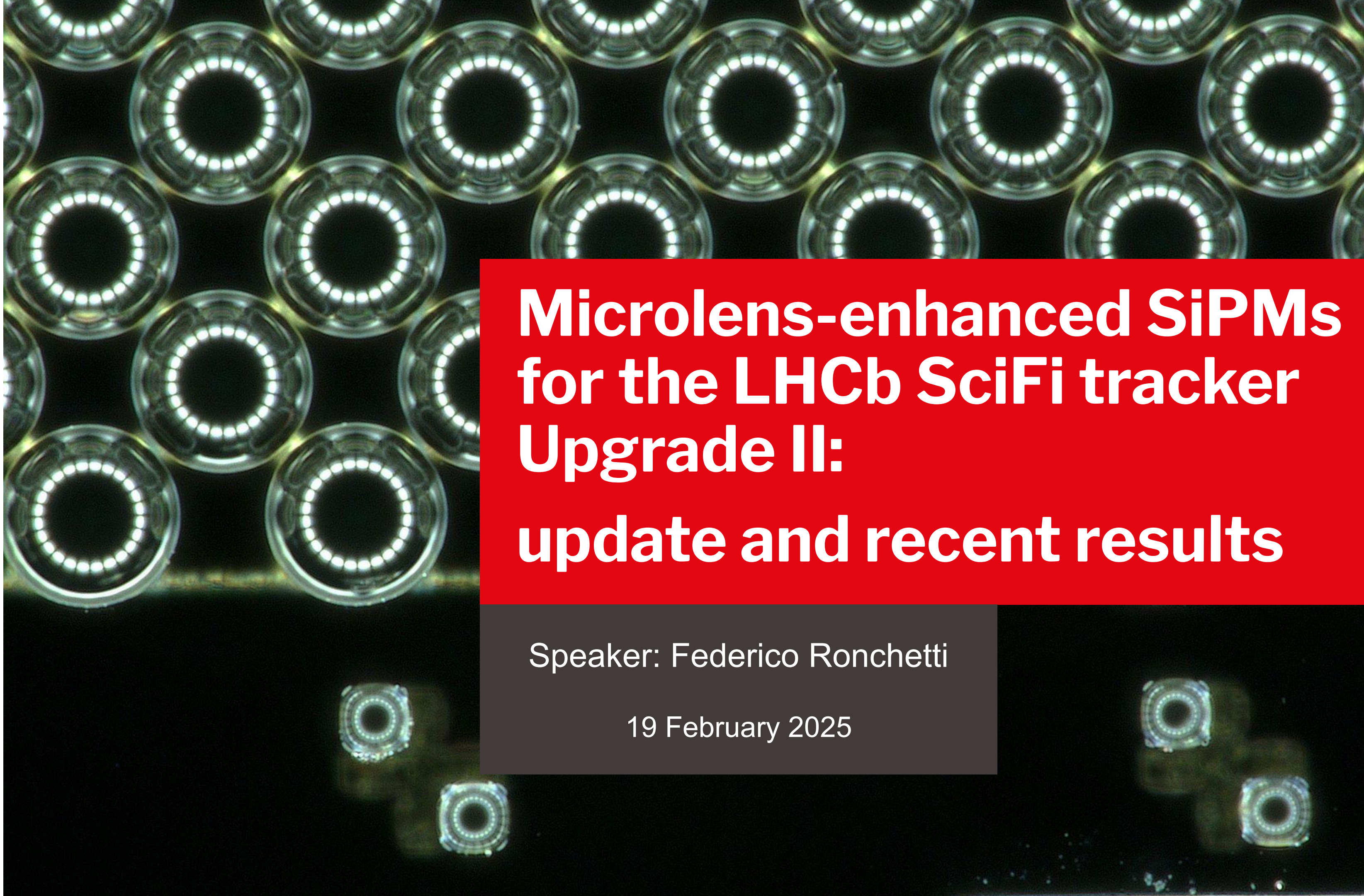


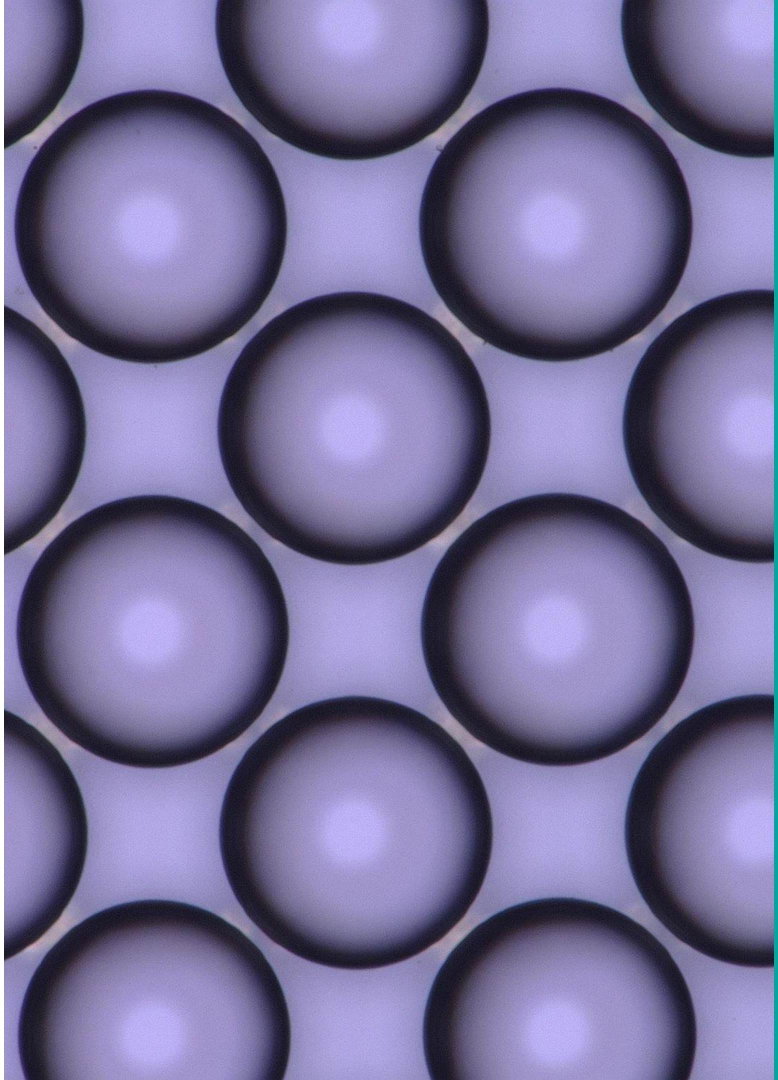
Microlens-enhanced SiPMs for the LHCb SciFi tracker Upgrade II:

update and recent results

Speaker: Federico Ronchetti

19 February 2025

VCI17, Vienna 2025



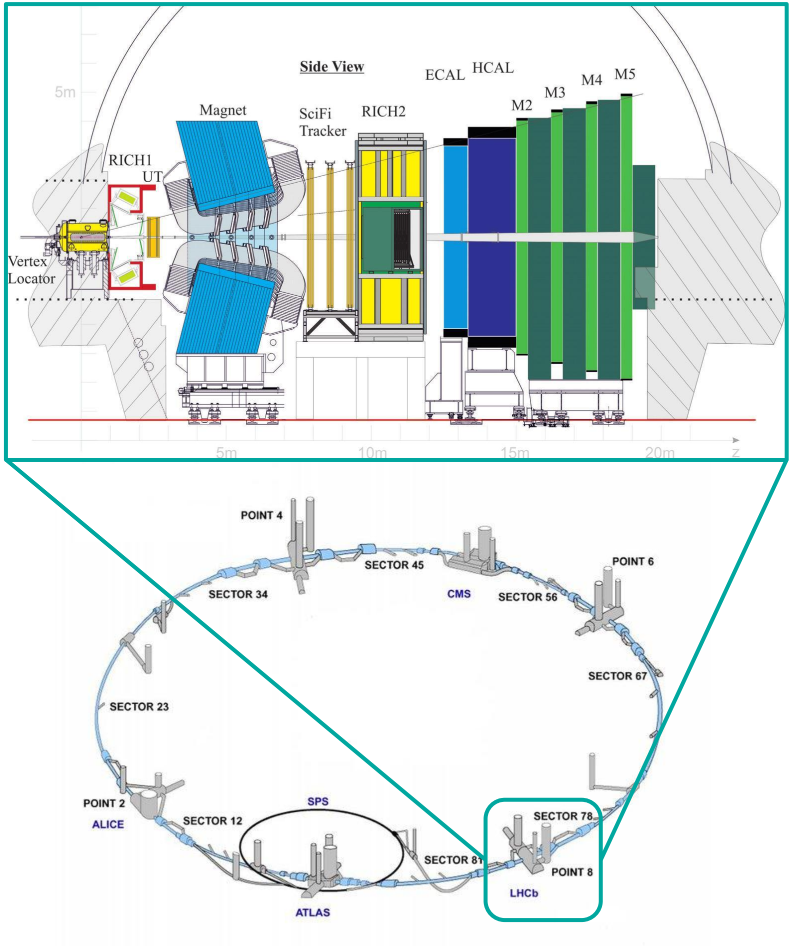
Contents

- R&D context
- Microlens-enhancement concept
- From 2022 to 2025: R&D updates
- Results:
  - PDE
  - Cross-talk
  - Timing

Context: 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!**



Federico Ronchetti

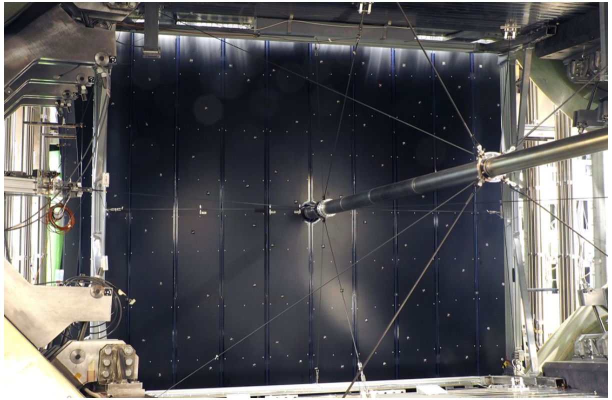
Context: LHCb SciFi

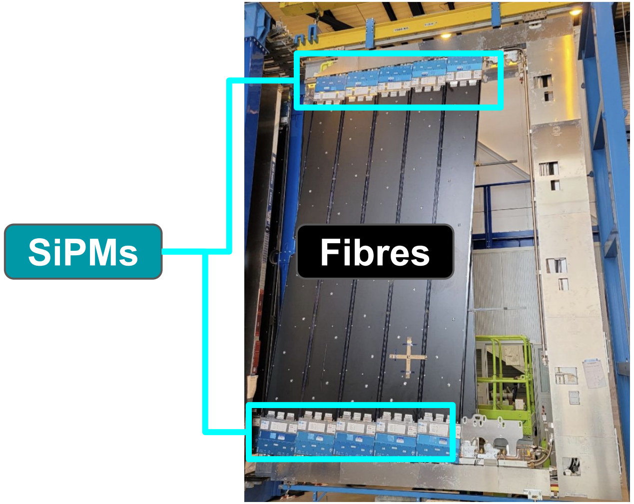
The **Scintillating-Fibre (SciFi) tracker** is one of the **LHCb sub-detectors**, placed after the LHCb magnet. It is made of 12 layers in 3 tracking stations for a total **sensitive area of 340 m^2**, **500k channels** and a **spatial resolution < 100 μm**.

