Z, W, Higgs and top
- Strict requirements on jet energy resolution to achieve precision
  - ➤ $\sim 30\%/\sqrt{E} \rightarrow$ needed to statistically separate hadronic W and Z decays
  - ➤ Achieved via particle flow: Tracker for charged particles, ECAL for photons and **HCAL only for neutral hadrons**

**FCC (-ee/hh)**
$\varnothing = 80 - 100$ km
Energy: 100 TeV (pp)
$> 350$ GeV$(e^+e^-)$



**LHC/ LEP**
$\varnothing = 27$ km
Energy: 14 TeV (pp)
209 GeV$(e^+e^-)$

Adapted from: https://fccis.web.cern.ch/overview

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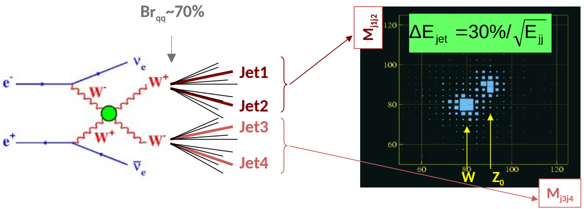
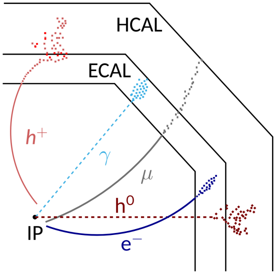


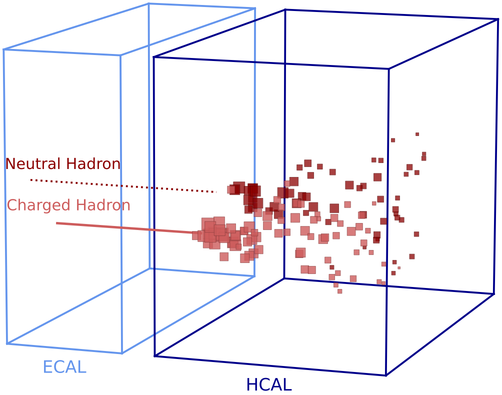

Adapted from:
https://flc.desy.de/hcal/basics/particle_flow/index_eng.html

# Hadronic Calorimeter

- Crucial for detection of neutral hadrons
  - ➤ No momentum reconstruction in tracker possible
- W, Z decay in jets (70% hadronic)
  - ➤ Requires **high granularity** $\sim 3 \times 3\,\text{cm}^2$ to
    - $\rightarrow$ Separate overlapping hadronic showers
    - $\rightarrow$ Distinguish neutral and charged deposits in jets

How to achieve this high granularity?

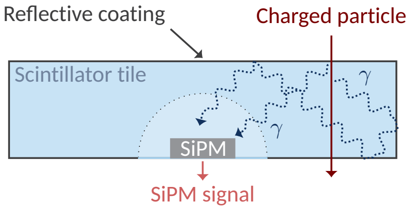
➤ Read out segmented scintillator tiles individually directly coupled with photo-detector

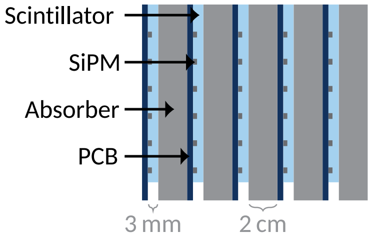


# State of the Art: HCAL for Particle Flow

CALICE collabortation ($\sim$ 20 years in R&D) demonstrated that this high granularity is possible

- Readout segmented scintillator tiles directly coupled to photon-detectors (SiPMs)
  - Longitudinal segmentation: 3 mm scintillator, $\sim$ 2 cm absorber (steal)
  - Lateral segmentation: $3 \times 3\,\mathrm{cm}^2$ cell size



# State of the Art: HCAL for Particle Flow

CALICE collabortation

- Detector build for **linear collider** (ILC)
  - Bunch train structure (beam on 1 % of time)
  - No permanent power for electronics needed $\rightarrow$ power-pulsing

**What is needed for FCC-ee?**

- Bunch crossings $\sim$ 25 ns (40 MHz)
- Crossings in continuous mode without bunch trains
  - Electronics has to be permanently powered
  - High data rate
    - $\rightarrow$ High instantaneous power demand

# About the Project

Group of former CALICE institutes prepares next prototype for FCC-ee requirements

- Want to **adapt concept of CALICE** for continuous mode
  - Development of electronics suitable for continuous operation (to not heat up detector)
  - Simplify production of scintillator tiles

