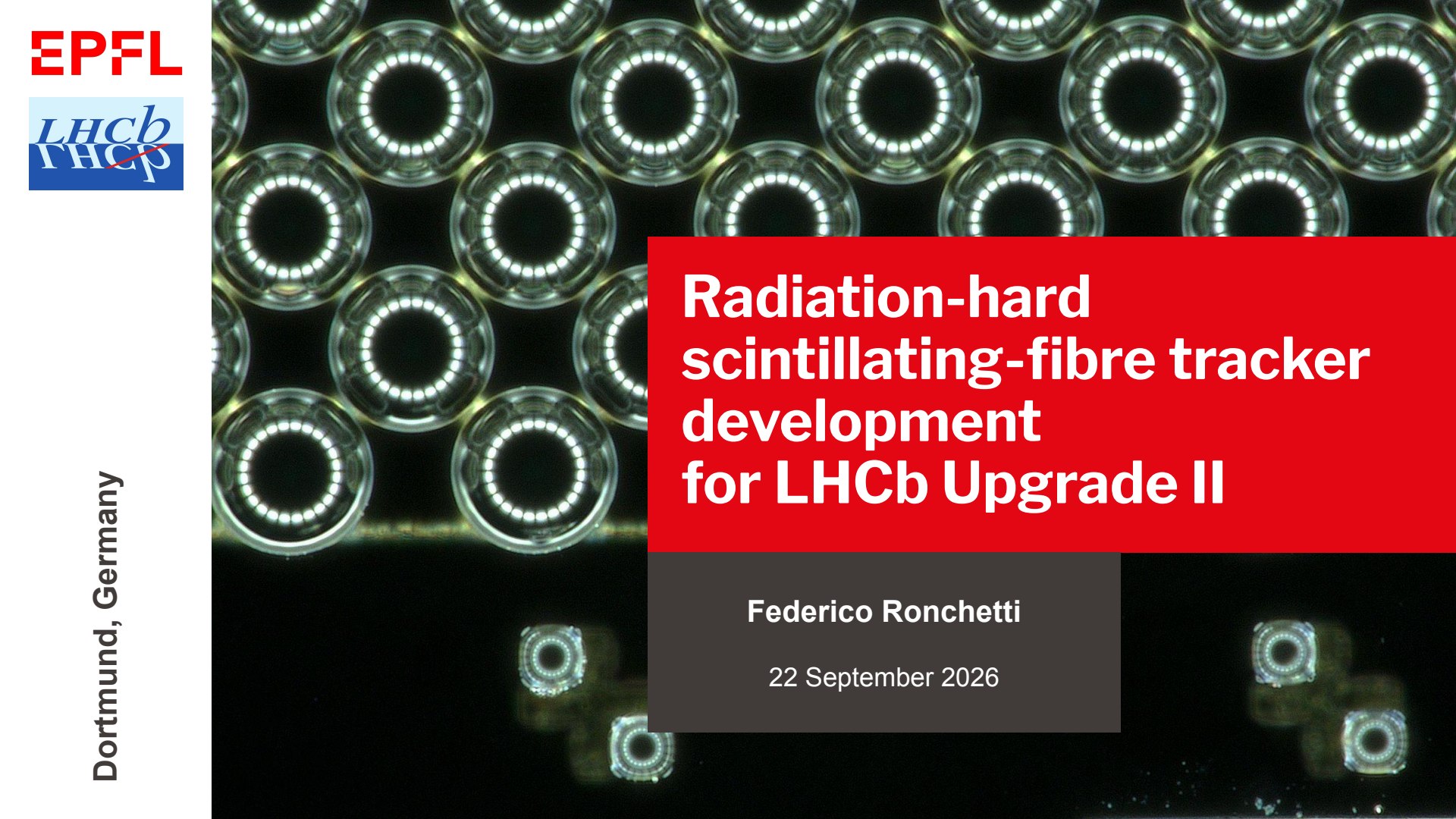




EPFL



Dortmund, Germany



Radiation-hard scintillating-fibre tracker development for LHCb Upgrade II

Federico Ronchetti

22 September 2026

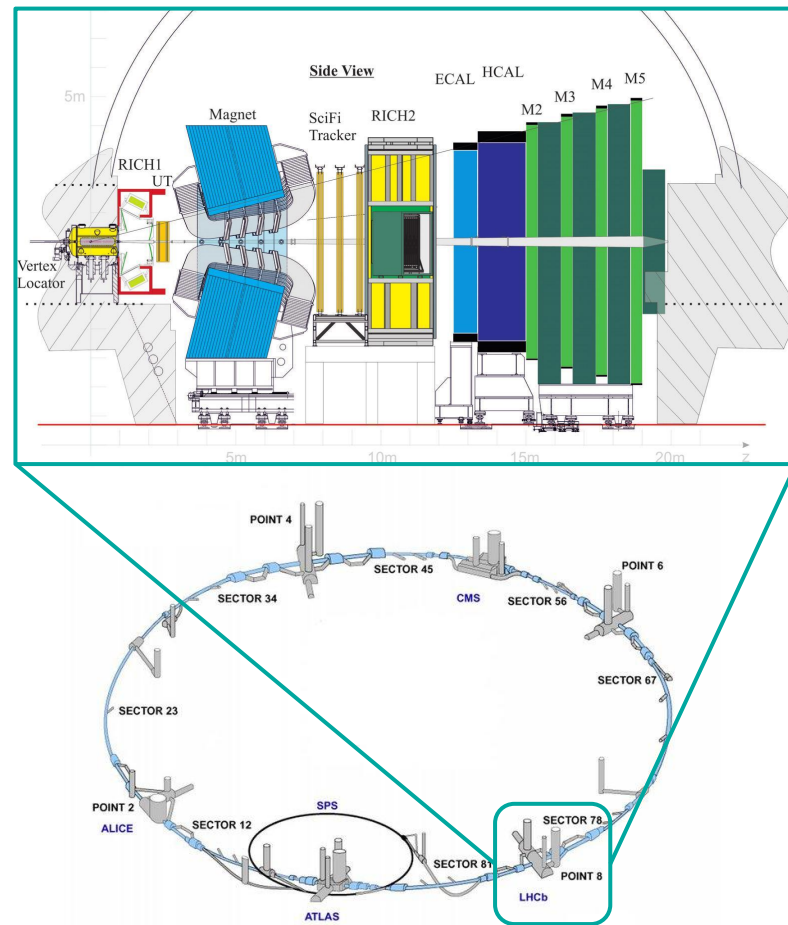
Contents

- LHCb SciFi and LHCb Upgrade II
- Microlens-enhancement SiPMs
- Single Photon Time Resolution
- Characterisation of a long fibre mat
 - light yield
 - time resolution
- LHCb SciFi Dark Count Rate

The LHCb experiment

- Particle physics experiment at the Large Hadron Collider (LHC) at CERN, Geneva
- Studies CP symmetry violation in B meson decay by proton-proton collision
- In 2018-2021 → major upgrade (LHCb Upgrade I)
 - Complete new tracking system
 - Update of the RICH systems
 - New readout electronics

→ Installation of the SciFi tracker!

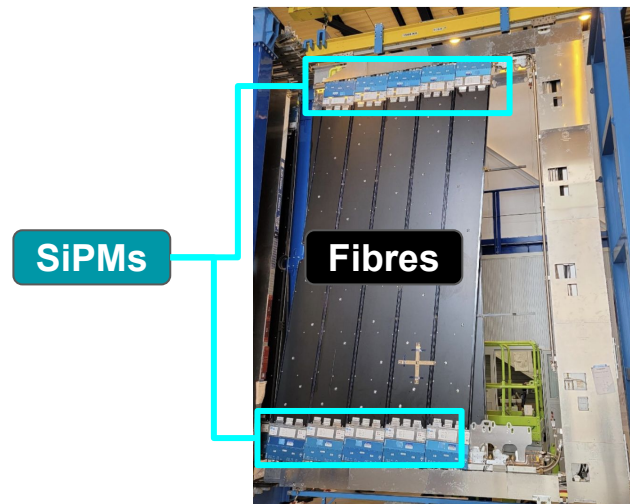
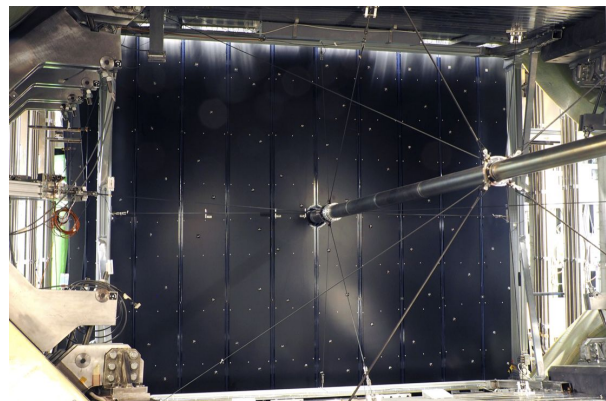


The LHCb SciFi tracker

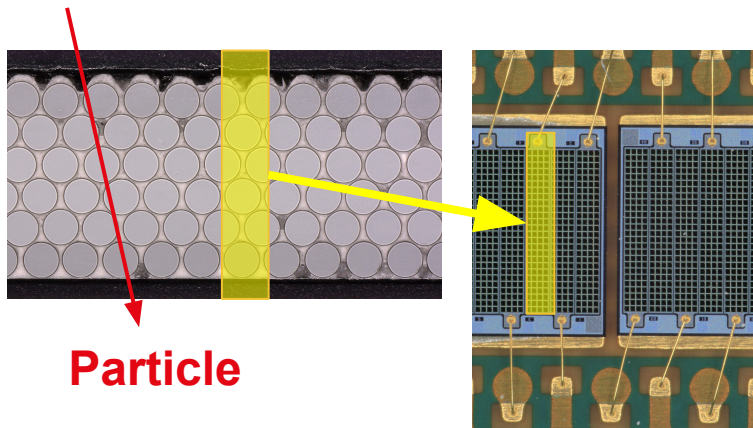
The **Scintillating-Fibre (SciFi) tracker** is one of the **LHCb sub-detectors**, placed after the LHCb magnet. It is made of 12 layers in 3 tracking stations for a total **sensitive area of 340 m²**, **500k channels** and a **spatial resolution < 100 μm** .

Fibre mats are made of **250 μm scintillating fibres** **2.5m long**, staggered and glued together. The readout is performed by **Silicon PhotoMultipliers arrays** of 128 channels operated at -40°C. SiPMs are required to have

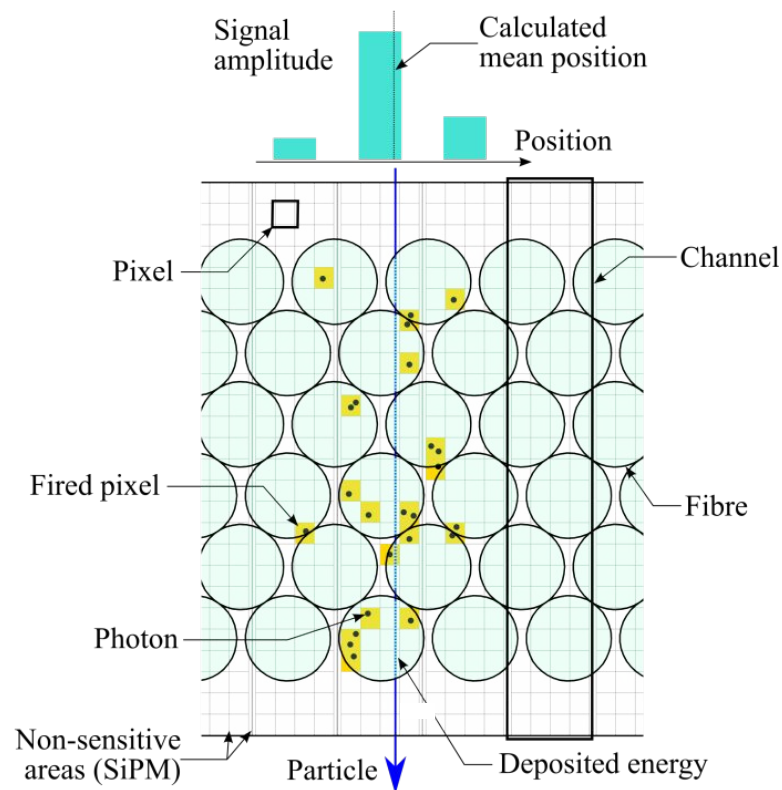
- low correlated noise
- high PDE (average number of photoelectrons per traversing particle is 10-15)
- low DCR after irradiation



SciFi working principle



1. A **charged particle** leaves energy in the fibre mat
2. The energy is converted in **light**
3. Light is transported along the fibres
4. **Photons are detected** at the end of the fibres by **SiPMs**
5. **Hit position** is computed

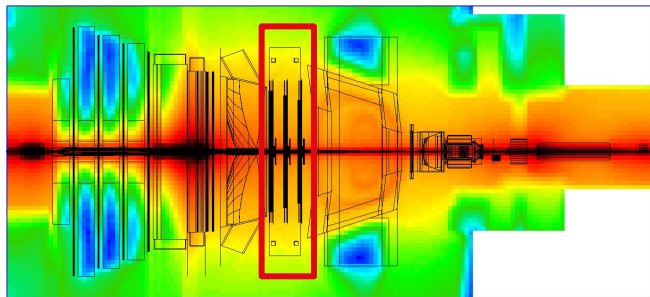


LHCb from Upgrade I to Upgrade II

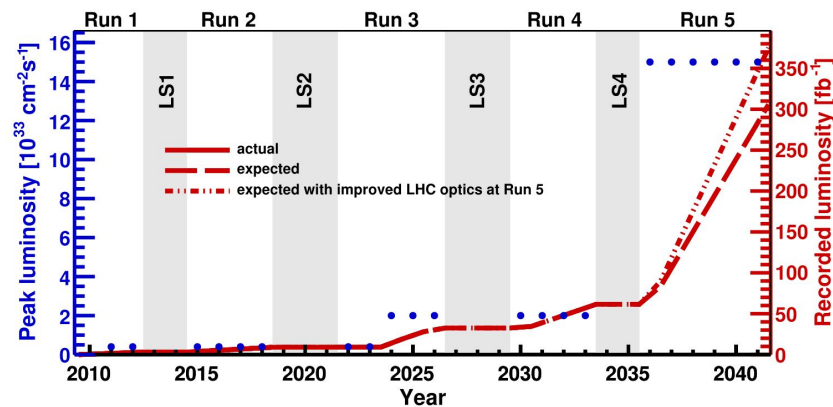
UPGRADE I

Due to radiation (charged particles and backscattered neutrons), the overall performance will get worse **after 50 fb⁻¹** (LHC Run 3 and 4):

- **35 kGy** dose for the **fibres** → 40% less light yield
- **6×10^{11} 1 MeV n_{eq}/cm²** neutron fluence for the SiPMs = DCR will increase up to 14 MHz



SciFi



UPGRADE II

High Luminosity LHC Run 5 will provide 5 times the luminosity of previous runs (300 fb⁻¹).

- **x 5** dose for the **fibres**
- **3×10^{12} 1 MeV n_{eq}/cm²** neutron fluence for the SiPMs
- Larger number of collisions = high occupancy

Mighty Tracker

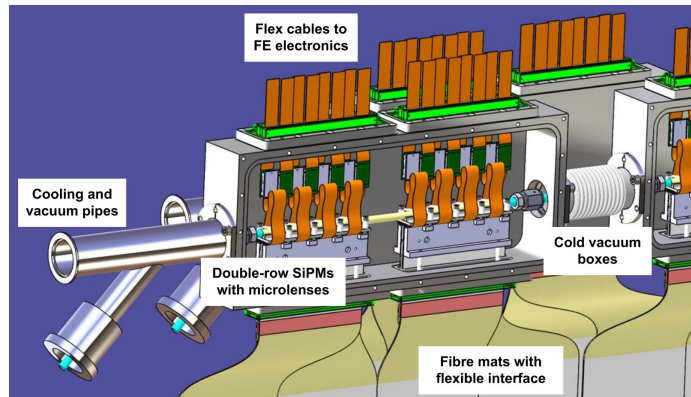
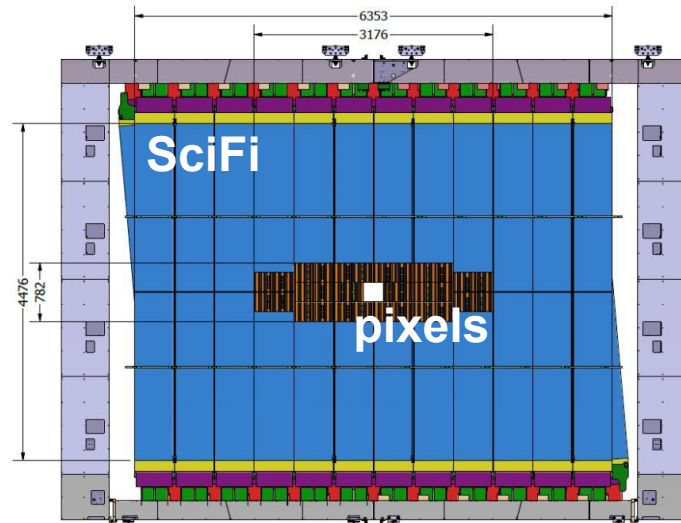
The **high occupancy** in the innermost part of the detector will require finer segmentation and fibres will be replaced by **silicon pixels**, in a new hybrid detector called **Mighty Tracker**.