Fibre mats are made of **250 μm scintillating fibres 2.5 m 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

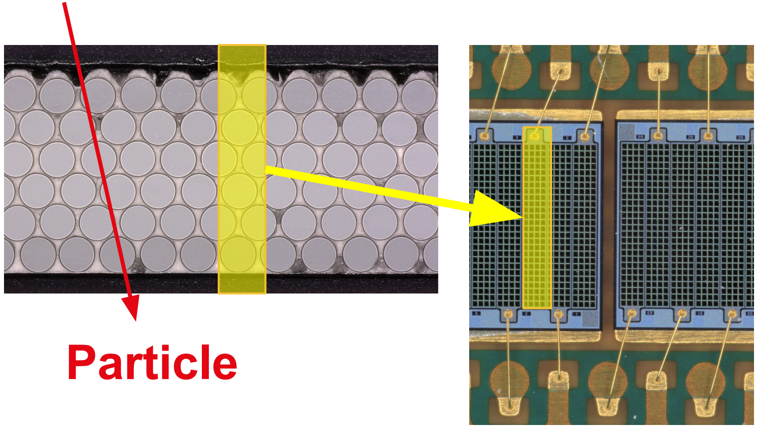
- low correlated noise
- high PDE (average number of pe per MIP is 15)
- Low DCR after irradiation.

SciFi operation in Poster Witola 2025



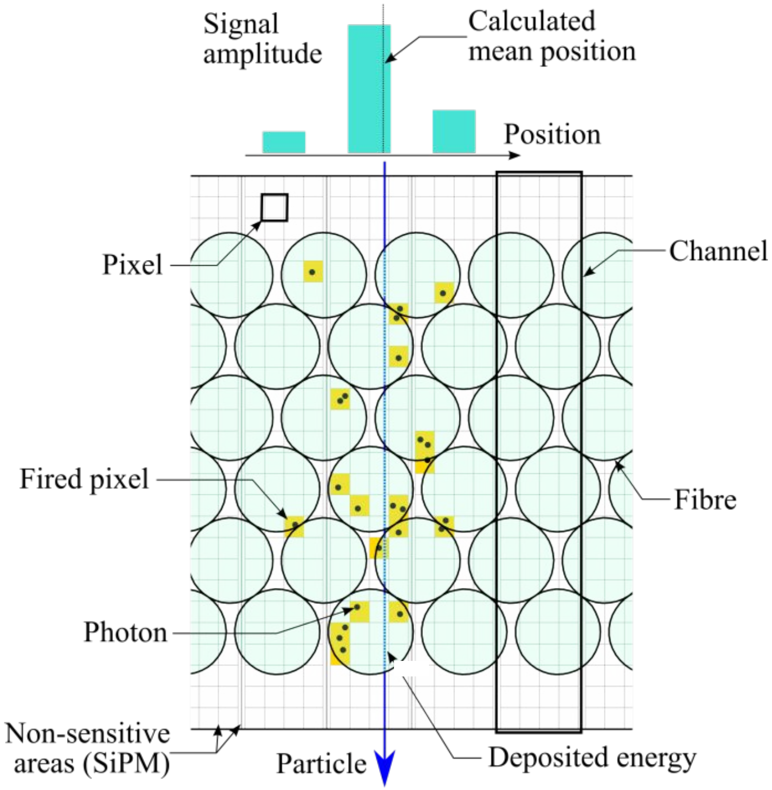


SciFi working principle



Particle

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

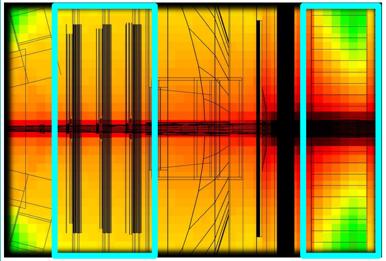


Context: LHCb Upgrade II

UPGRADE I

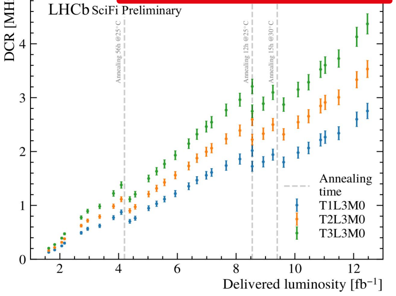
Due to radiation (charged particles and backsplashed neutrons), the overall performance will get worse **after 50 fb^{-1}** (LHC Run 3 and 4):

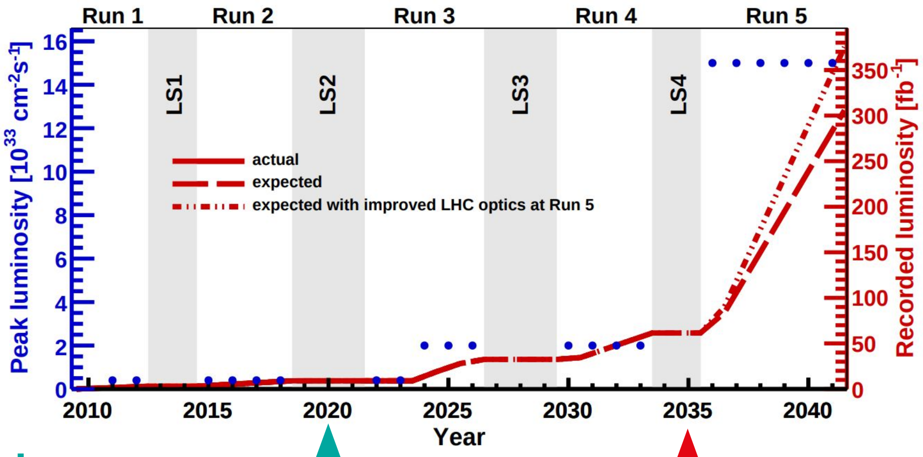
- **35 kGy** dose for the **fibres** = 40% less light yield
- **6×10^{11} 1 MeV n_{eq}/cm^2** neutron fluence for the SiPMs = DCR will increase up to 14 MHz



SciFi Calo

SiPM DCR today





UPGRADE II

High Luminosity LHC Run 5 will provide 5 times the luminosity of previous runs (350 fb^{-1}).