- **Institutes**:
  - University of Heidelberg
  - KIT
  - University of Mainz
  - DESY
  - **University of Hamburg**

  (University of Heidelberg, KIT, University of Mainz, DESY: Electronics & Scintillator tiles)

  → **SiPM selection, characterization, calibration, systematic studies on overall energy resolution**

# What is a SiPM?

**SiPM** (**Si**licon **P**hoto**M**ultiplier)

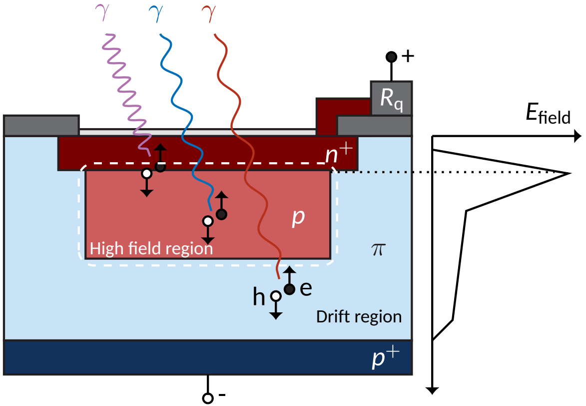
- Array of parallel connected SPADs (pixels)

**SPAD** (**S**ingle-**P**hoton **A**valanche **D**iode)

- Reverse biased photodiode, operating above the breakdown voltage $V_{\mathrm{bd}}$
  - Geiger mode (avalanche multiplication)

**Working principle:**

- When a photon hits a pixel, the generated e-h pair trigger an **avalanche multiplication**



# Mega-tile Concept

CMS HGCAL design (under production now)

Single tiles wrapped

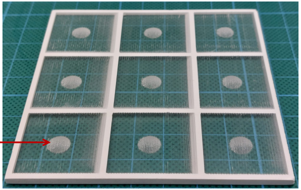
de Silva, "SiPM-on-Tile Modules for the CMS High Granularity Calorimeter" (2023), Dissertation

Simplify production →

Dimple

Proposed design for FCC-ee

$3 \times 3$ Mega-tile



From: P. Kollar

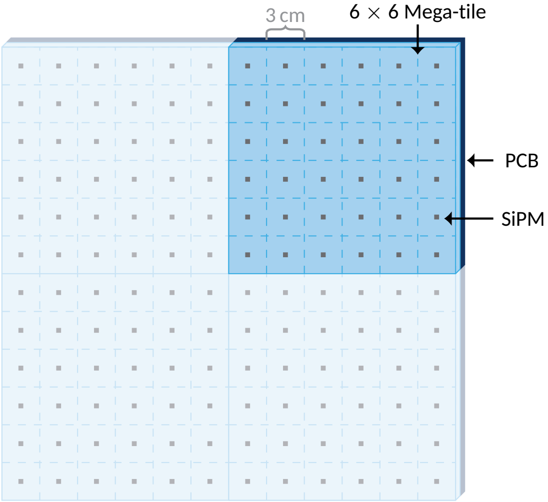
For prototype apply the concept of mega-tile!

- No singularly wrapped scintillator tiles used
- Structured scintillator plate with optically insulated elements replaces single tiles

# The Prototype

Development of a high granular hadron calorimeter prototype based on SiPM-on-tile technology for FCC

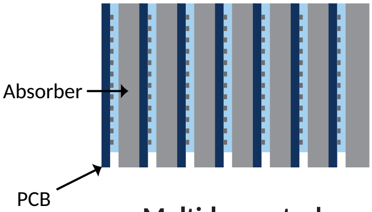
- **Single module**
  - 4 PCBs each with
    - → 36 SiPMs
    - → One 6 × 6 Mega-tile
  - In total 144 channels with common
    - → Power supply
    - → Readout-electronics



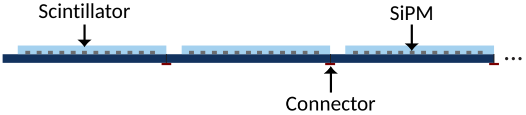

- For prototype 6 modules planned!

# Tests

- **Multi-layer-stack** to test
  - Temperature behavior & distribution within device
  - Self-heating of SiPMs
- **Thermal layer demonstrator** to test
  - Thermal and electronic properties of one complete slab ($\sim$ 2 m long)
  - Communication
    - $\rightarrow$ Can signals be send/received synchronously over entire length without loss of information?