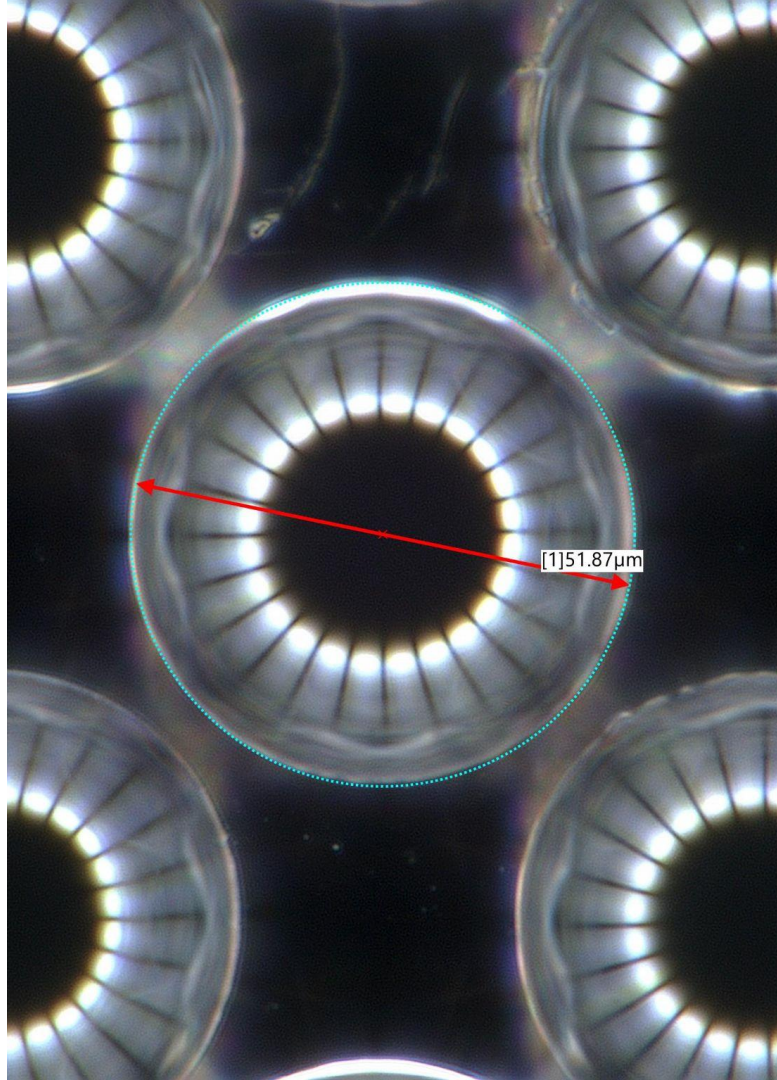
The pixel detector allows to cope with high track density (xy position determination) and to avoid ghosts, but it is expensive in terms of money and material budget.

To cover a **large area** with minimum material budget SciFi will still be employed in the outer region.

The new **Mighty SciFi**, will have to face 5 times the radiation level, so R&D is in progress to:

- **improve light detection** from irradiated fibres
 - new more radiation hard fibres
 - **Microlens-enhanced SiPMs**
- achieve **less noise** in the SiPMs
 - **LN2 cryo-cooling**

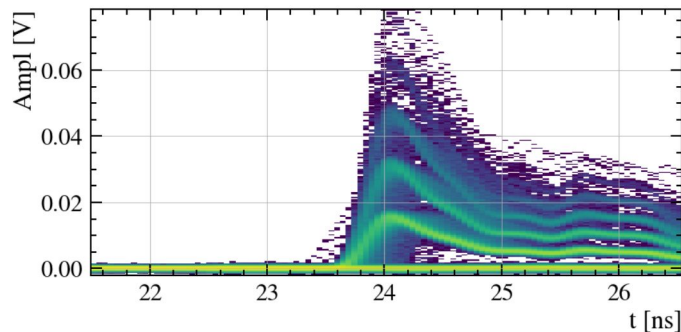
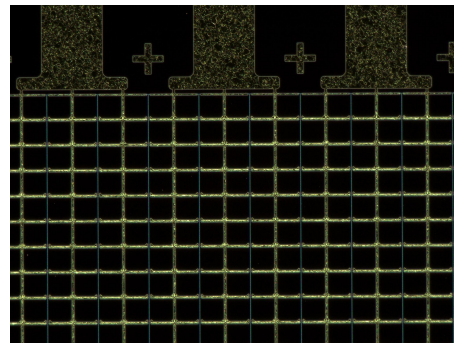
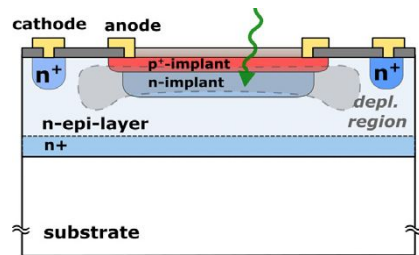
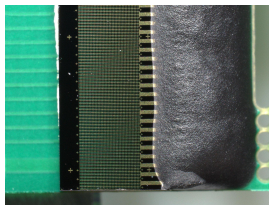




Microlens-enhanced SiPMs

The SiPM technology

- Matrix of Single Photon Avalanche Diode (**SPAD**) connected in parallel
- it's **not a pixel device**, but pixels are used to count the incident photons: the output signal is proportional to the number of detected photons
- Very high gain** $\sim 10^6 \rightarrow$ single photon sensitivity
- High detection efficiency
- Intrinsically **fast** thanks to fast avalanche build-up
- Compact devices** and low power needed
- Insensitive to magnetic field
- Can be arranged in arrays to cover large areas
- Largely used** in many applications

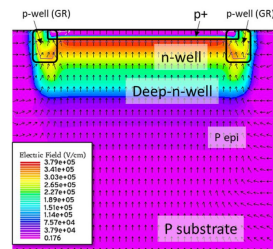
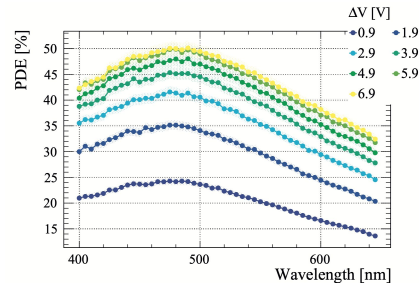


SiPM Photon Detection Efficiency

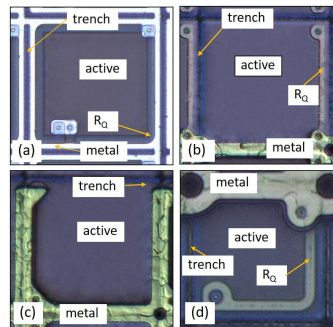
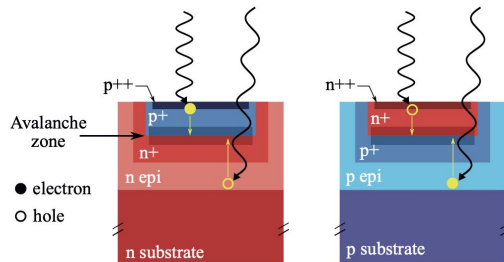
The SiPM PDE is the probability that an incident photon produces a detectable signal. Depends on:

- Silicon properties of absorbing light at specific λ
- The electric field in the pixel
- The pixel design
- Pixel and electric field geometry

$$\text{PDE} = \underbrace{\text{QE}(\lambda)}_{\text{Si property}} \times \underbrace{\text{GFF}(\Delta V)}_{\text{Geometry}} \times \underbrace{\text{P}_{\text{avalanche}}(\Delta V)}_{\text{Si property}}$$



Acerbi 2019

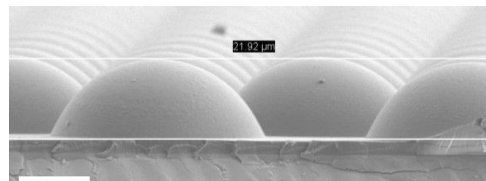
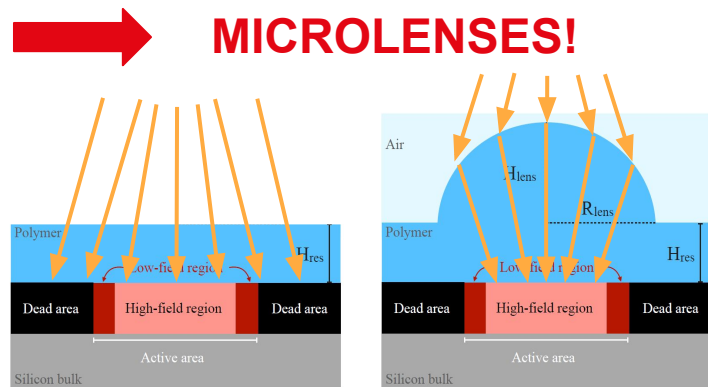


Haefeli 2025

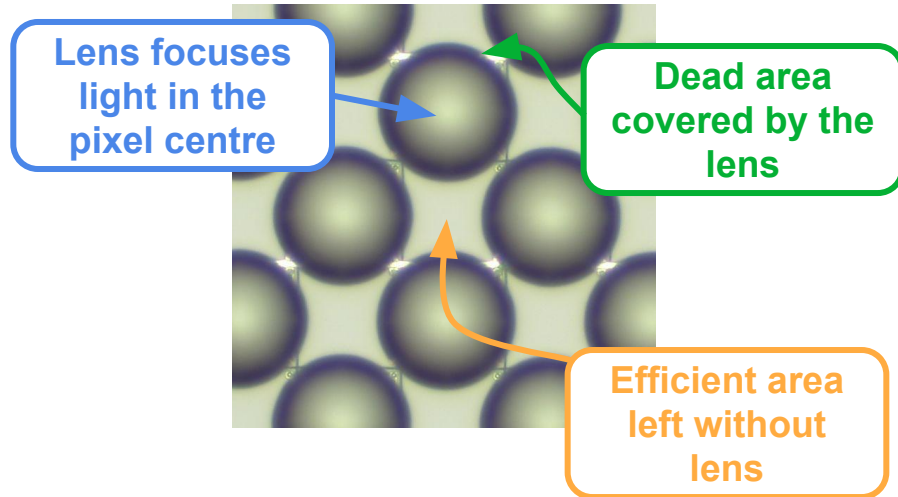
Sensitivity-enhanced SiPMs

To detect **more light**, SiPM PDE can be increased by increasing the Geometrical Fill Factor (GFF) → **recovering light** from non-sensitive pixel's area.

This increases the effective geometrical fill factor EGFF, leading to a **higher PDE**.



Checkerboard configuration



NOTE: an optical system works differently depending on the incident light distribution → spherical lenses work the best when the light is a **normal incident light**.

The light from a fibre is a **collimated light** → microlens can profit from this

Microlens simulation

How to get the **best improvement** within manufacturing limitation?

Pixel

Squared pixels of a chosen SiPM technology. **Dead area** defined by the measured GFF. **Low field region** around the active area as a region with efficiency $\varepsilon_{LF} \leq 100\%$.

Microlens

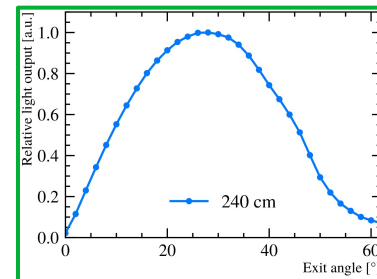
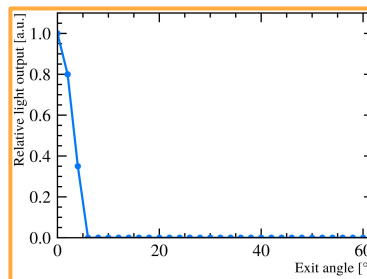
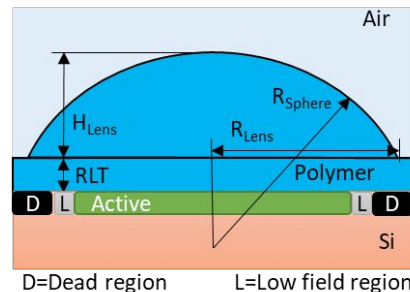
We implemented a **ray-tracing simulation** to **optimise microlens parameters**: lens height, lens radius and residual layer thickness for different SiPM designs.

- Lens radius fixed by the pixel size, distance between lenses and manufacturing
- Max lens height fixed by manufacturing

Light source

Two light sources used in the simulation, what changes is the angular distribution of the generated photons:

- **Normal incident light** → PDE setup
- **SciFi-like incident light** → measured on a fibre mat



Microlens simulation

By counting the number of generated and detected photons one computes the Effective Geometrical Fill Factor (EGFF)

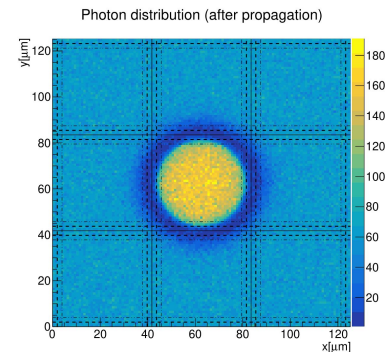
→ comparison between flat coated and microlens-enhanced SiPMs

■ Microlens-enhanced SiPMs

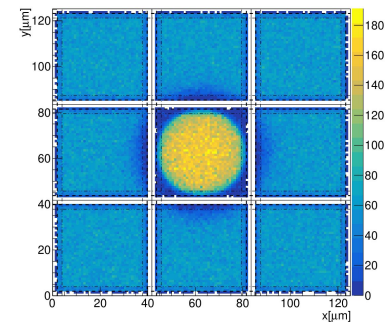
ϵ_{LF}	RLT [μm]	EGFF [%]	G_{LY} [%]
60%	No lens	75.0	-
	10	93.4	24.5
	12.5	93.6	24.6
	15	92.7	23.7
	17.5	91.6	22.1
100%	No lens	81.5	-
	10	96.3	18.2
	12.5	96.7	18.6
	15	95.5	17.1
	17.5	94.6	16.1

SciFi-like light

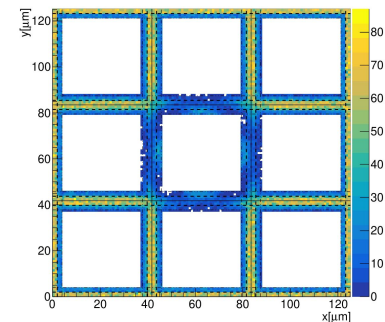
GFF [%]	Light source	LY_{enh} [%]
FBK, pixel size: $41.7\mu\text{m}$		
81.5	SciFi	24.57
	Narrow	27.91
HPK, pixel size: $41.7\mu\text{m}$		
68.5	SciFi	38.98
	Narrow	45.93
FBK, pixel size: $31.3\mu\text{m}$		
77.7	SciFi	27.51
	Narrow	39.87



active area hits

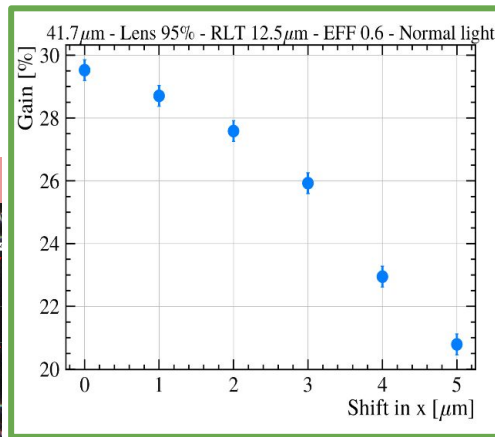
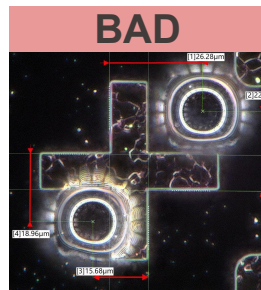
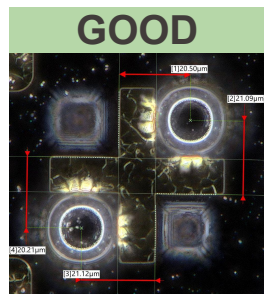


Dead area hits



Microlens simulation

The simulation gives also informations on the effect of **possible production misalignments** between lenses and pixels and on the dependance on the wavelength of the incident light in terms of **refractive index** of the lens



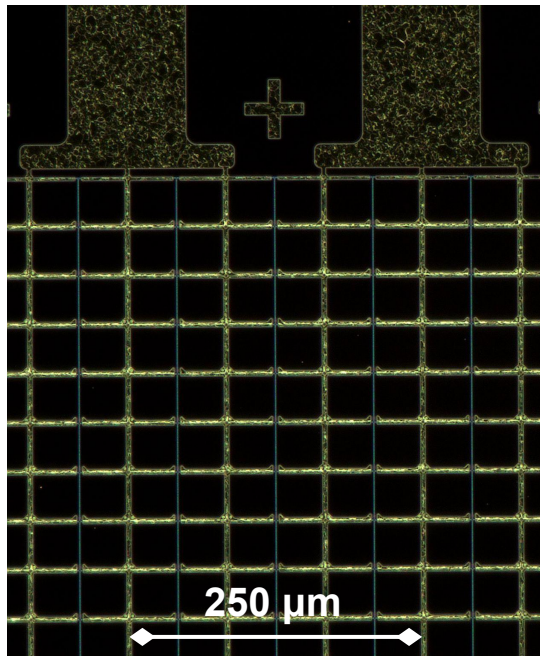
n	EGFF [%]	G_{LY} [%]
1.51	96.2	28.3 ± 0.3
1.52	96.1	28.2 ± 0.3
1.53	96.5	28.7 ± 0.3

The simulation with lens n given by the manufacturer doesn't show any relevant dependance

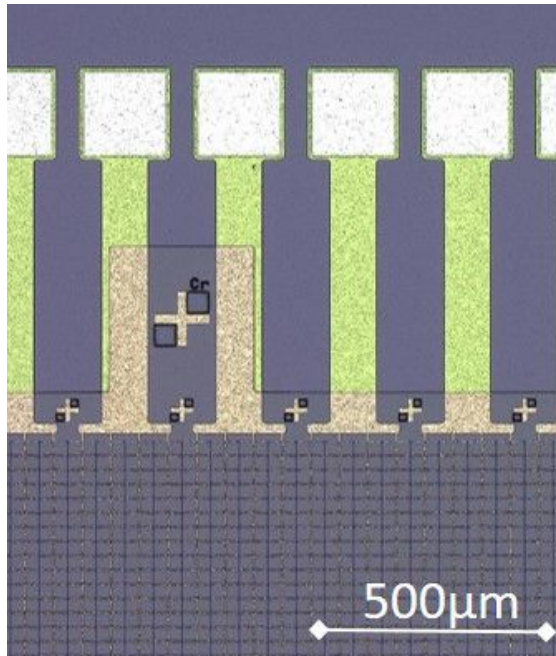
Simulation with lens not aligned with the pixel → **dramatic reduction!**