- **x 5** dose for the **fibres**
- **3×10^{12} 1 MeV n_{eq}/cm^2** neutron fluence for the SiPMs
- Larger number of collisions = high occupancy

EPFL

LHCb

Context: Mighty Tracker

The **high occupancy** in the innermost part of the detector will require higher segmentation and fibres will be replaced by **silicon pixels**.

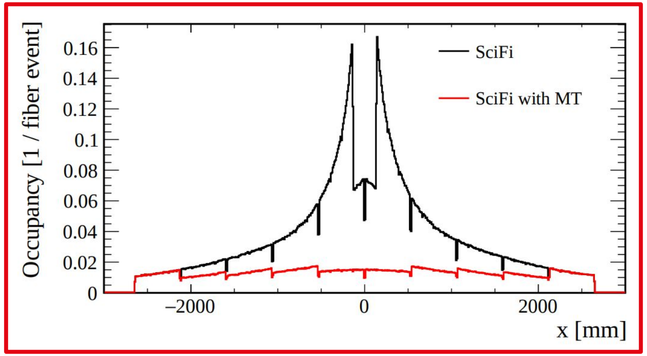
The new detector, called **Mighty Tracker** (De Aguiar Francisco 2025) will have to face 5 times the radiation level, so R&D is in progress to:

- **improve light detection** from irradiated fibres

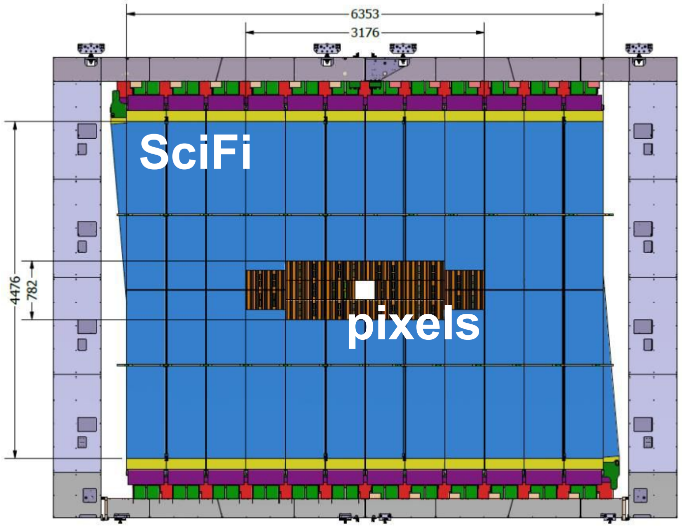
  → **Microlens-enhanced SiPMs** (this talk)

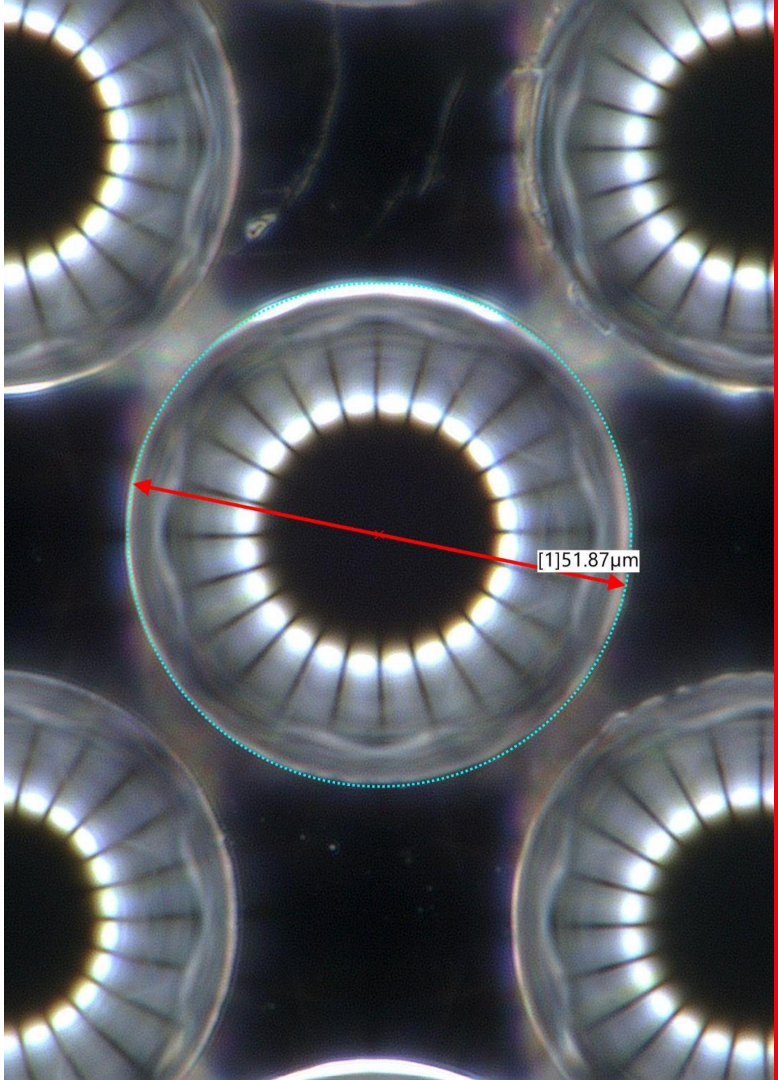
- achieve **less noise** in the SiPMs

  → **LN2 cryo-cooling** (Curras Rivera 2025)