**Multi-layer-stack**




**Thermal layer demonstrator**

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# Timeline

## 2026

- Specification, selection and full characterization of SiPMs

## 2027

- Production & characterization of electronic boards and scintillator tiles
- Focus:
  - SiPM on board characterization
  - MIP characterization

## 2028

- System commissioning and test

# Which SiPMs to Choose?

To select appropriate SiPMs for prototype all physical and technical requirements need to be considered

- **Geometry and Package**
  - Package area & height
    - $\rightarrow$ Determined by dimple shape of scintillator tile
- **SiPM design specifications**
  - Need to cover a high dynamic range, while be able to detect 1 MIP with $S/N > 10$
    - $\rightarrow$ Restrictions on *PDE* and $N_{\text{pix}}$
- **SiPM properties (at operation voltage)**
  - Readout electronic restrictions on multiple parameters (i.e. gain, *DCR*, breakdown voltage spread,...)

> **Task:** Measure parameters at high precision

$S/N$: Signal-to-noise ratio, *PDE*: Photon detection efficiency, $V_{\text{bd}}$: Breakdown-voltage, $p_{\text{XT}}$: Crosstalk probability

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- **SiPM properties (at operation voltage)**
  - ➤ Readout electronic restrictions on multiple parameters (i.e. gain, *DCR*, breakdown voltage spread,...)

| Parameter | Data sheet | Requirement |
|---|---|---|
| Pack. dim. $(W/L/H)$ [mm$^3$] | 3.54/3.77/1.23 | -/-/$1.5 \pm 0.15$ |
| Active area $A_{si}$ [mm$^2$] | $3 \times 3$ | $\lesssim 3 \times 3$ |
| Pixel pitch [$\mu$m] | 18 | - |
| Pixel number $N_{pix}$ | 27339 | - |
| $PDE$ @ $\lambda_{peak}$ [%] | 40 @ 420 nm | - |
| $V_{bd}$ [V] | 32.5 | spread: $< 1$ V |
| $dV_{bd}/dT$ [mV/K] | 30 | 60 |
| $DCR$ [kHz/mm$^2$] | 90 | 150 |
| Gain $G$ | $1.3 \cdot 10^6$ | $\gtrsim 1.35 \cdot 10^5$ |
| $p_{XT}$ [%] | 3 | <10 |
| $PDE \cdot A_{si}$ | 3.6 | $\geq 0.83$ |
| $N_{pix}/(PDE \cdot A_{si})$ | 7594 | $> 3600$ |

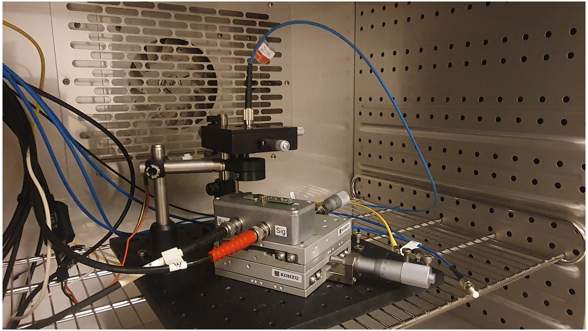
$S/N$: Signal-to-noise ratio, $PDE$: Photon detection efficiency, $V_{bd}$: Breakdown-voltage, $p_{XT}$: Crosstalk probability

➤ **Task:** Measure parameters at high precision

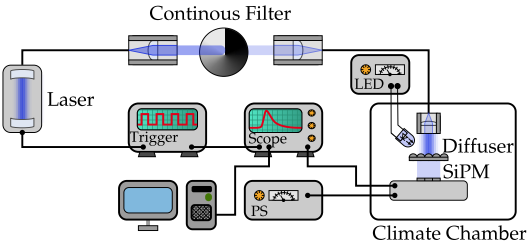
# How to Characterize SiPMs?

Characterizing SiPMs from following measurements:

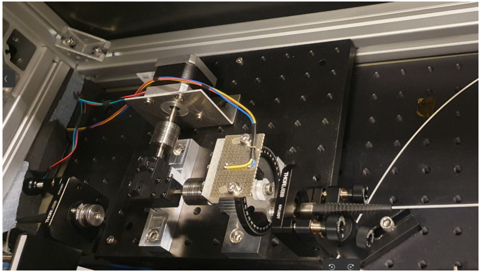
- Low-light intensity
- Response curve (low $\rightarrow$ high-light intensity)



L. Brinkmann et al."Systematic Characterisation and Non-Linear Response Correction of SiPMs Using the Single-Step Method for High-Precision Calorimetry", (2026) DOI: https://doi.org/10.3390/instruments10020024