SiPM coatings

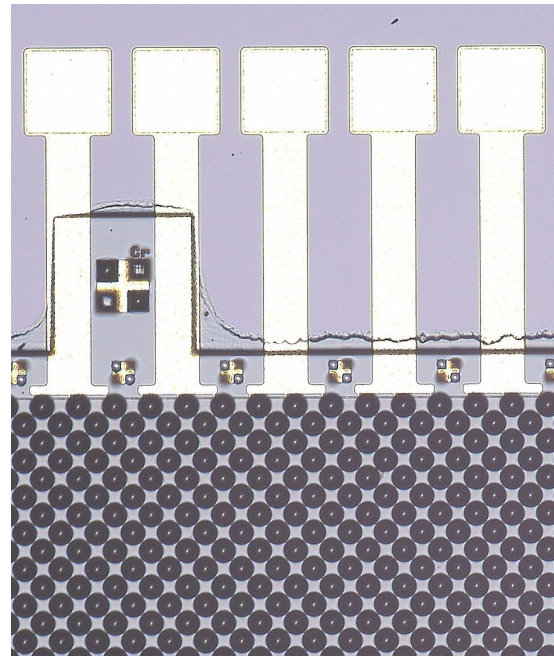
Bare silicon



Flat polymer coating

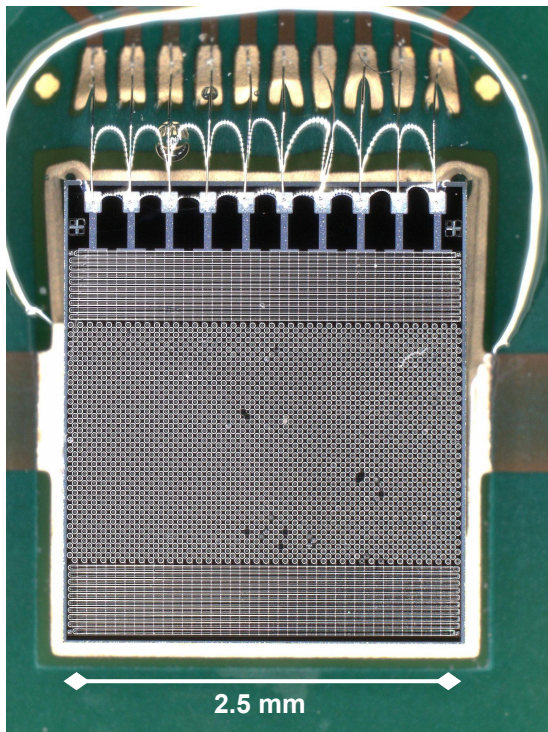


Microlens coating



Where we were before (2022)

[Tripl, Thesis 2023](#)

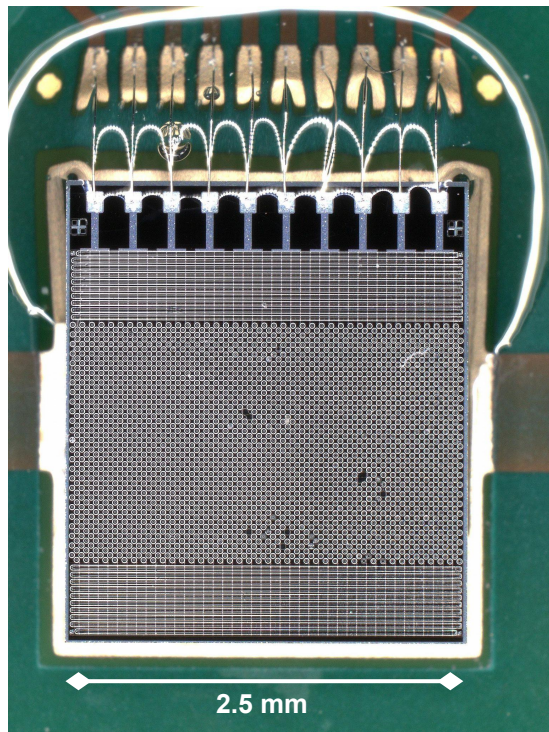


■ Microlens-enhanced SiPMs

First prototypes

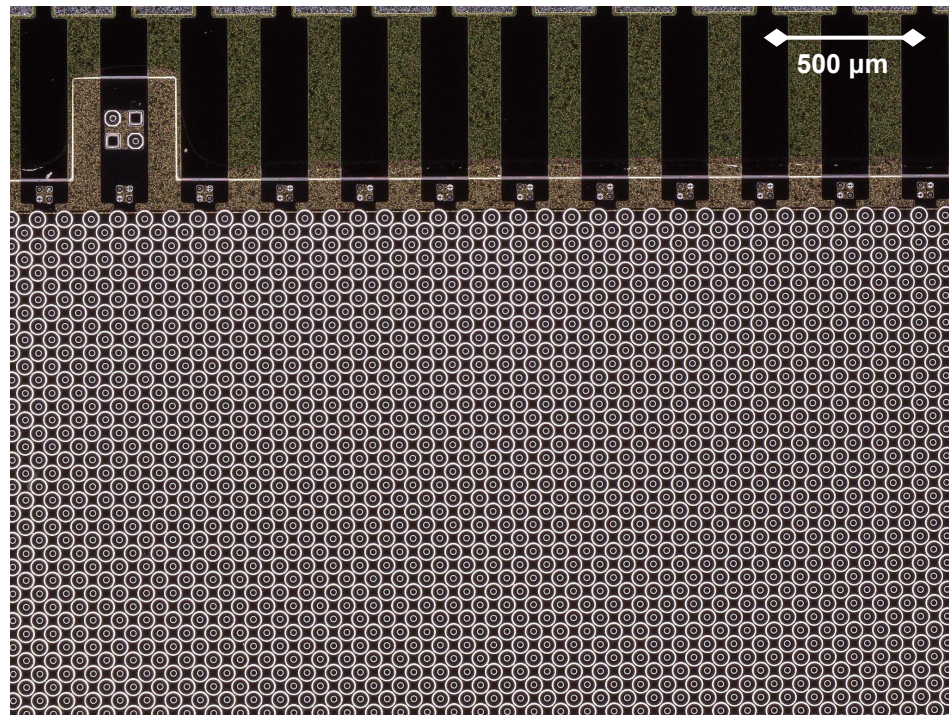
- SiPM technology with very **limited operation range** (0 to 2V OV), large cross-talk, FBK SiPM 40 μ m
- **10 channel** array, too small for SciFi operation and characterisation because of too many boundaries
- Spherical microlenses + cylindrical spacers on the sides
- **Production defects:** many defects and little homogeneity over the die - large sample to sample variation
- Results showed an **improvement** between **0% and 15%** with respect to conventional coating

Where we were before (2022)



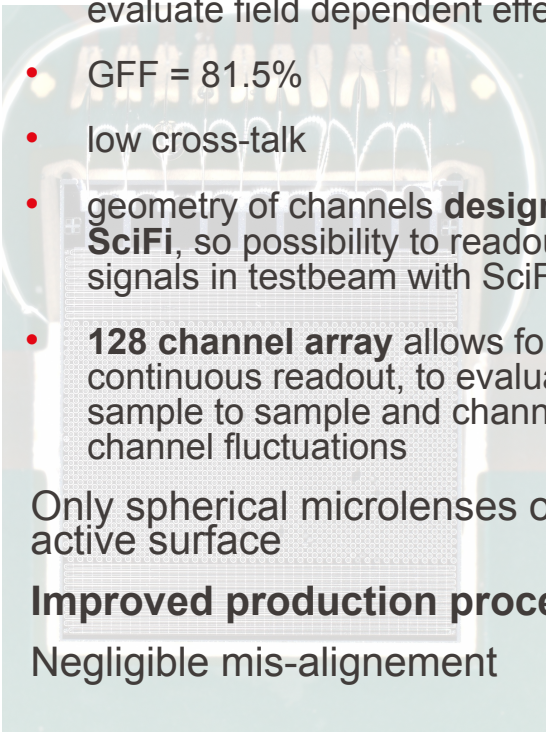
■ Microlens-enhanced SiPMs

Where we are now (2026)

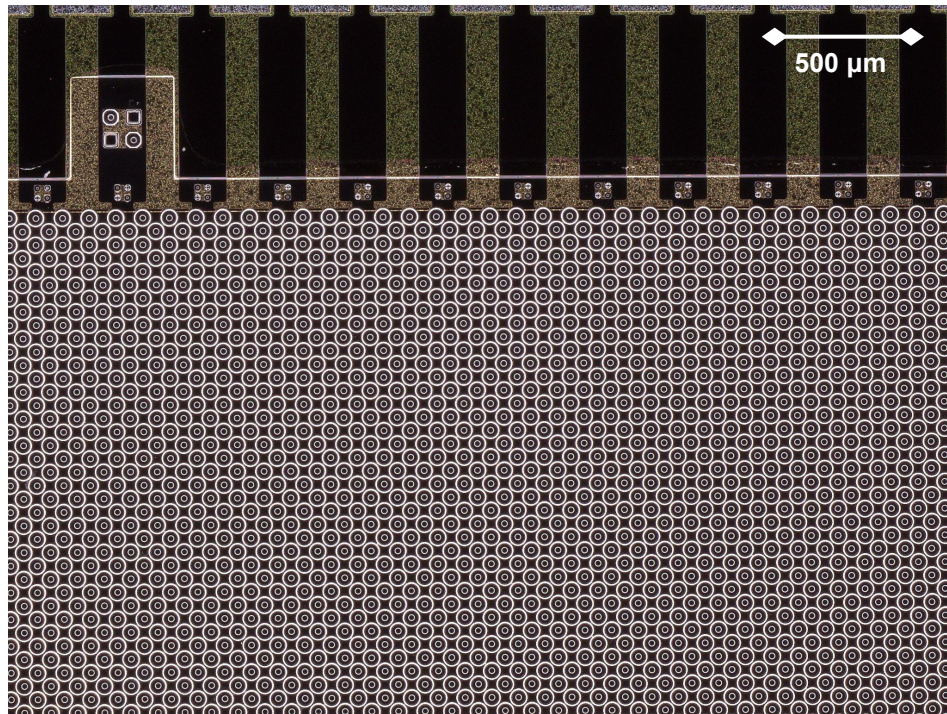


Full detector

- FBK NUV-HD SiPM 42 μ m
 - **large operation range**, allows to evaluate field dependent effects
 - GFF = 81.5%
 - low cross-talk
 - geometry of channels **designed for SciFi**, so possibility to readout signals in testbeam with SciFi
 - **128 channel array** allows for large continuous readout, to evaluate sample to sample and channel to channel fluctuations
- Only spherical microlenses on the active surface
- **Improved production process**
- Negligible mis-alignment

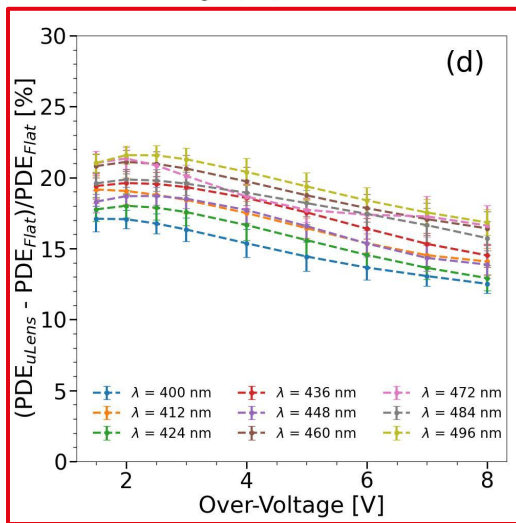
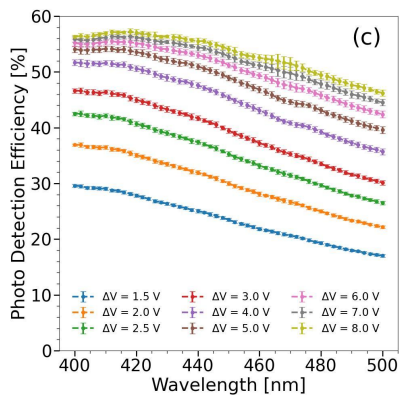
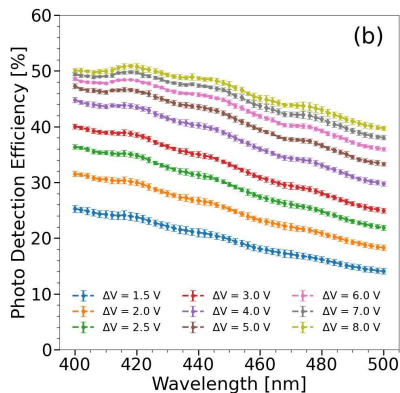
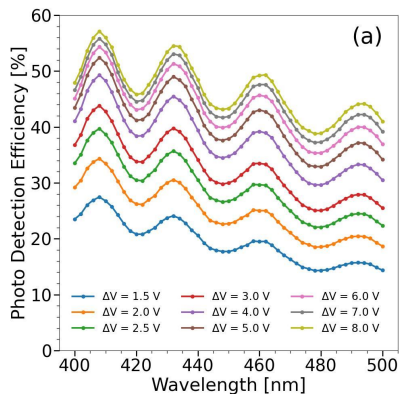


Where we were few years ago (2024)



PDE enhancement

FBK 2022 42μm

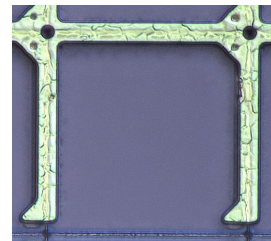


- PDE measured for **bare die** (a), **flat** (b) and **microlens coated** (c) SiPMs
- Narrow angle incident light
- PDE increase** (d) calculated as

$$\text{PDE}_{\text{gain}} = \frac{\text{PDE}_{\mu\text{lens}} - \text{PDE}_{\text{flat}}}{\text{PDE}_{\text{flat}}}$$

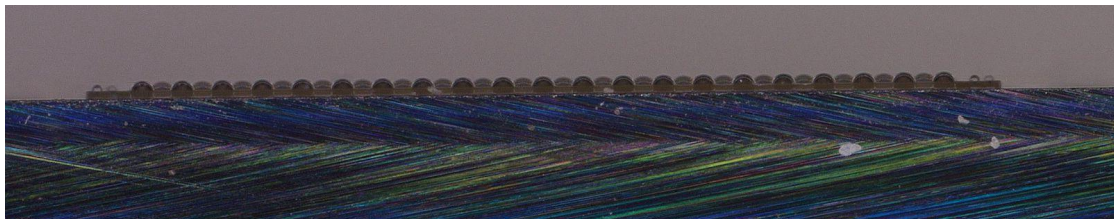
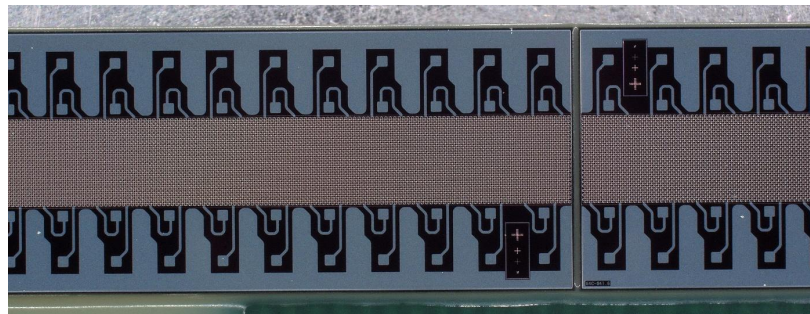
- PDE increase reaches its maximum at **low overvoltage** → the lens effect is more important when efficient area is smaller
- Maximum PDE gain

- 2 V OV = 22%**
- 8 V OV = 17%**

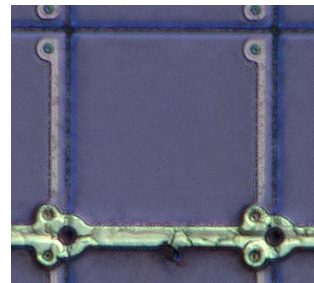
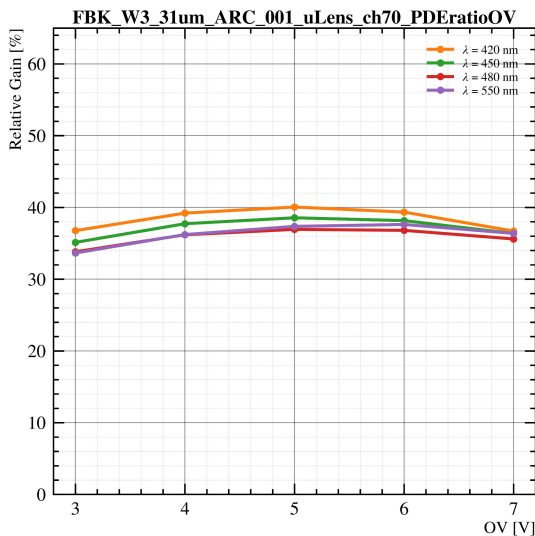
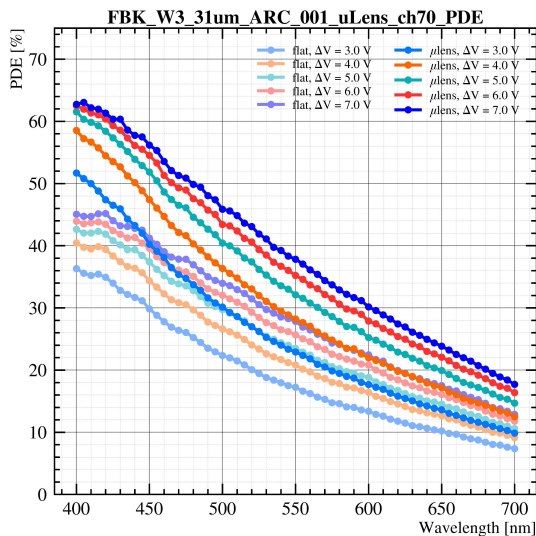


Where we are now (2026)

- Implementation **on FBK and HPK arrays** for different pixel sizes
 - the external manufacturer CSEM has implemented the dual-SAG technique to print **two types of lenses with the same mold**
- **Radiation-hard** lens material
- 100 samples produced in one step **without defects**
- Characterisation of the array in terms of RLT and mis-alignment (done by Jou-An Chen)
- All sample types **tested in the lab** and in dedicated several **testbeam campaigns** at CERN