LHCb UII TDR





Microlens-enhanced SiPMs

Sensitivity-enhanced SiPMs

arxiv.org/abs/2411.09358

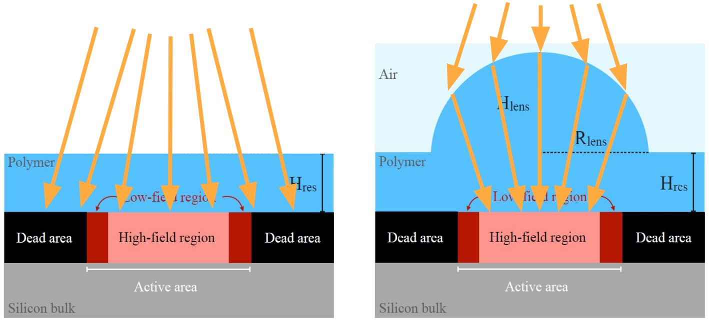
To detect **more light**, SiPM PDE can be increased by increasing the Geometrical Fill Factor (GFF) → **recovering light** from non-sensitive pixel's area.

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

$$\mathrm{PDE} = \boxed{\mathrm{QE}(\lambda)} \times \boxed{\mathrm{GFF}(\Delta V)} \times \boxed{\mathrm{P}_{\mathrm{avalanche}}(\Delta V)}$$

Si property | **Geometry** | **Si property**

→ **MICROLENSES!**

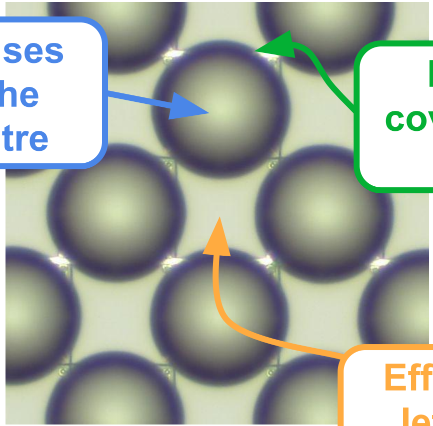


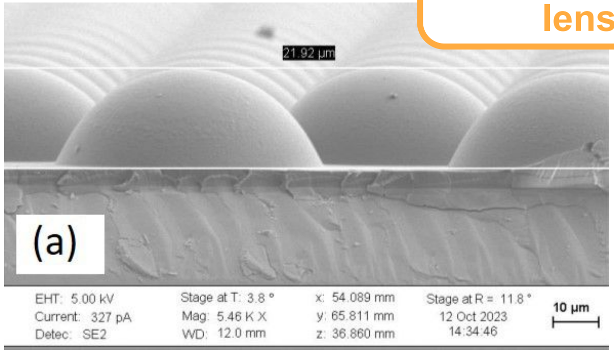
Checkerboard configuration

Lens focuses light in the pixel centre

Dead area covered by the lens

Efficient area left without lens



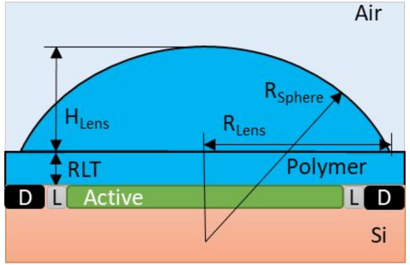


Microlens simulation

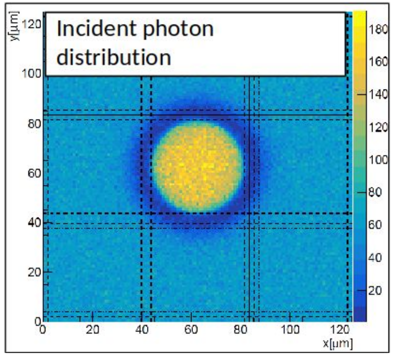
How to get the **best improvement** within manufacturing limitation?

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

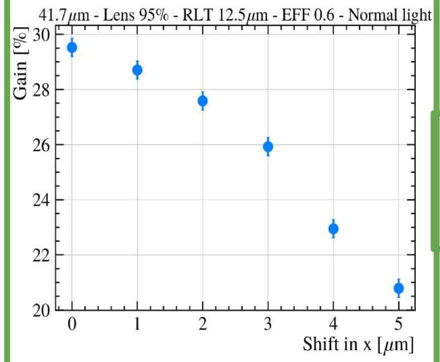
The simulation gives also informations on the effect of **possible production misalignments** between lenses and pixels and returns the **expected gain in light yield** between microlens-enhanced and conventional detectors.