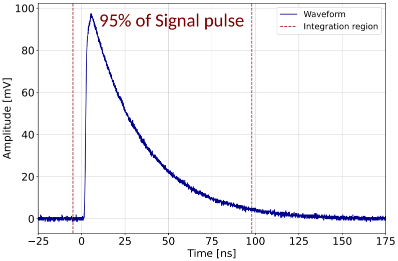



From: L. Brinkmann



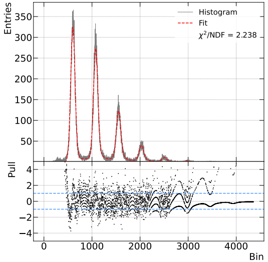
# Characterization at Low-light Intensity

Example waveform: $T = 25\ ^{\circ}\mathrm{C}|$ Laser




Integration →

Fitted low light intensity spectrum:




- Fit spectra with PeakOTron (physics model of the SiPM signal, considering its operation parameters)
- Extracted parameters with $\sim$ 1% precision:
  - Gain ($G$), gain spread ($\sigma_1$), pedestal position ($Q_0$), pedestal width ($\sigma_0$), prompt-crosstalk probability ($p_{XT}$), mean number of photons ($\mu$), dark-count rate ($DCR$), after-pulse (AP) probability ($p_{AP}$), AP time constant ($\tau_{AP}$)

Rolph, J., et al. "PeakOTron: A Python module for fitting charge spectra of Silicon Photomultipliers", (2023) DOI: https://doi.org/10.1016/j.nima.2023.168544.

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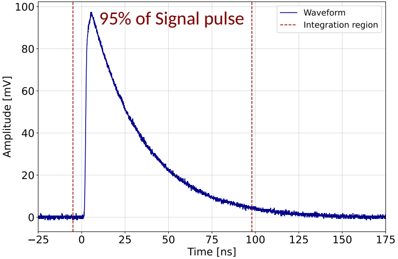
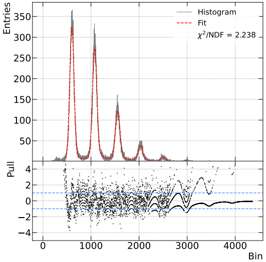



Integration

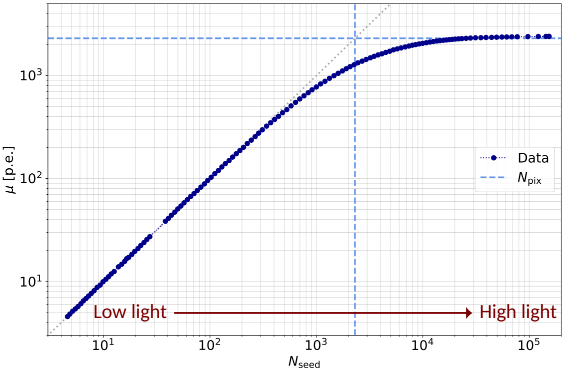
Fitted low light intensity spectrum:




- Full parameter characterization crucial to monitor parameter spread in mass production
  - ➤ **Systematic uncertainty**
- Gain calibration of each channel essential for equalization of calorimeter cells & threshold
  - ➤ Constant term of **energy resolution**

# Characterization at High-light Intensity

Example Response curve:




- Measurement of full dynamic range of SiPM
- Correction of non-linear response possible
  - ➤ Linearization of SiPM response essential to calibrate calorimeter response

# Summary & Outlook

- Concept of a high granular hadron calorimeter prototype based on SiPM-on-tile technology developed
- SiPMs for prototype are selected & order of 900 SiPMs is placed
- **Next steps**
  - Development of a Setup to measure unsoldered SMD mountable SiPMs
  - Characterization of 4% of the SiPMs (36 out of 900)
  - Production and characterization of Readout boards and scintillator tiles
  - Characterization of SiPMs on Readout-boards and MIP characterization
  - System commissioning and test

**Thank you for your attention!**

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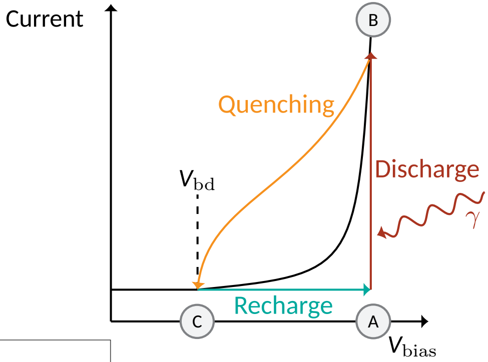
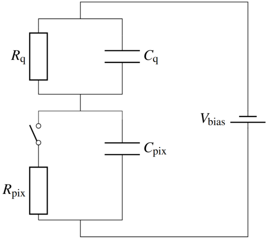
# Backup