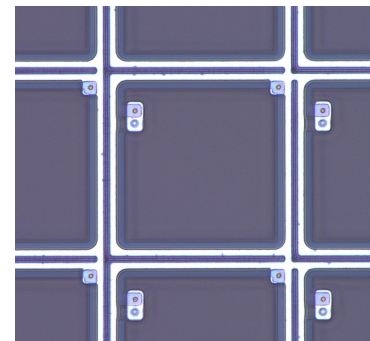
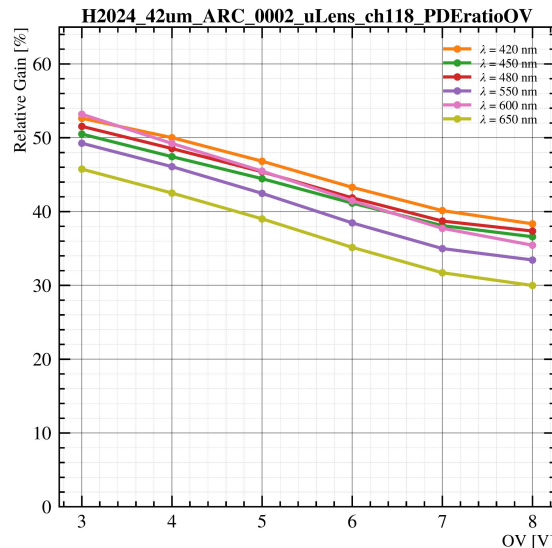
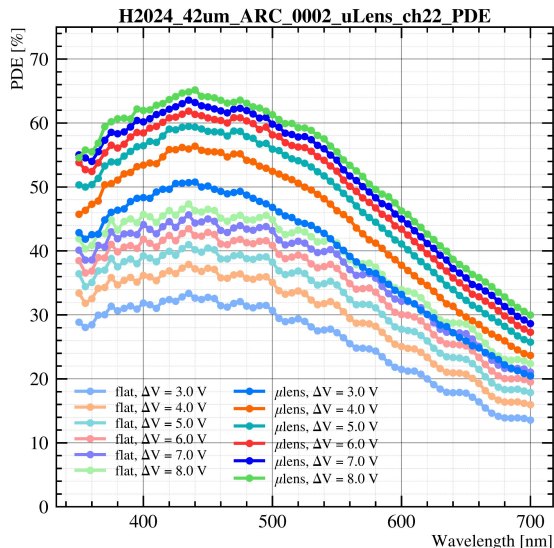
PDE enhancement

FBK 2022 31 μ m

GFF = 77.7%

- Larger PDE increase due to lower pixel GFF → the lens effect is more important when efficient area is smaller
- Maximum PDE gain **up to 40%**

PDE enhancement HPK 2024 42 μ m



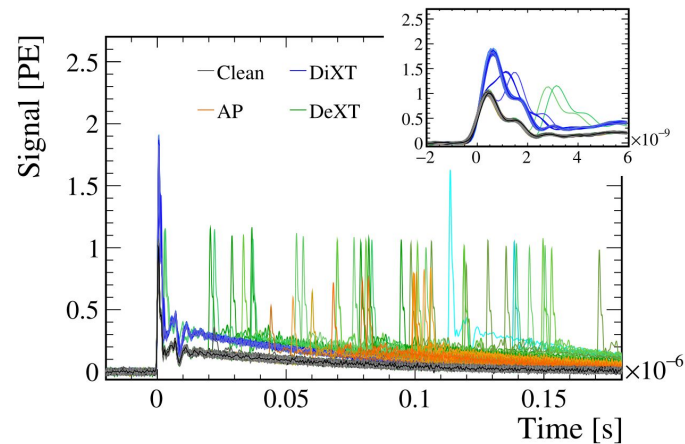
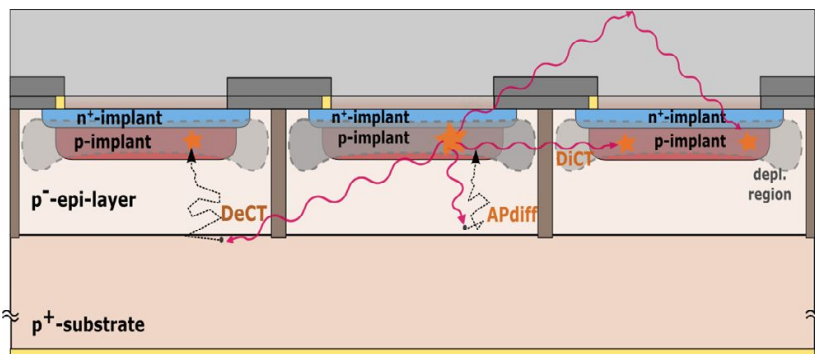
GFF = 68.5%

- Maximum PDE gain **up to 50%**
- Even at low overvoltage, microlenses keep the PDE higher than without enhancement $\rightarrow$ allow to operate SiPMs at low OV, so less noise

SiPM correlated noise

SiPMs are characterised by two sources of noise: uncorrelated (later in this presentation) and correlated one.

- **Optical cross-talk** → depends on pixel design and coating
 - Direct
 - Delayed
 - External
- **Afterpulsing** → depends on the silicon

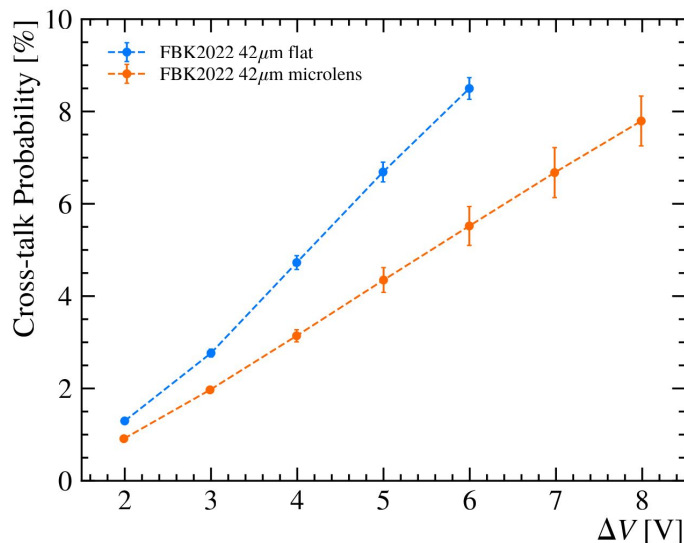


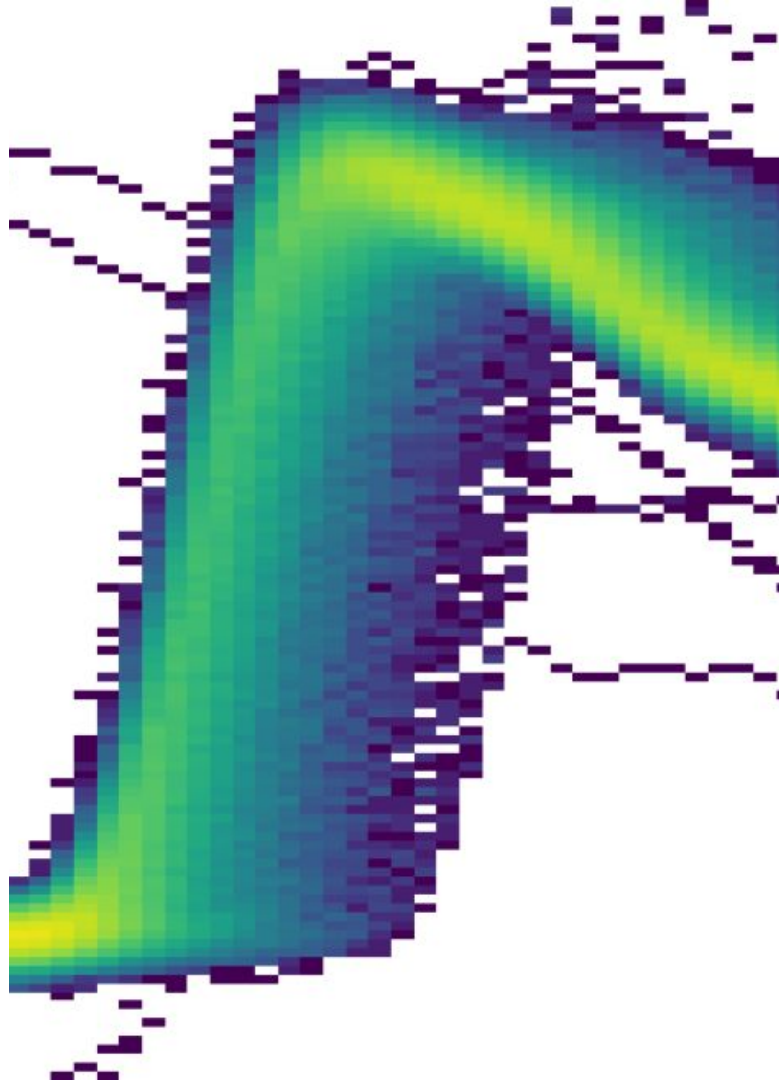
Microlens SiPMs cross-talk

Cross-talk reduced by more than 40% for microlens-enhanced SiPMs with respect to flat coated ones

→ microlens traps, defocuses or focuses back emitted photons generated in the avalanche

Remember: the microlens array covers only half of the pixels





SiPM Single Photon Time Resolution

The SiPM Single Photon Time Resolution is a crucial parameter in photon-starve applications where precise timing is needed. The measured SPTR depends on:

- **SiPM properties**, like pixel homogeneity σ_{ccv} , readout grid length σ_{tts} , pixel intrinsic resolution σ_{SPAD}
- **measurement setup** (light source jitter, electronic jitter...)

$$\sigma_{\text{measured}}^2 = \sigma_{\text{SPAD}}^2 + \sigma_{\text{tts}}^2 + \sigma_{\text{ccv}}^2 + \sigma_{\text{noise}}^2 + \sigma_{\text{DAQ}}^2 + \sigma_{\text{source}}^2$$

Measured in this work

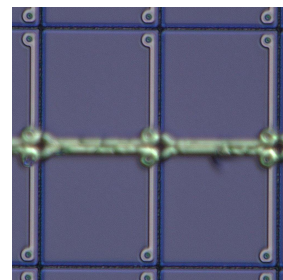
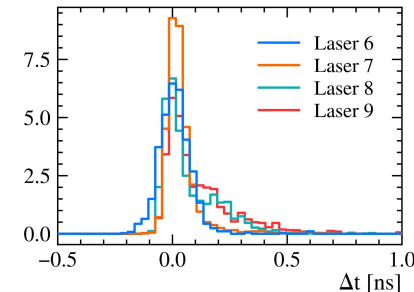
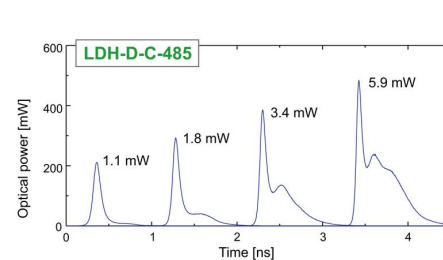
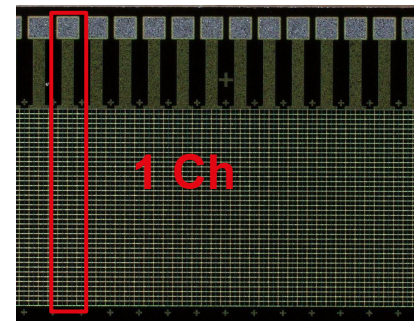
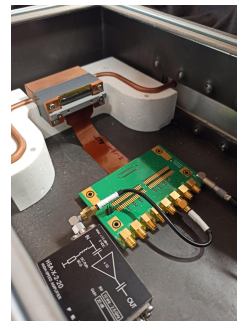
Calculated as

$$\sigma_{\text{noise}} = \frac{\sigma_{\text{baseline}}}{V_{\text{slope}}}$$

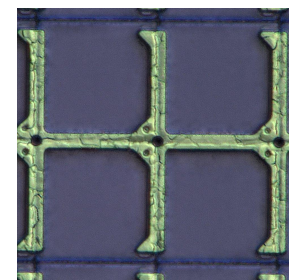
Setup

- 450 nm Picoquant LDH Series laser → power tuned to have minimum spread ~ **56 ps** (from datasheet)
- FEMTO 40dB high-speed amplifier (2GHz BW)
- Faraday-cage box
- Teledyne LeCroy hdo6054b oscilloscope at 20ps/div (2MHz BW)
- 6 SiPMs:
 - Hamamatsu** 42 μm and 50 μm
 - FBK** 42 μm bare and microlens
 - FBK** 31 μm masked and non-masked

→ one channel acquired (**0.4 mm²** surface)



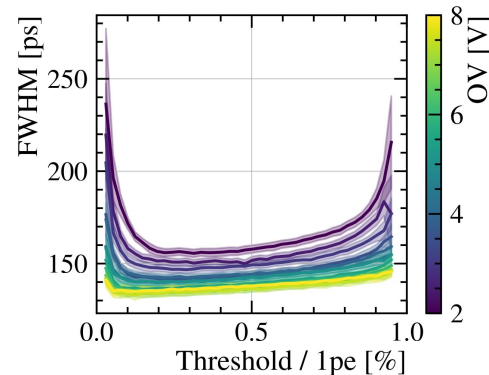
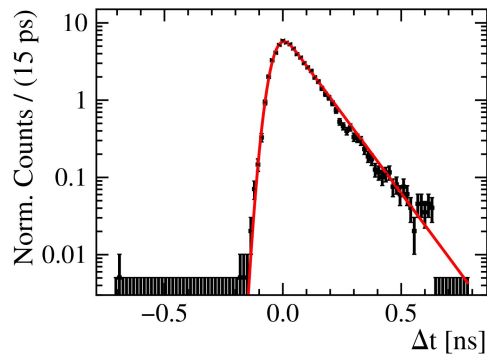
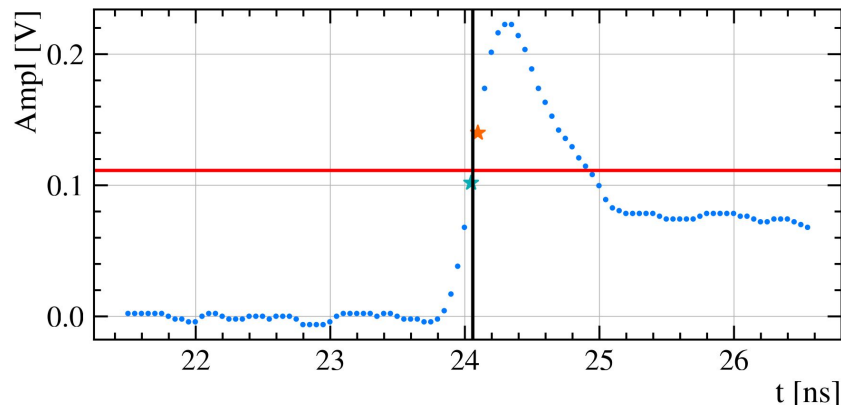
FBK 31 μm



**FBK 31 μm
masked**

Measurement technique

- Selection of the single photon pulses
- Threshold set as a percentage of the 1pe pulse amplitude
- Timestamp of the leading edge measured by interpolating between the two samples around the threshold value
- The time distribution fitted with EMG to extract the FWHM
- Scan in threshold values and OV
- Noise jitter subtraction

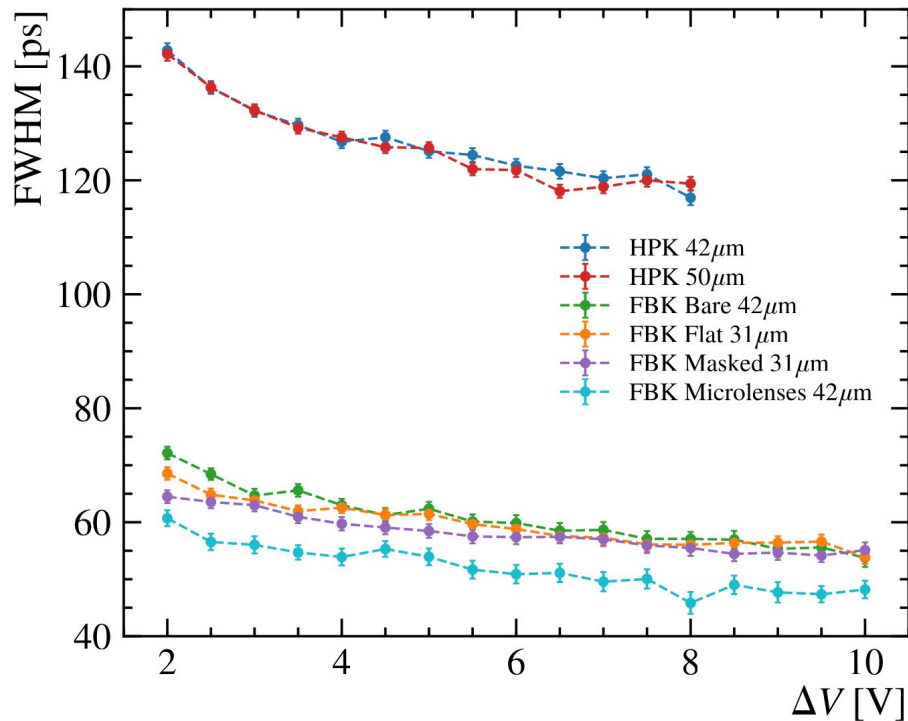


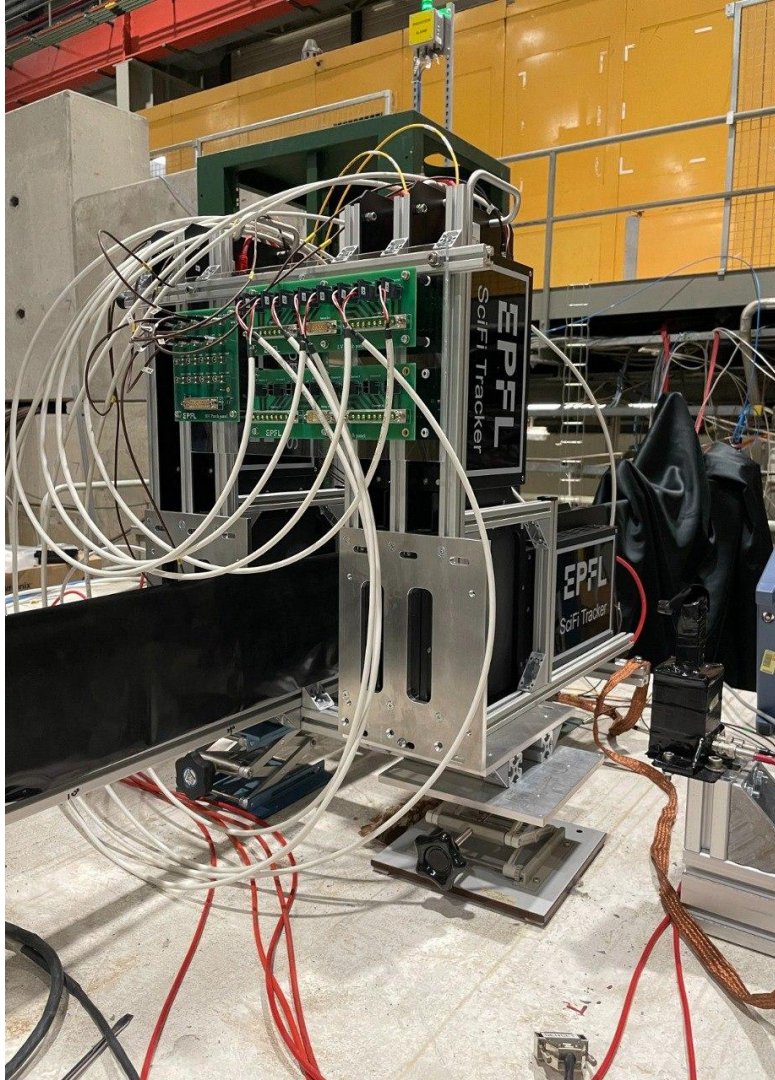
Results

- Results presented with noise jitter and laser contribution subtracted
- Hamamatsu worse due to pixel design → deep junction not optimised for timing
- Microlens-enhanced SiPMs are faster** thanks to focusing in the high field and homogeneous region of the pixels
- Metal mask proved to fasten the signals

How so fast?