D=Dead region L=Low field region



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



Simulation with lens not aligned with the pixel

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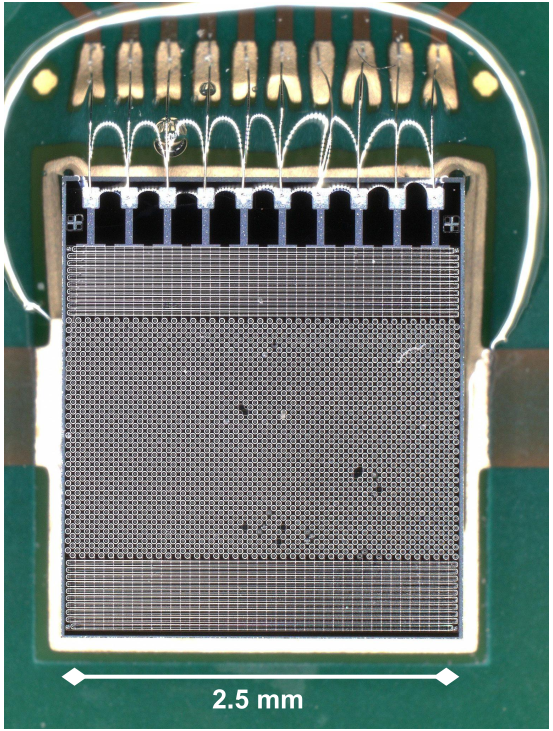
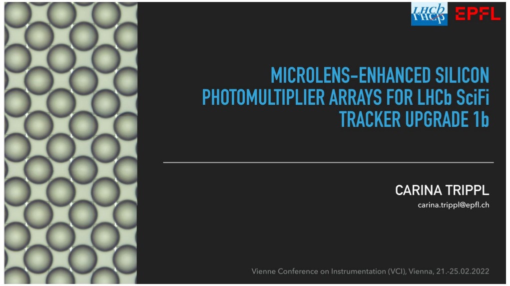
EPFL

LHCb

Where we were before (2022)

Trippl, VCI 2022



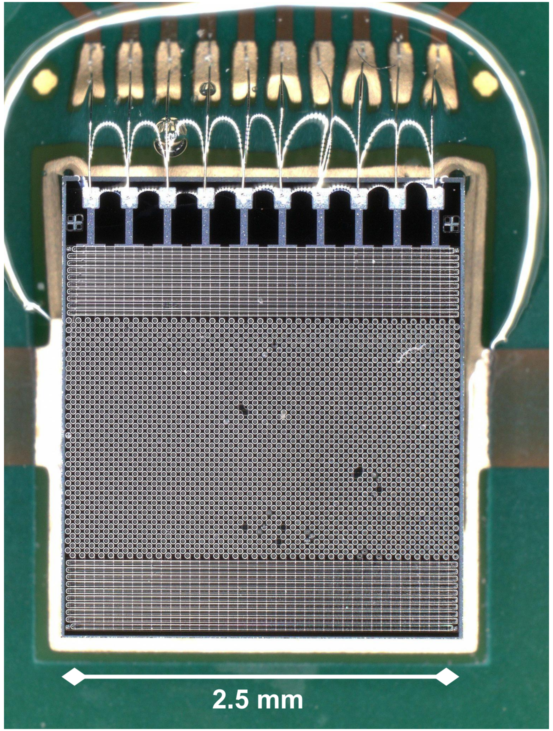


First prototypes

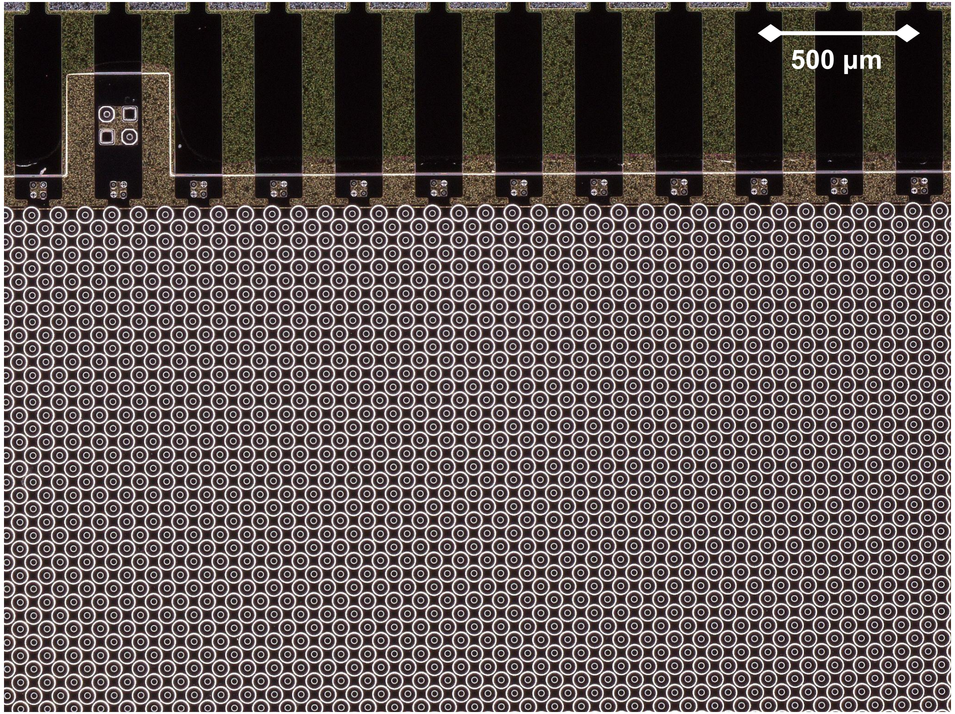
- SiPM technology with very **limited operation range** (0 to 2V OV), large cross-talk, FBK SiPM 40µm
- **10 channel** array, too small for SciFi operation and characterisation because too many boundaries
- Spherical microlenses + cylindrical spacers on the sides
- **Production defects:** many defects 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)

Trippl, VCI 2022



Where we are now (2025)