# How does a SiPM work?

- (A): SiPM is biased $V_{\text{bias}}$ above breakdown voltage $V_{\text{bd}}$ & no current flows (switch open)
- (A)→(B): Photon initiates an avalanche breakdown (switch closed)
  - Pixel capacitance starts to discharge
  - Rising current flows through SiPM
- (B)→(C): Avalanche quenched due to $R_q$
  - (C): Voltage drops down to $V_{\text{bd}}$
- (C)→(A): Pixel capacitance become recharged

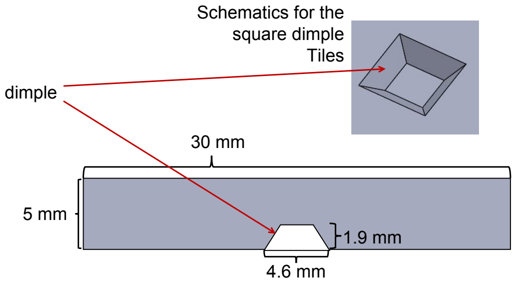


# LY of tiles on different SiPM sizes

## Single tile (square dimple tile):

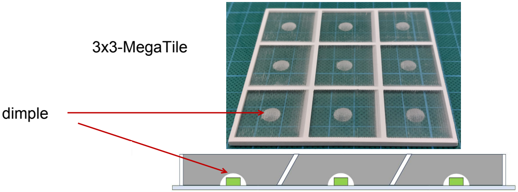
| Model | $A_{eff}$ [mm$^2$] | FF [%] | $A_{eff} \cdot$ FF [mm$^2$] | LY (pe) |
|---|---|---|---|---|
| S13360-1325PE | 1.69 | 47 | 0.79 | $10.5 \pm 0.1$ |
| S13360-2050VE | 4 | 74 | 2.96 | $33 \pm 1$ |
| S13360-3050VE | 9 | 74 | 6.66 | $81 \pm 1$ |




## $3 \times 3$ MegaTile (rounded dimple tile):

| Model | $A_{eff}$ [mm$^2$] | FF [%] | $A_{eff} \cdot$ FF [mm$^2$] | $x_{pred}$ [p.e.] |
|---|---|---|---|---|
| S13360-1325PE | 1.69 | 47 | 0.79 | $7.6 \pm 0.2$ |
| S13360-2050VE | 4 | 74 | 2.96 | $23 \pm 2$ |
| S13360-3050VE | 9 | 74 | 6.66 | $59 \pm 6$ |

$$x_{pred} = x_{3\times3-MT} \cdot \frac{LY(SiPM)}{LY(1.3\times1.3)}$$






Figures and values taken from: P. Kollar, V. Büscher, F. Piermaier, S. Ritter, S. Schönfelder, Q. Weitzel: "LY estimation based on measurements" JGU Mainz, 21.04.2026

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# SiPM design Specifications

Using the values given in in the table on slide 4 for the rounded dimple for the SiPM S13360-1325PE the emitted number of photons from the tile for 1 MIP can be calculated as:

$$N_{\gamma,\,1\,\mathrm{MIP}} = \frac{x_{\mathrm{pred}}}{A_{\mathrm{eff}} \cdot PDE} = \frac{7.6\ \mathrm{p.e.}}{1.69\ \mathrm{mm}^2 \cdot 0.25} \approx \mathbf{18\,\frac{photons}{mm^2}}$$

For 1 MIP the detected number of photons $N_{\mathrm{photon}}$ should be $\mathbf{N_{photon} \geq 15}$, defined as

$$N_{\mathrm{photon}} = N_{\mathrm{emitted,\,1MIP}} \cdot PDE \cdot A_{\mathrm{eff}}$$

with $A_{\mathrm{eff}}$ in $\mathrm{mm}^2$ as the silicon (active) area of the SiPM. Therefore, the first requirement is:

$$\mathbf{1)\quad PDE \cdot A_{eff} \geq 0.83}$$

The SiPM should not be saturated for 200 MIPs, e.g. the SiPM's number of pixel should full fill: $N_{\mathrm{pix}} > 200 \cdot N_{\mathrm{emitted,\,1MIP}} \cdot A_{\mathrm{eff}} \cdot PDE$. Therefore, the second requirement is:

$$\mathbf{2)\quad N_{pix}/(PDE \cdot A_{eff}) > 3600}$$