- SiPMs are intrinsically fast thanks to high gain and fast readout
- Small area device





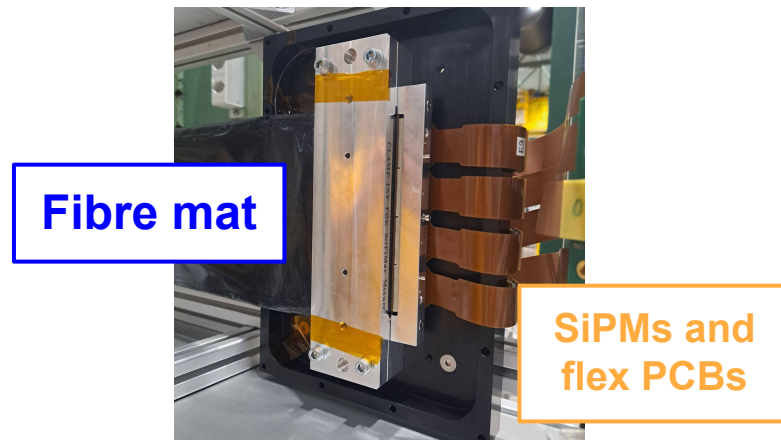
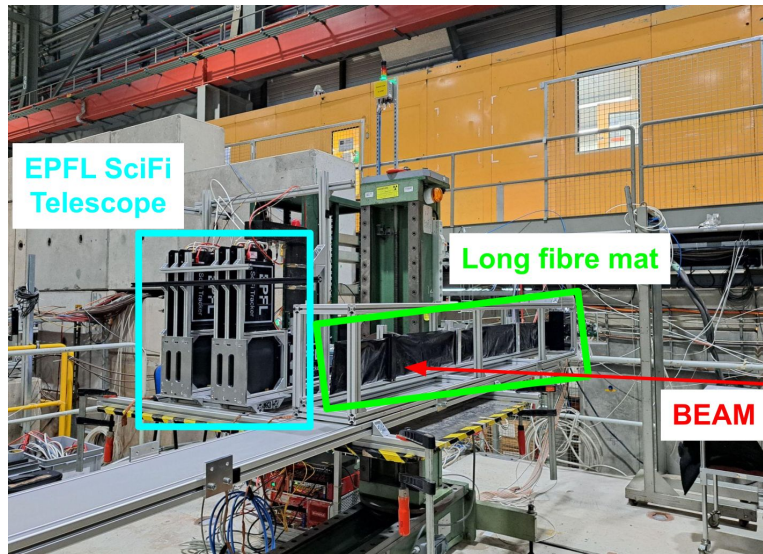
**Characterisation in a
testbeam of a 2.4 m
long fibre mat read out
by SiPMs arrays**

Light yield and time measurements

The light yield and the timing performance of a long fibre mat (SciFi-like) have been evaluated in **dedicated testbeams**

- CERN SPS H8 extracted beam line
- Collimated beam of 180 GeV/c muons and hadrons → MIP-like

Different mats and SiPMs have been tested together, but only **non-irradiated samples** have been evaluated in this work



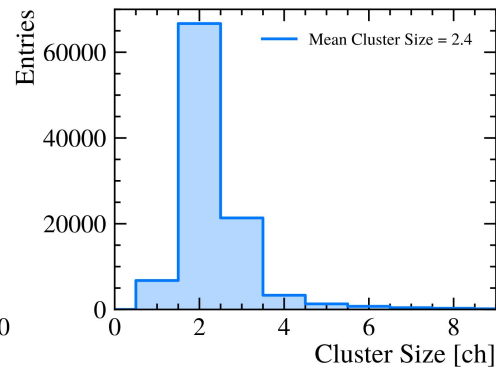
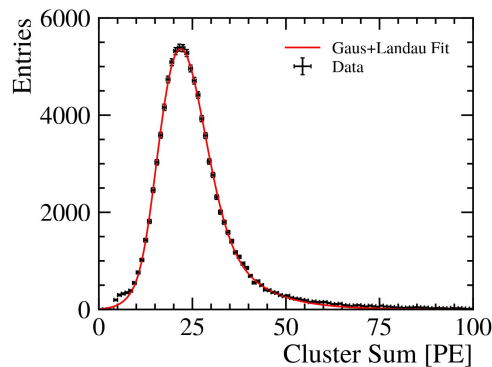
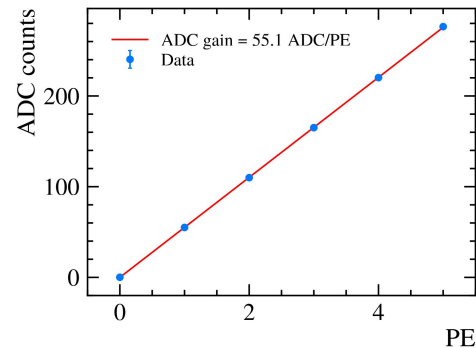
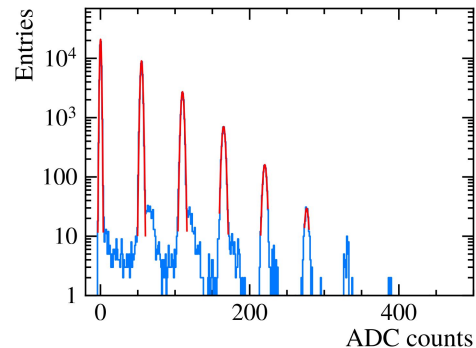
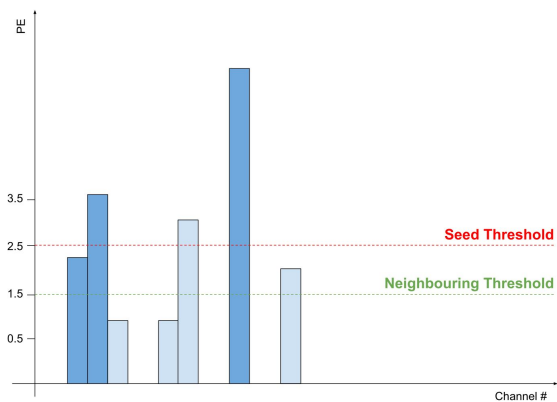
Light yield



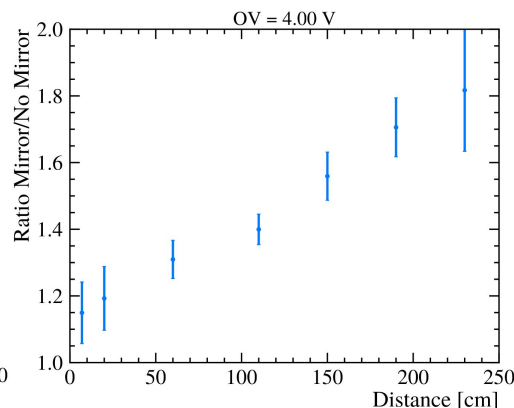
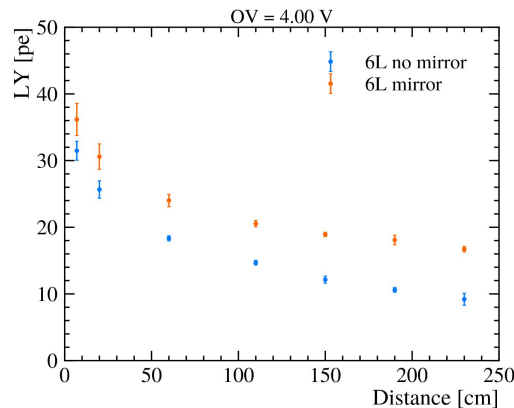
The light yield has been measured by reading out the SiPMs with the **VATA64 ASIC** → saves the raw amplitude signal of every channel to be processed offline

The ASIC has been calibrated to have the **amplitudes in number of photoelectrons (pe)**

A **clustering algorithm** groups channels belonging to the same particle by applying three thresholds: seed (2.5pe), neighbouring (1.5pe) and sum (4.5pe)

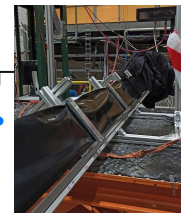
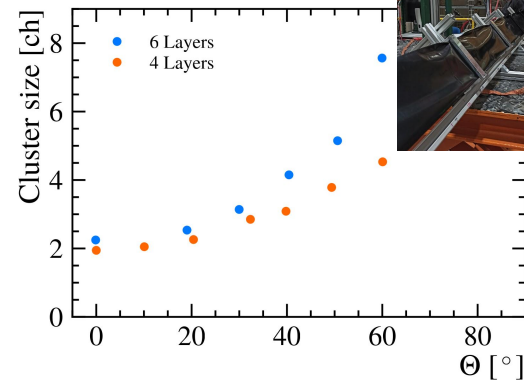
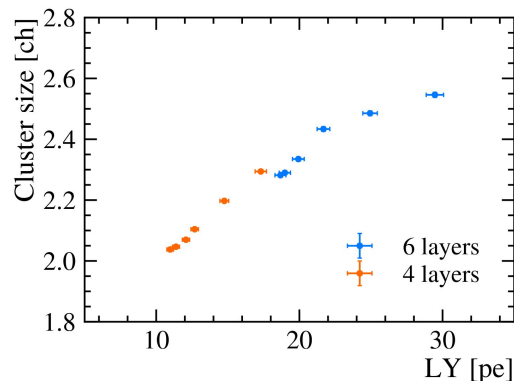


- Same 6 layer mat measured with and without mirror with H2024 SiPMs
- 80% more LY thanks to the mirror at the far end of the mat

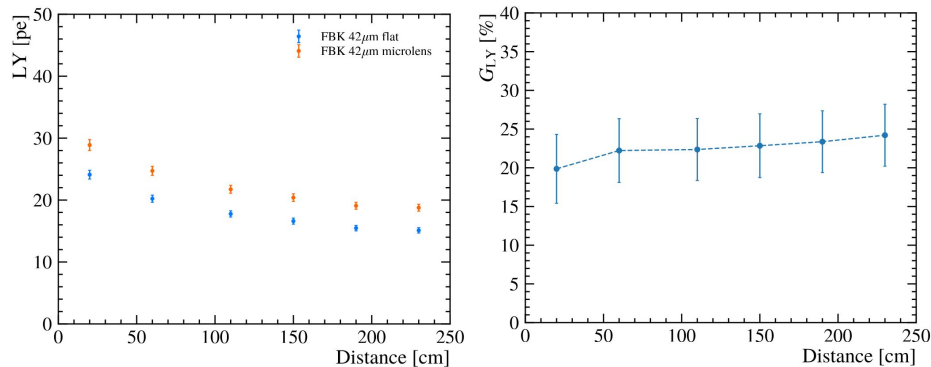


6 vs 4 layers

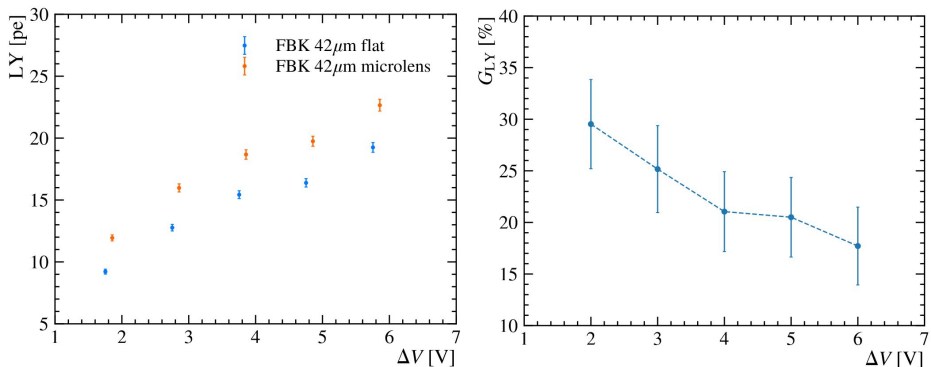
- 6 and 4 layer mats read out with FBK 42 μ m microlens SiPMs
- 4L has smaller cluster size at the cost of ~70% of LY
- 4L keeps the clusters size small even for high angle tracks



FBK 42 μ m @ 4V OV



FBK 42 μ m @ 230cm

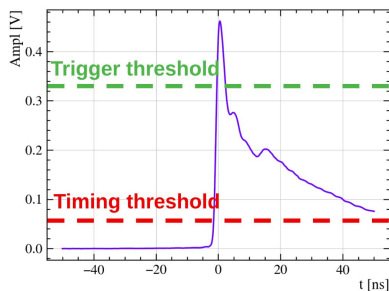


Microlens-enhanced SiPMs outperform the flat coated ones by more than 20% along the whole mat

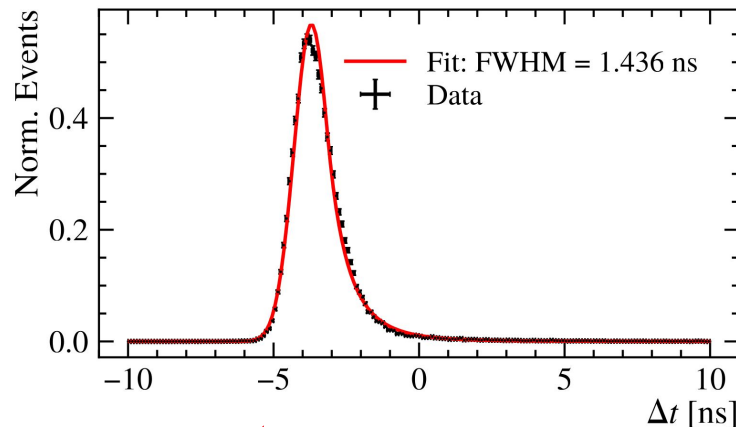
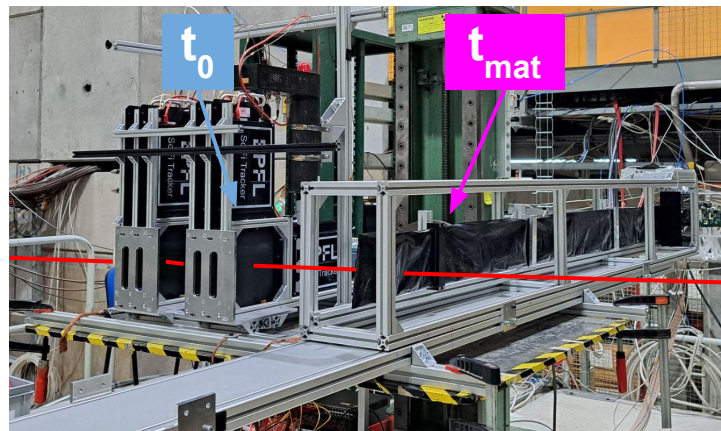
- **Higher gain in LY moving away from the SiPMs** → the light from the fibres is more collimated
- **Lower gain in LY at high overvoltage** → microlens effect is less important due to larger high-field region in the SiPM pixels
- **Very high gain in LY at low OV**

Timing

- **EPFL SciFi telescope** for tracking and time reference → **time resolution of 250 ps**
- Readout electronics of tele and long mat based on the **TOFPET2 ASIC**
 - asynchronous readout
 - TDC with 40 ps of time binning
 - dual threshold trigger
 - amplitude ~ 2.5 pe
 - timestamp at < 1 pe



- The coincidence time resolution is the FWHM of the time difference distribution between long mat and a telescope plane, fitted with an EMG

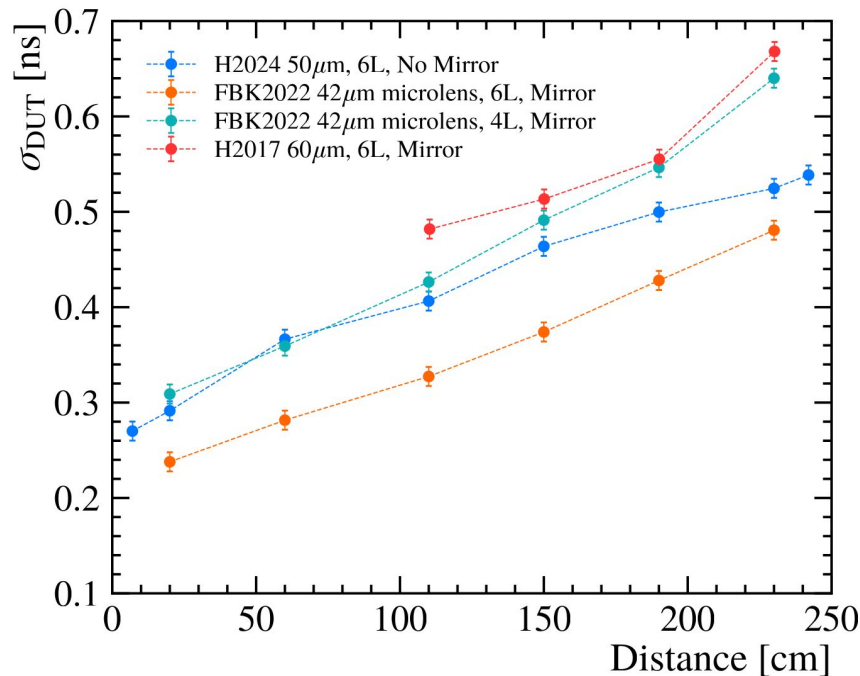
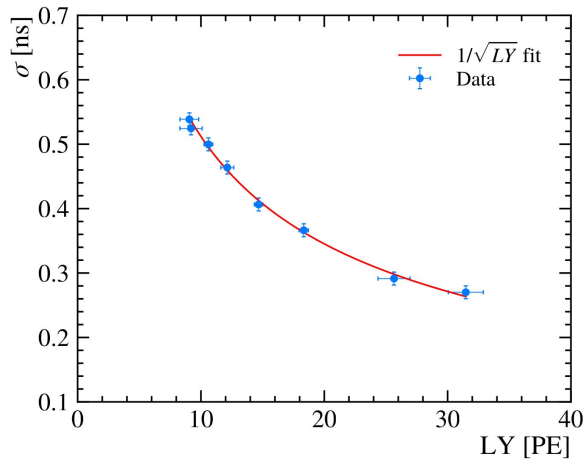