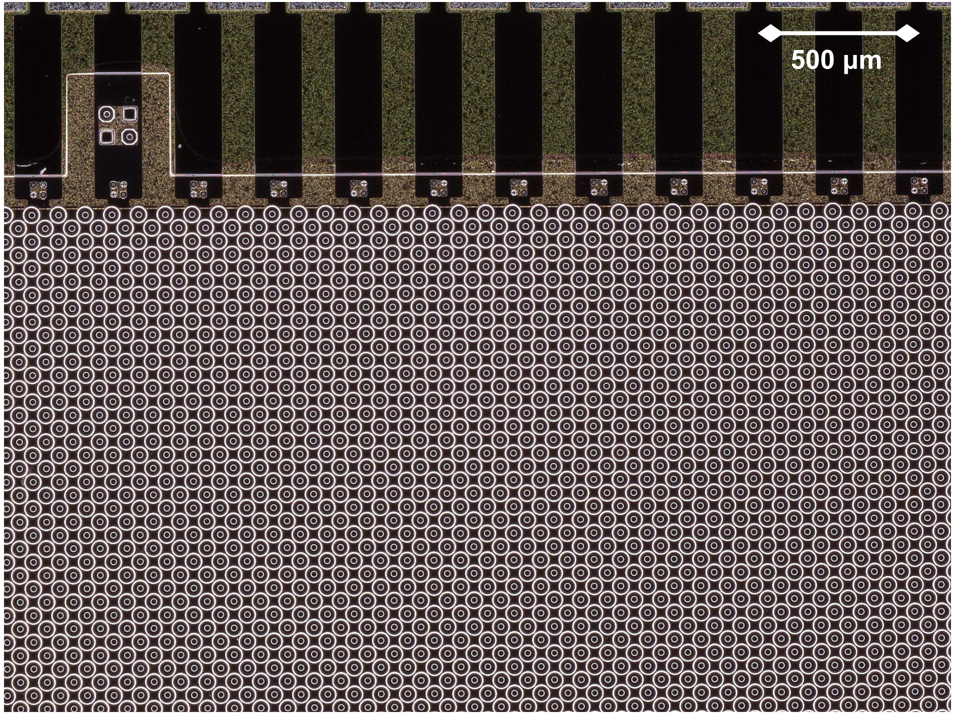
Where we were before (2022)

Full detector

- FBK NUV-HD SiPM 42µm
  - **large operation range**, allows to evaluate field dependent effects
  - 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

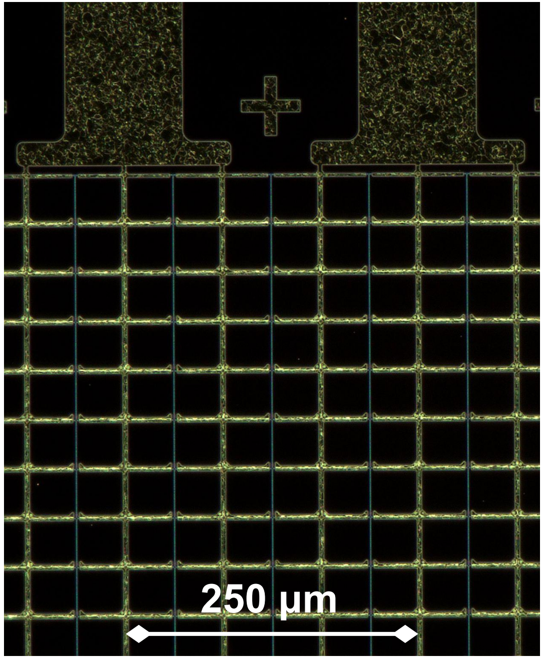
Where we are now (2025)