Timing: results

Time resolution as σ and with telescope resolution subtracted

The resolution is dominated by the light yield and the scintillator decay time

$$\sigma_t \propto \sqrt{\frac{\tau_r \tau_d}{LY}}$$



Better time resolution with

- higher PDE SiPMs (i.e. microlens-enhanced)
- higher number of fibre layers in a mat



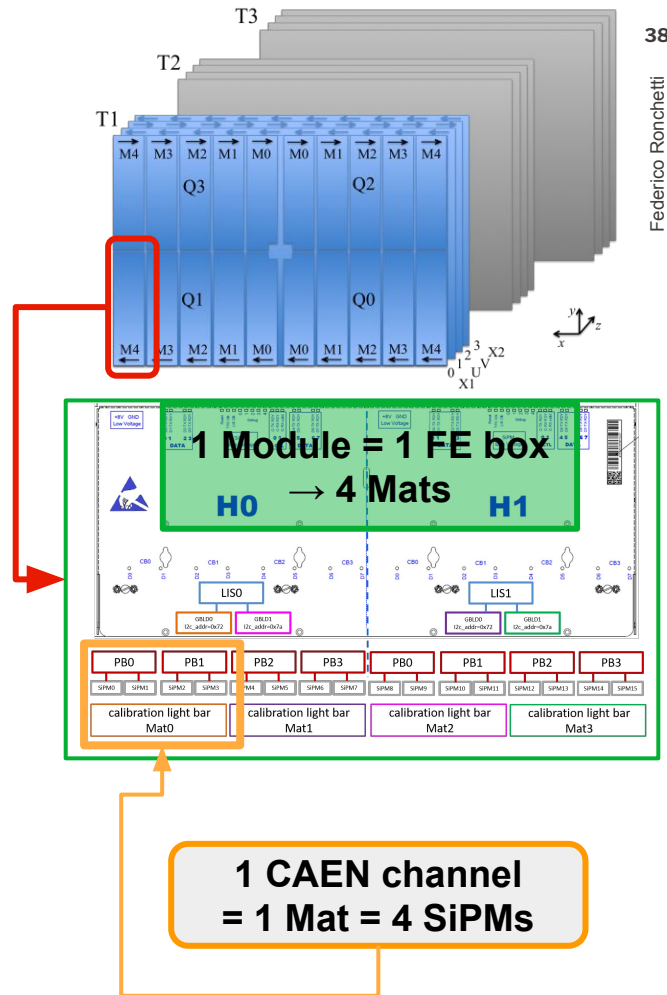
SiPM radiation-induced damage in the LHCb SciFi tracker

SciFi SiPMs biasing scheme

- The SciFi HV SiPM bias system is organised in CAEN channels
- Each CAEN channel provides the bias voltage to 4 SiPM arrays that are reading out one fibre mat
- The applied bias voltage is such to have 3.5 V above the average V_{BD} over 4 SiPM arrays

$$\Delta V = V_{bias} - V_{BD}(T)$$

- What do we measure?
 - **1 current** drawn by the 4 SiPM arrays (512 channels) → leads to an **averaged measurement**
 - 1 applied bias voltage
 - **4 temperatures**



Temperature scan

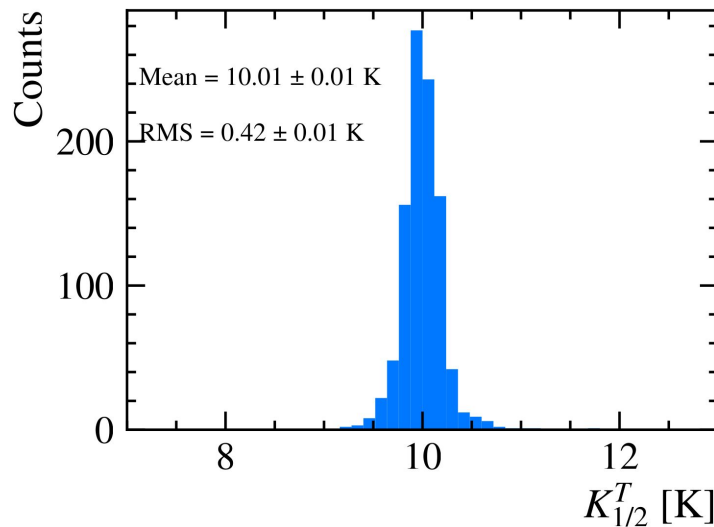
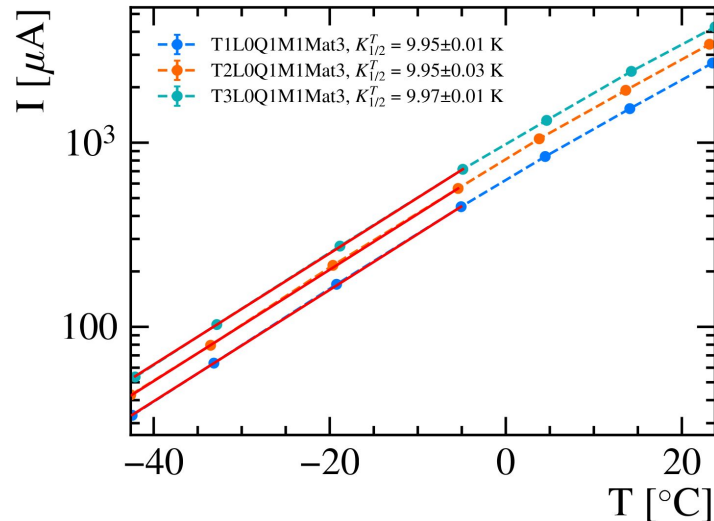
The DCR dependence on the temperature has been studied in the R&D phase ([Gruber, 2020](#))

$$I(T) = I(T_0) \cdot 2^{\frac{T - T_0}{K_{1/2}^T}}$$

The scaling constant is a crucial parameter for understanding the impact of a temperature change on the noise

Can we measure it for all the SciFi SiPMs?

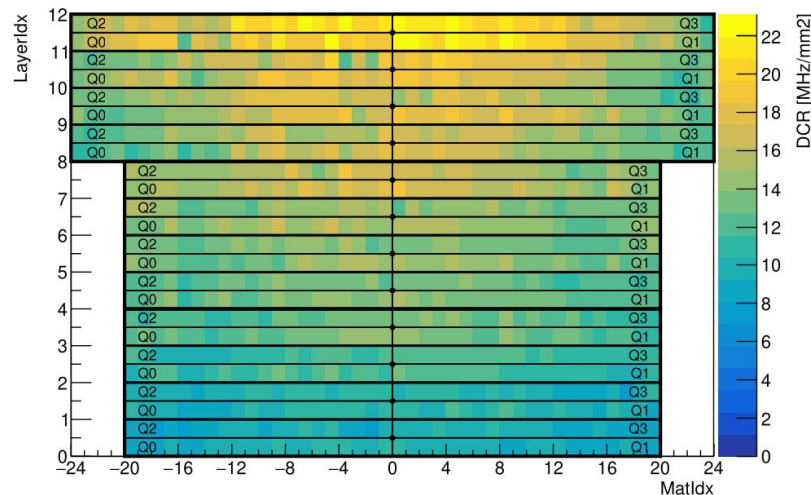
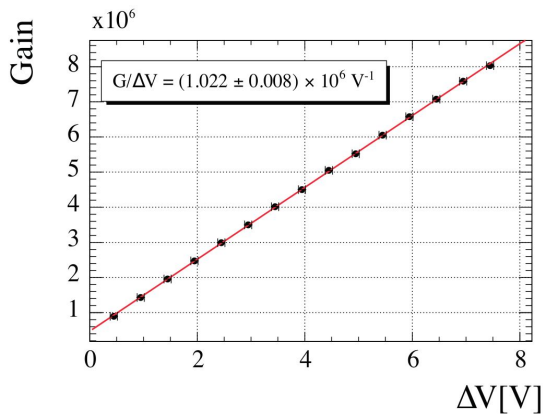
Result for 1024 sets of 4 SiPM arrays



Dark Counts Rate measurement

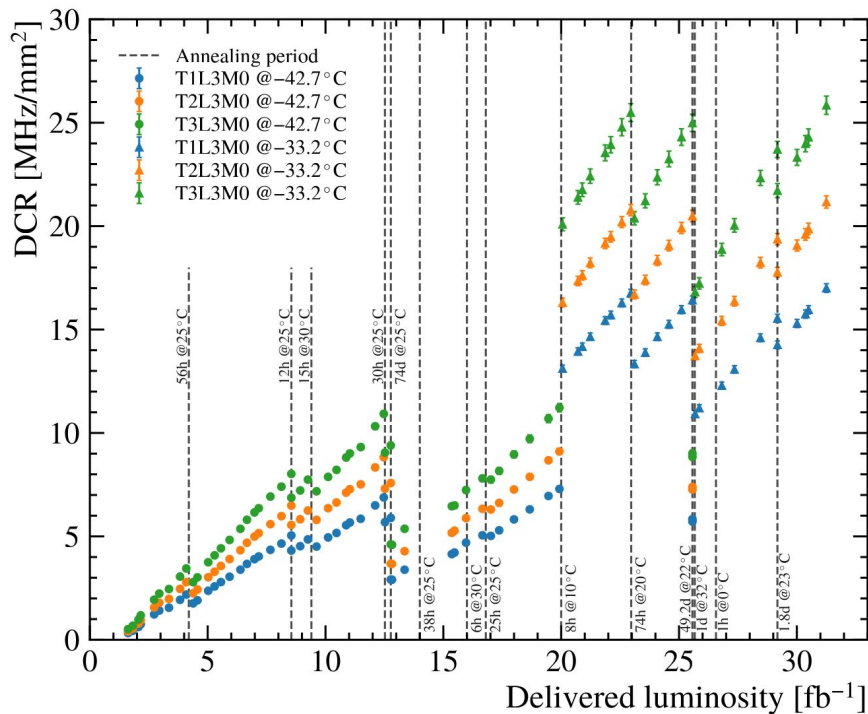
Assuming the **gain G** to be uniform within the four SiPM arrays, the average **DCR per mm^2** in one mat is

$$\text{DCR} = \underbrace{512}_{\substack{\text{\# of SiPM} \\ \text{channels in} \\ \text{one mat}}} \cdot \underbrace{G}_{\substack{\text{SiPM gain} \\ \text{from R\&D}}} \cdot e \cdot \underbrace{0.4 \text{ mm}^2}_{\substack{\text{SiPM channel} \\ \text{area}}}$$



DCR/ mm^2 for every bias line after 23.11 fb^{-1} , measured at -33.2°C

DCR vs Luminosity



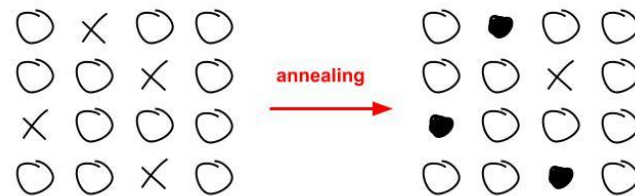
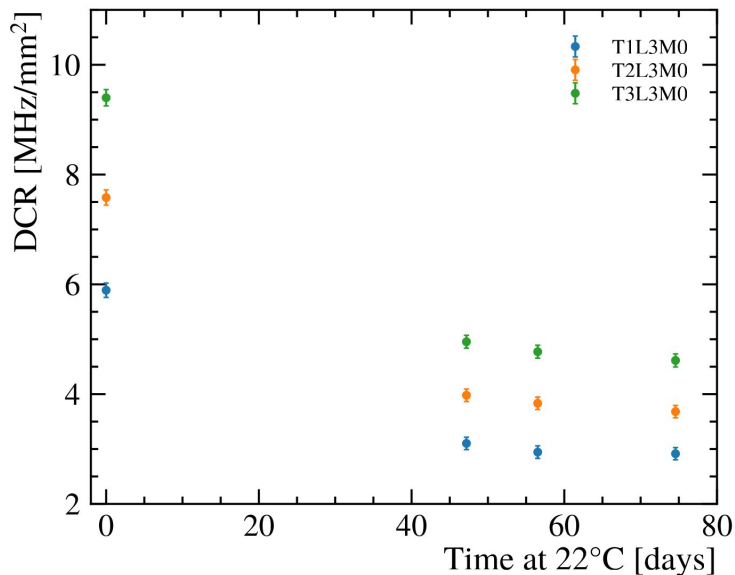
Average of the mats of the innermost modules in the last layer of each station

- **Linear growth** with the luminosity
 - Different irradiation in the three stations
 - **Reduction due to annealing** during warm periods at ~20°C
 - Two operating temperatures: -42.7°C and -33.2°C
- **factor ~2 difference** in noise as expected

Annealing

Radiation-induced damages in the silicon can be **recovered by warming up** the SiPMs

The amount of damages that can be recovered **depends on the annealing temperature**



X → damage or not recovered

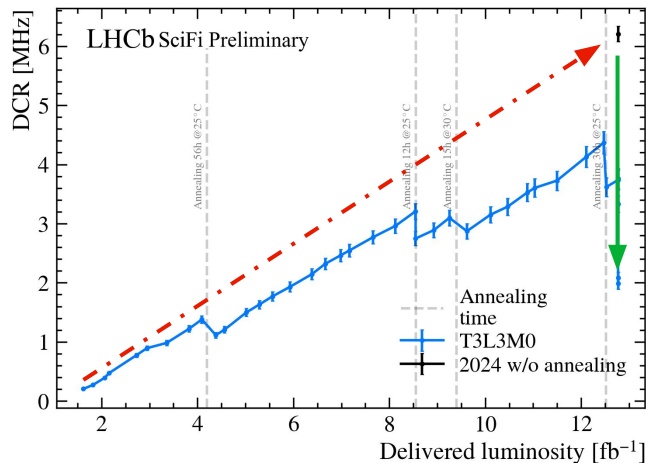
● → recovered by annealing

SciFi has been warmed up to $\sim 22^\circ\text{C}$ during the end-of-year technical stops to perform **total annealing**

We monitored the annealing curve by cooling down and measuring the DCR at different times

NOTE: this curve is **only part of the annealing** of the detector. Annealing happened already during operations when SciFi was warmed up for few days

DCR predictions

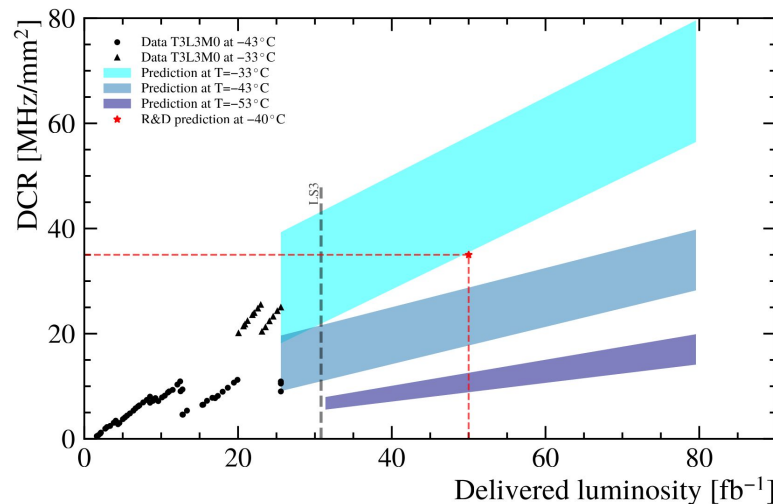


Using the foreseen amount of luminosity per year and the taking into account complete annealing during technical stops, one can **extrapolate** the **predictions of the DCR** for different cooling scenarios

Knowing the **slope DCR/luminosity**, one can calculate the DCR without annealing at a given luminosity

The ratio between DCR without and after complete annealing quantifies the total annealing experienced by the SiPMs

→ **factor 3 less DCR**





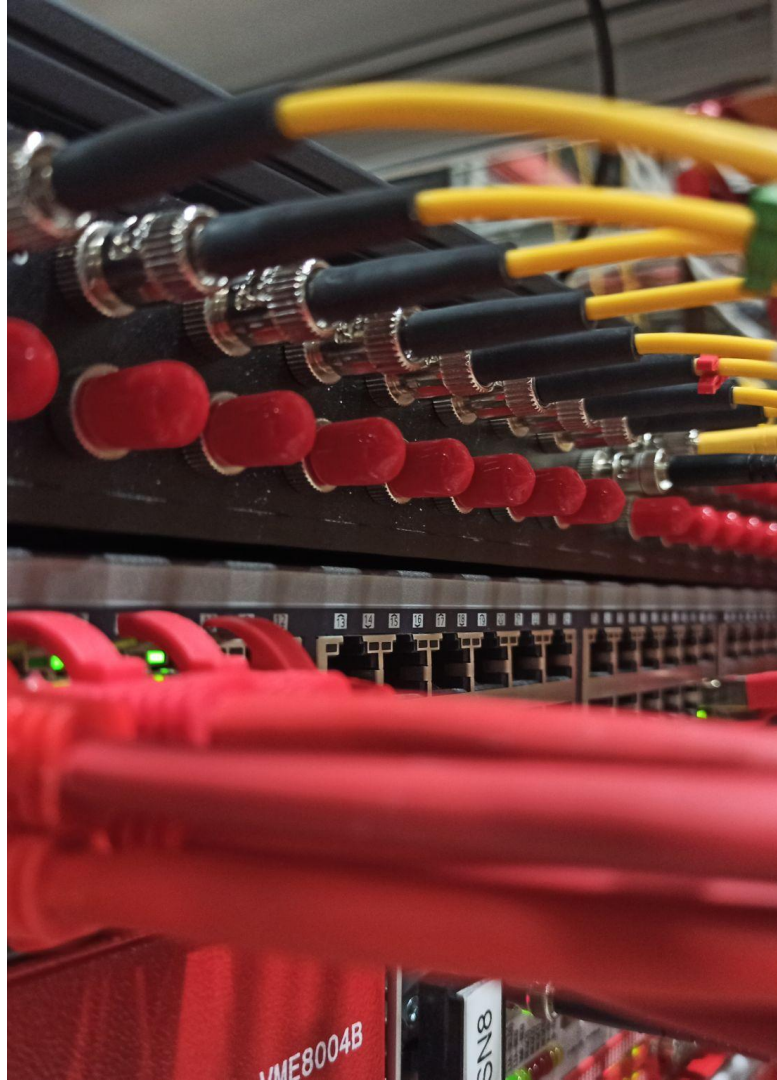
Conclusions

Conclusions

- R&D in progress to upgrade the LHCb SciFi tracker in view of LHCb Upgrade II
- **Microles-enhanced SiPM** is a novel concept developed and studied in order to **recover light** from non-sensitive to efficient area of SiPM pixels. Results demonstrated the validity of the enhancement:
 - increase in SiPM PDE up to 50%
 - reduction in optical cross-talk of 40%
 - better Single Photon Time Resolution with respect to conventional coating
- This leads to an **overall increase in SciFi light yield** and better detector time resolution
- Light yield and timing performance measured in dedicated **testbeams at CERN**:
 - comparison between mirrored and non-mirrored fibre mats and between 6-layer and 4-layer mats
 - **time resolution between 250ps and 650ps** depending on the particle hit position with respect to the SiPM readout
- Monitoring of the **radiation-induced damage of the LHCb SciFi SiPMs**
 - the SiPMs are behaving as expected and in good agreement with the R&D measurements
 - measurement of the **annealing** effect and predictions for future operation
 - first study to match the silicon damage with the expected radiation fluence computed by the FLUKA simulation
- This work has provided many **inputs for the LHCb Upgrade II TDR**, led to **publications** on peer reviewed journals, has been presented in **international conferences** and in numerous **collaboration meetings**



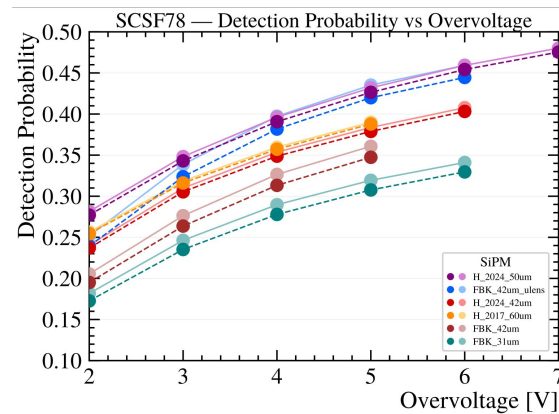
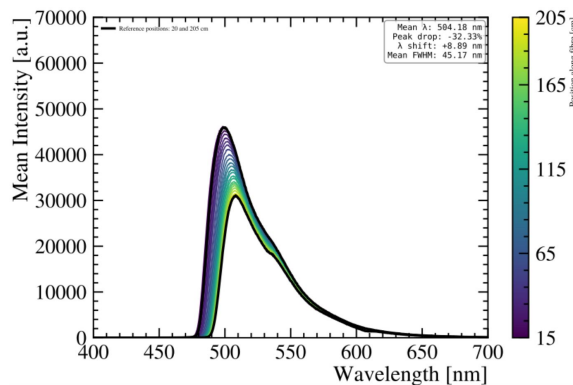
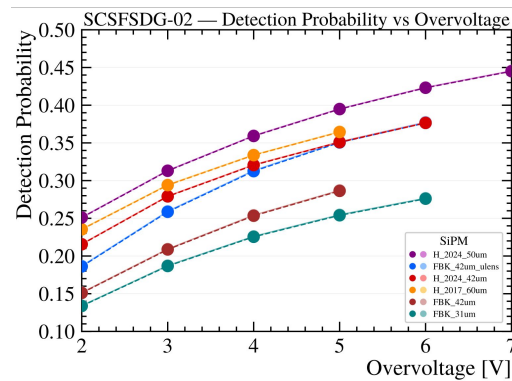
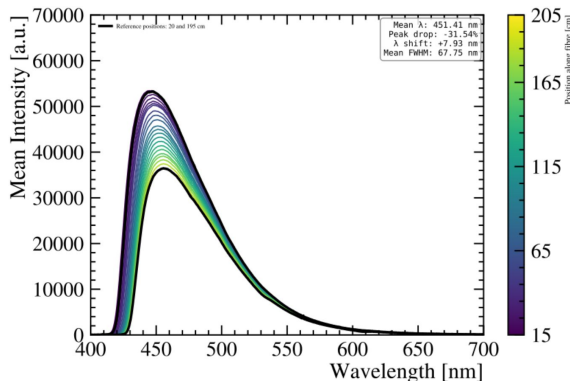
Thanks for the attention



Backup slides

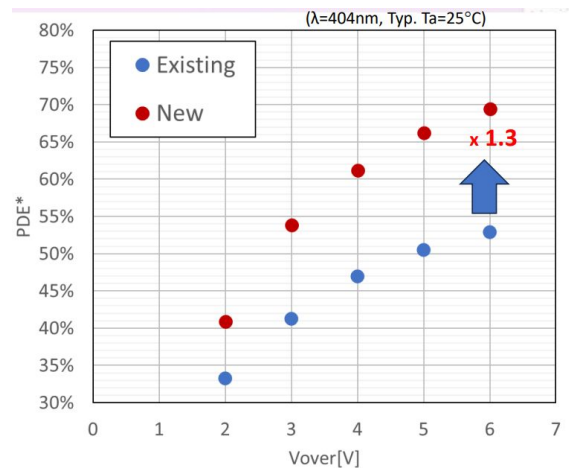
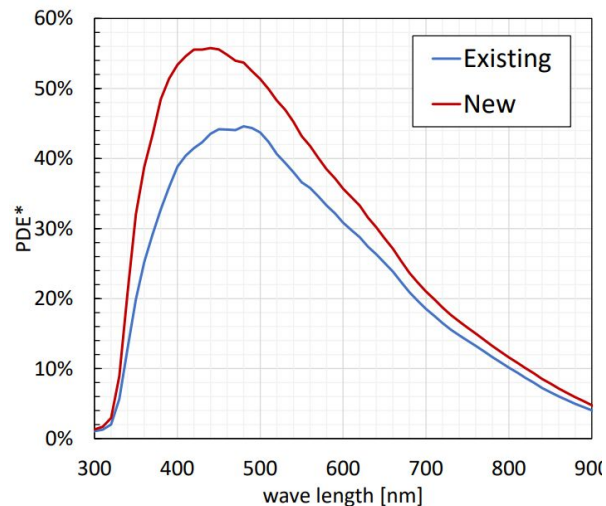
Effective SiPM efficiency

Convolution of the fibre emission spectrum and the SiPM PDE curves



Next generation HPK devices

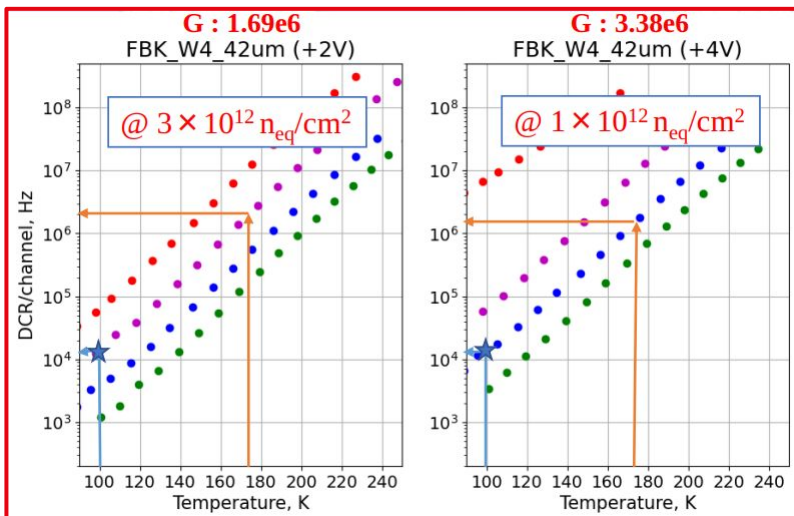
New Hamamatsu devices in production with improved PDE
→ 1.3 more PDE than current devices



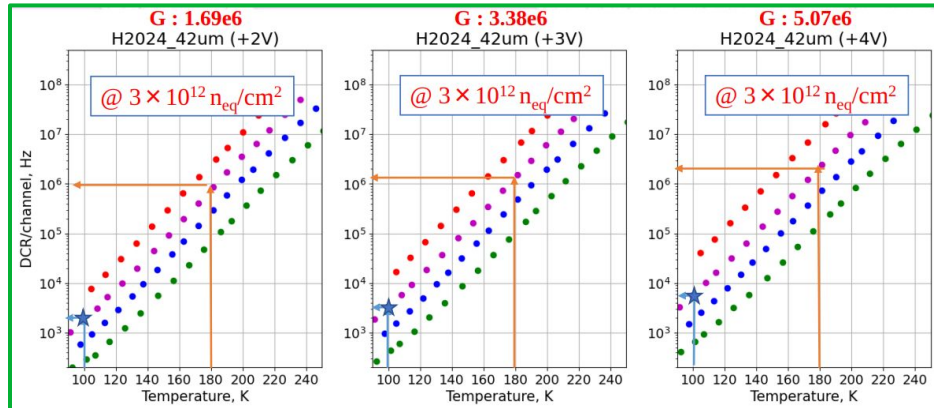
Radiation hardness

DCR vs temperature for different irradiation profiles

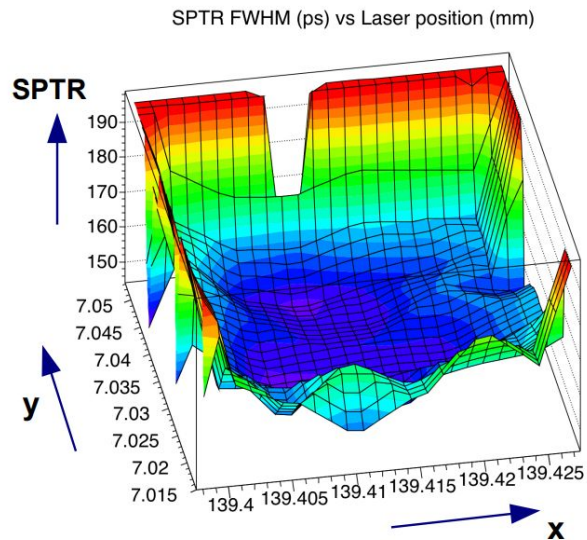
FBK 42 μ m



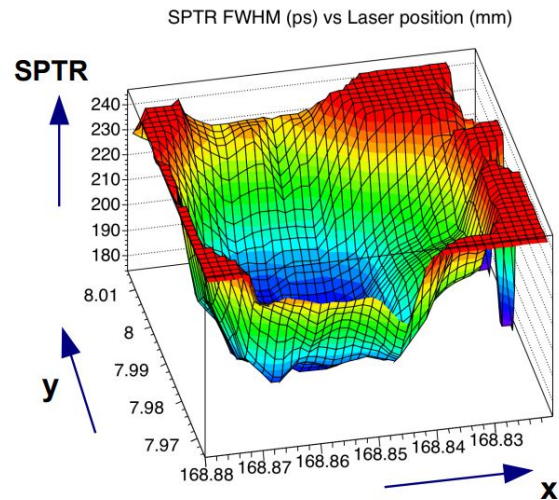
HPK 42 μ m



Distribution of the SPTR in one pixel from Nemallapudi 2016

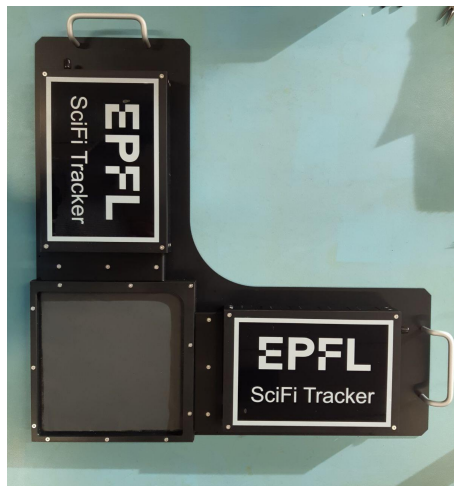


FBK NUV

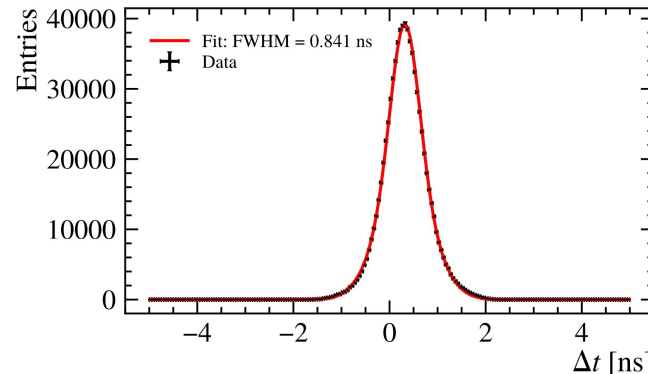
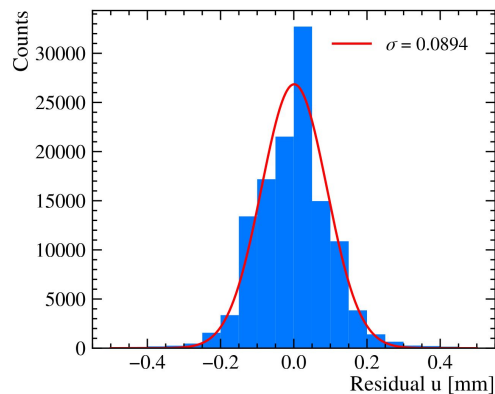
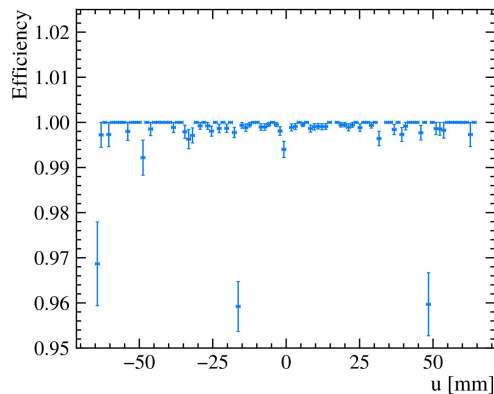


HPK TSV

The EPFL SciFi Telescope

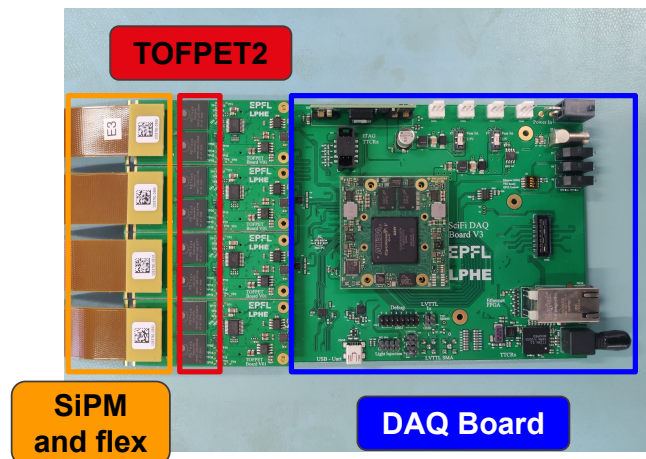


- 13x13cm² XY SciFi planes read out by SiPMs
- Readout electronics based on the TOFPET2 ASIC
- Track reconstruction: linear fit of tracks
- Efficiency > 98%
- Spatial resolution < 90μm
- Time resolution ~ 250ps



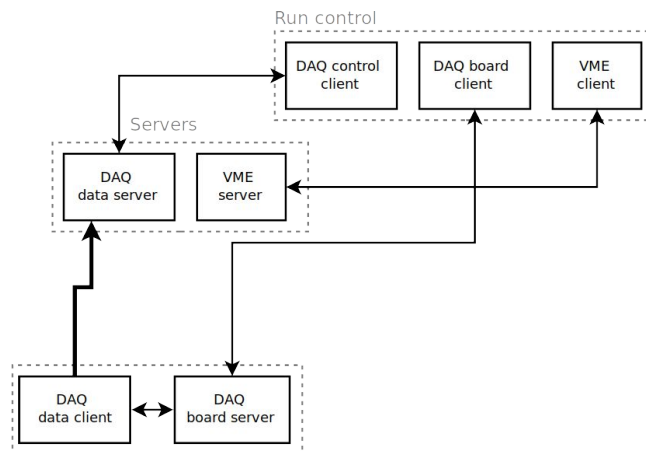
Hardware

- Front End: TOFPET2 ASICs
- DAQ Board: ALTERA Cyclone V FPGA + CPU
- **Asynchronous channel readout**
- Data sent via Ethernet to the PC, optical fibre for board synchronisation
- SiPM biasing via DAQ Board



Software

- Same as for SND@LHC
- DAQ data server → **online event builder** and noise suppression
- VME server-client → VME crate for clock generation and synchronous reset (TTC system)
- Run control written in python



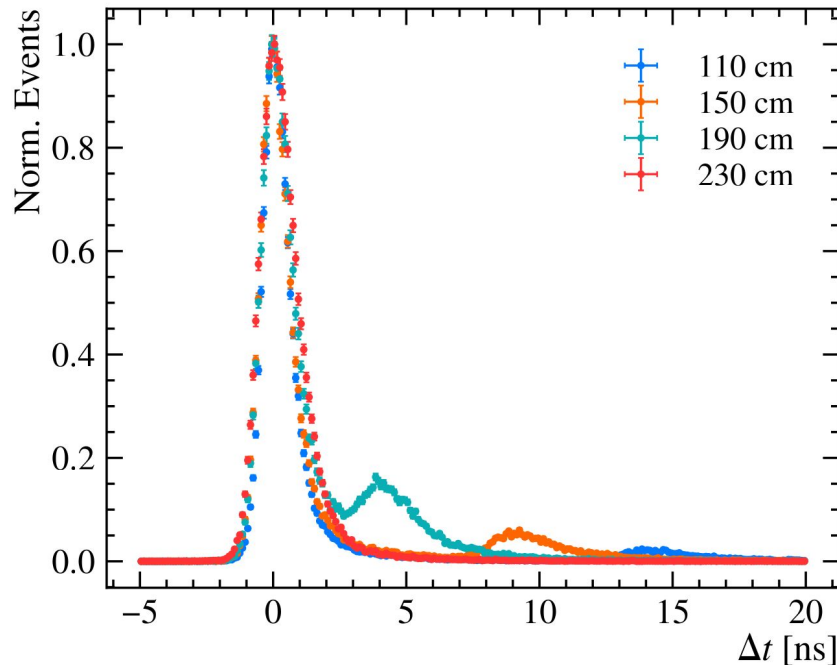
Effect of the mirror on timing

It happens the first photon that is detected is the one reflected by the mirror

→ second peak in the time difference distribution

The closer to the mirror, the closer the peaks are

→ at > 230 cm the two peaks merge and this can affect the measurement



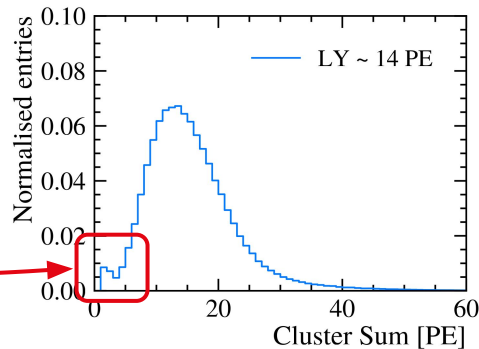
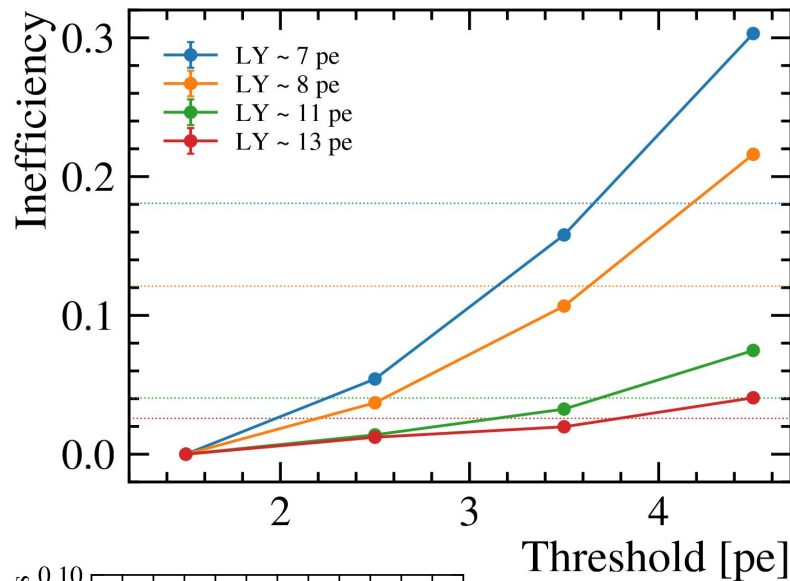
Clustering algorithm efficiency

Can we consider a **simpler clustering algorithm**?

Same data have been processed with a clustering algorithm with **one threshold**

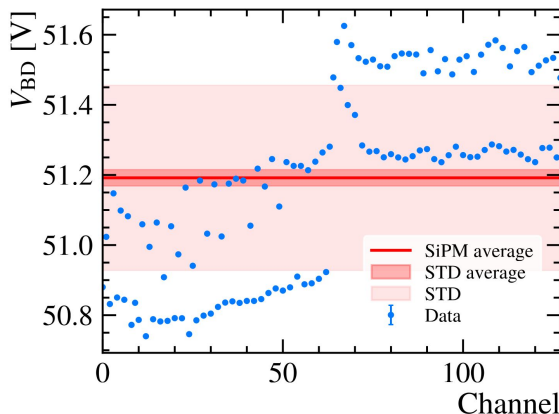
The relative efficiency has been calculated as the ratio between the number of detected clusters with threshold T and the detected ones with threshold 1.5pe

- The 3 thresholds algorithm (2.5,1.5,4.5) behaves as an algorithm with a single threshold of ~ 3.6 - 3.8 (dashed lines)
- The results presented here are in a “**worst-case**” scenario: **noise** at low threshold contributes to the counts of the detected clusters

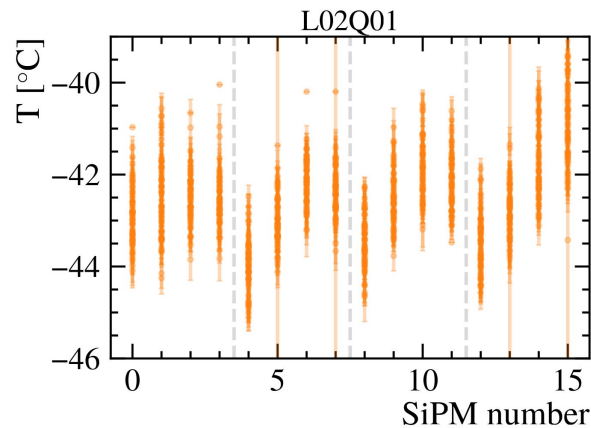


Spread in V_{BD} and temperature

- Channels in one SiPM array have different V_{BD} values with $\sigma \sim 250 \text{ mV}$
→ corrected in the PACIFIC ASIC
- The applied bias voltage is with respect to the **average** V_{BD} over 4 SiPM arrays



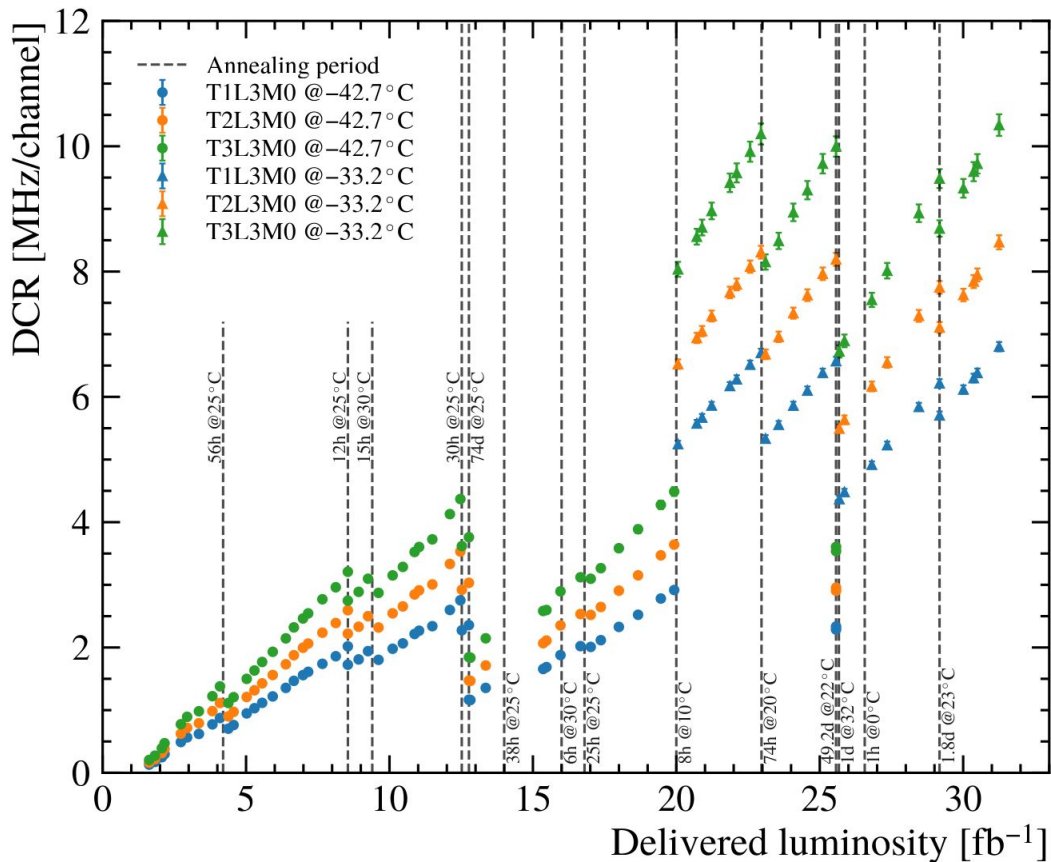
Example of V_{BD} spread in one SiPM



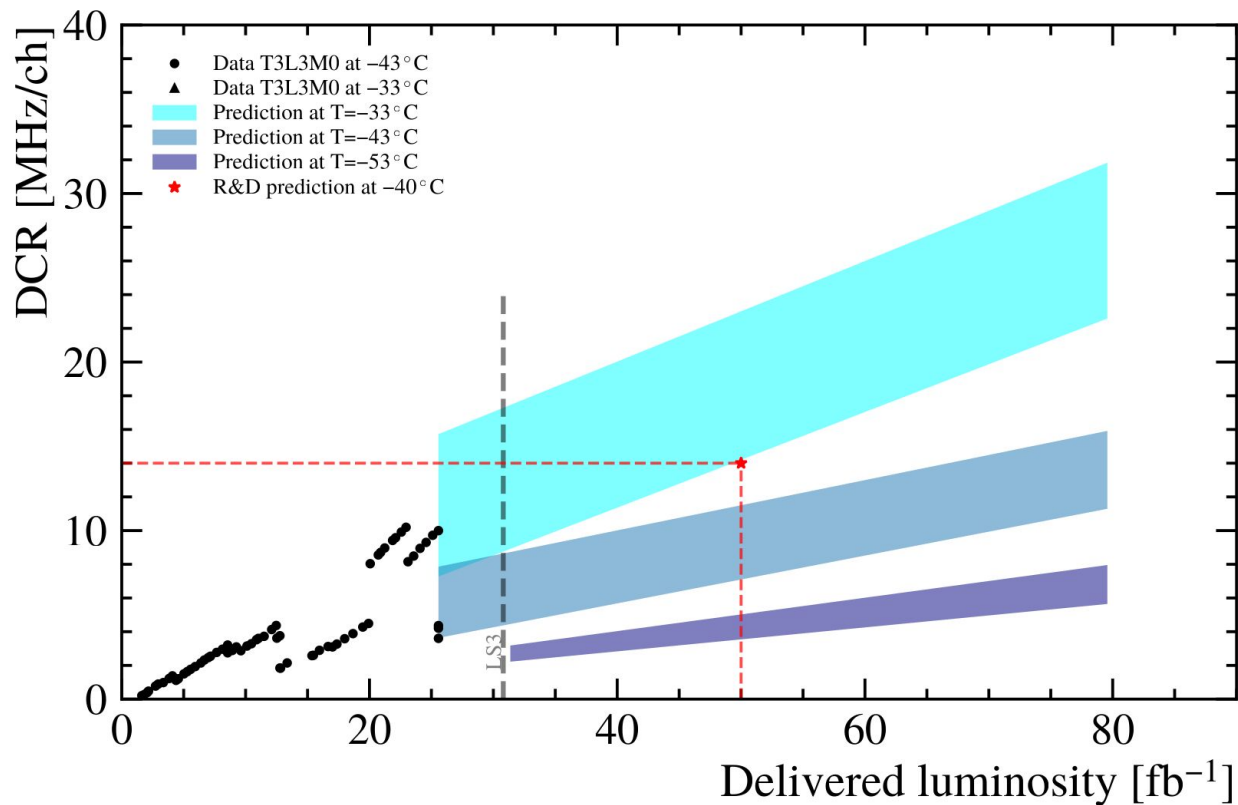
- The SiPM V_{BD} **changes with temperature** according to

$$V_{BD}(T) = V_{BD}(T_0) + 0.058 \text{ mV} \cdot (T - T_0)$$
 → the temperature measurement is crucial for correct biasing
- T is the mat temperature, but a **spread is present** within SiPMs in one mat

DCR vs Lumi (per channel)



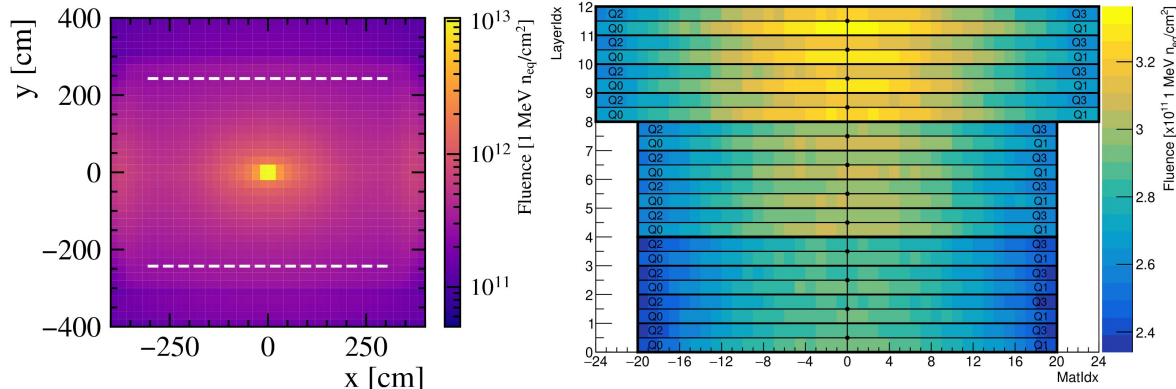
DCR vs Lumi predictions (per channel)



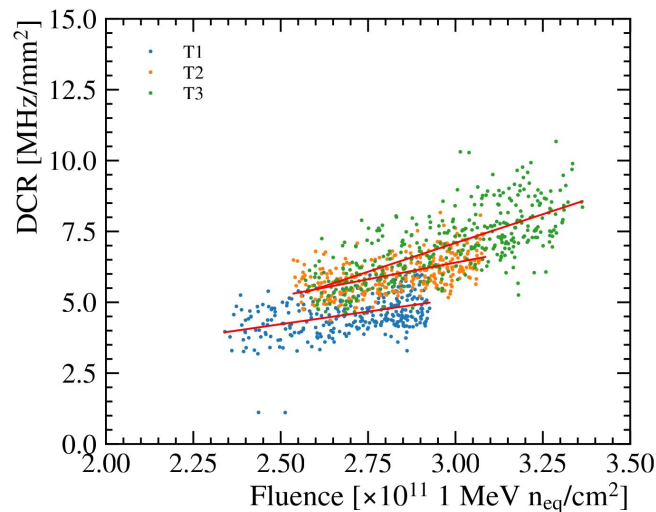
Comparison with FLUKA simulation

Can we have the DCR as a function of the fluence instead of luminosity?

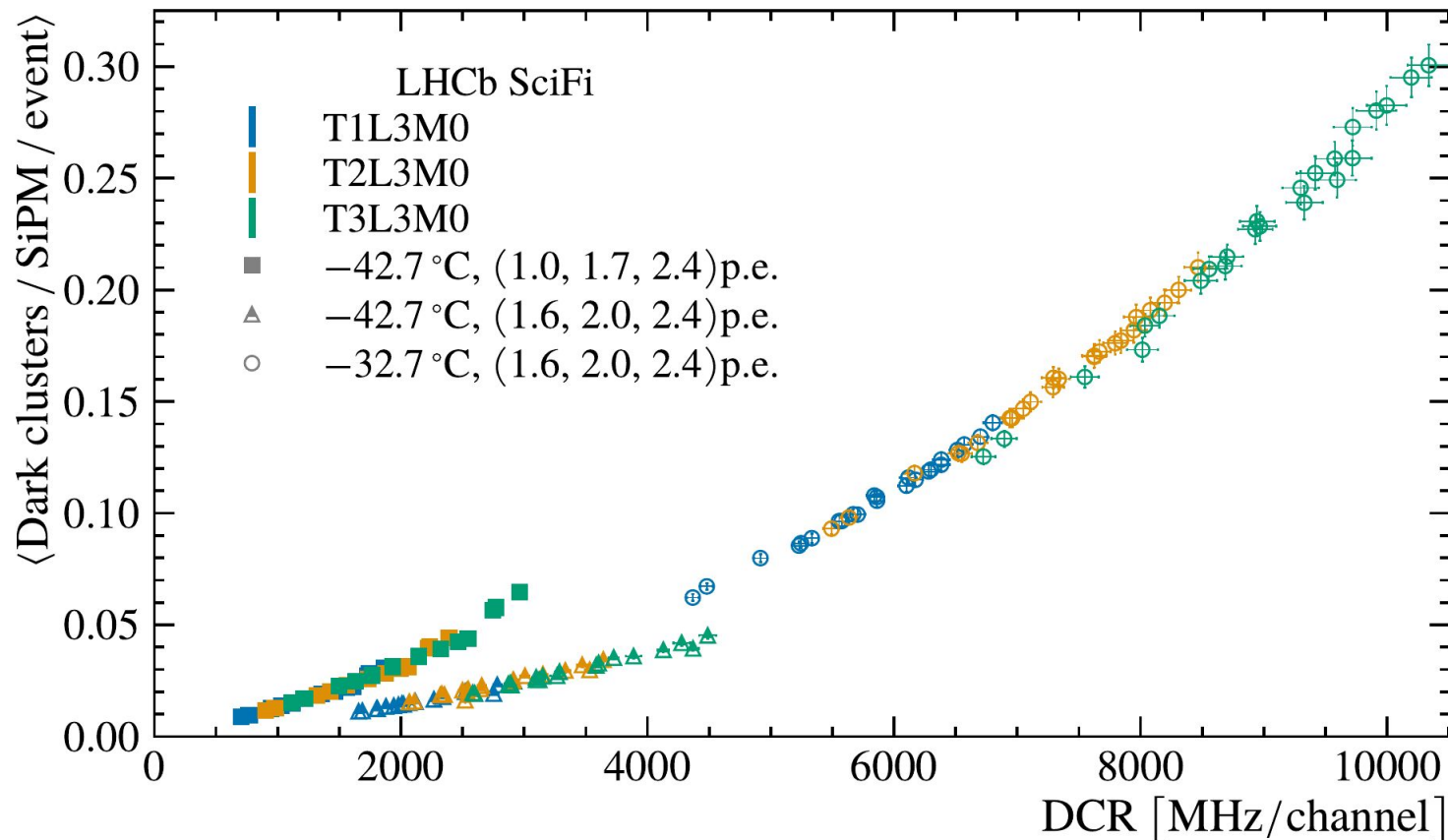
LHCb **FLUKA** simulation provides an estimation of the **1 MeV n_{eq}/cm^2 fluence** at the SiPM location



- Extracted fluences at the SiPM positions
 - DCR and fluence after 25.6 fb^{-1} and complete annealing
 - DCR vs fluence plot:
 - **Linear behaviour** of DCR vs fluence
 - **Slope and offset** different for the three stations, why?
- Wrong FLUKA scaling or wrong estimator for this type of damage



Noise clusters vs DCR



Flex PCB cross-talk

- Acquired 2 channels amplified by the same amplifier (40dB FEMTO fast amplifier)
 - SiPM (used to inject a signal) in the flex PCB placed in a Faraday box, aggressor is amplified outside the box and victim amplified inside
- Acquisition with full (4 GHz) and 200 MHz bandwidth on the oscilloscope, lines terminated at 50 Ohm on the oscilloscope
- Acquired different channel configurations on the flex
- Cross-talk as ratio between victim negative amplitude (orange) and aggressor amplitude (blue)