- **Improved production process**
- Negligible mis-alignement

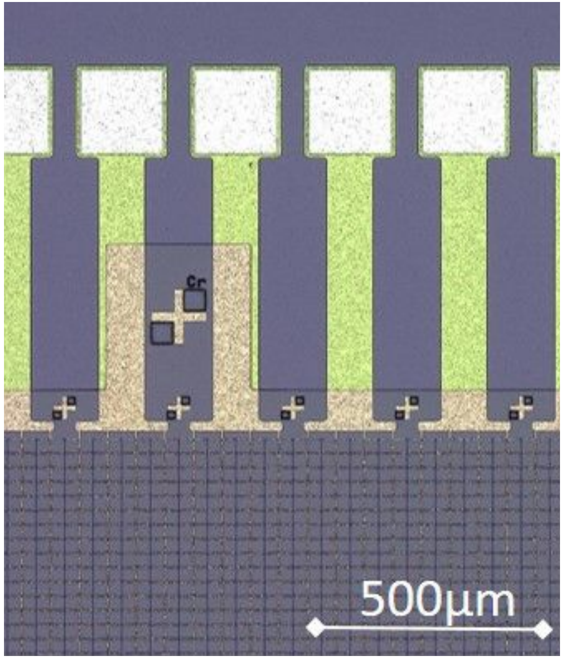


SiPM coating

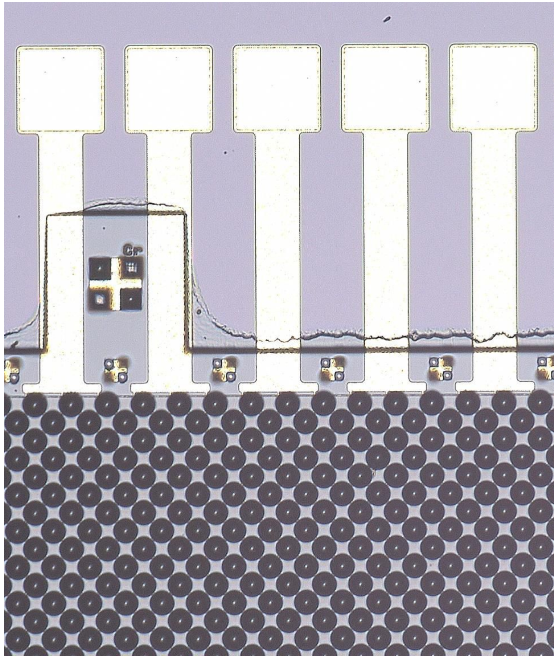
Bare silicon



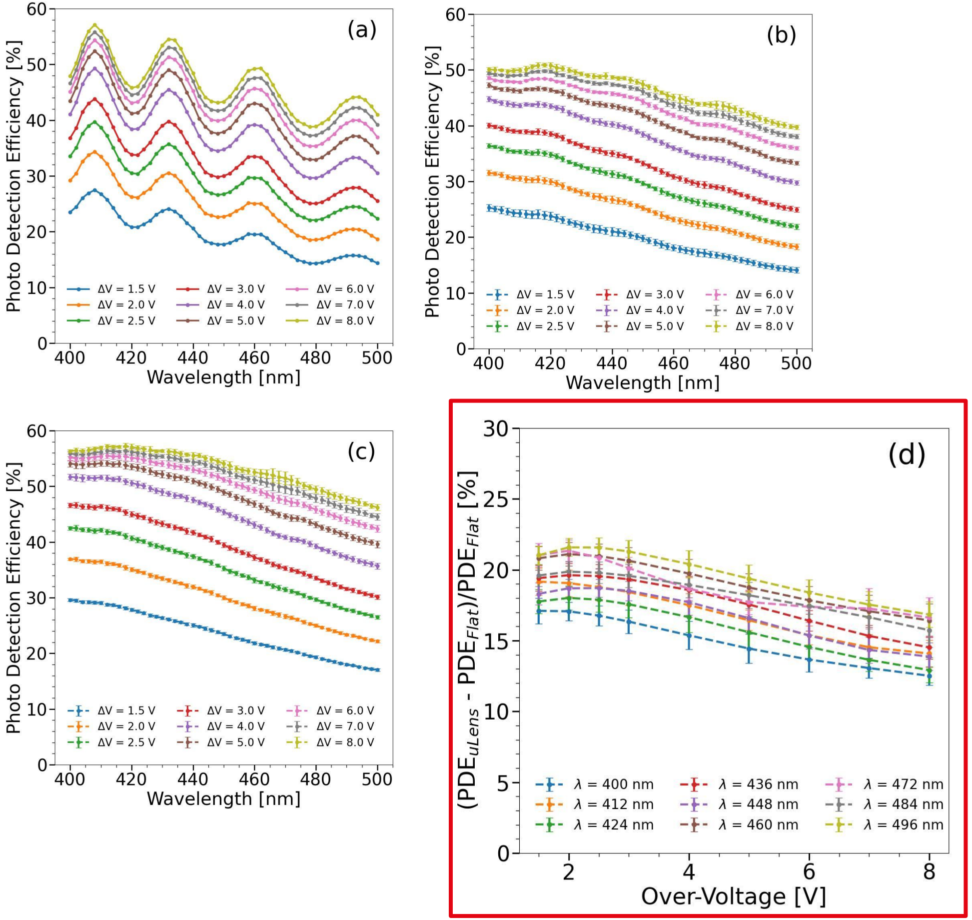
Flat polymer coating



Microlens coating



PDE enhancement FBK NUV-HD 42µm



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

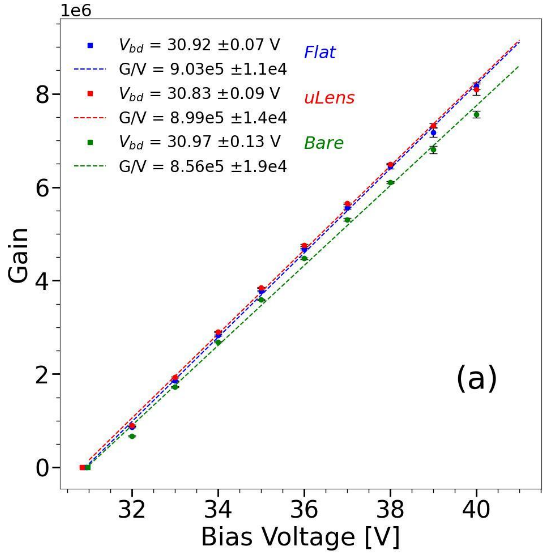
$$\mathrm{PDE_{gain}} = \frac{\mathrm{PDE}_{\mu\mathrm{lens}} - \mathrm{PDE_{flat}}}{\mathrm{PDE_{flat}}}$$

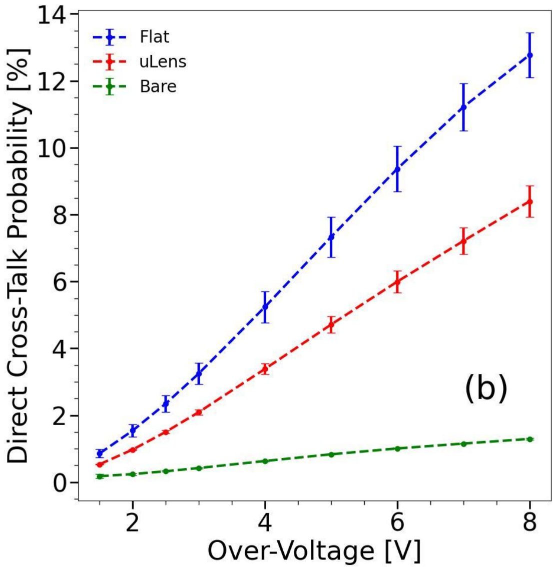
- PDE increase reaches its maximum at **low overvoltage** → the lens effect is more important when efficient area is smaller
- Maximum PDE gain
  - **2 V OV = 22%**
  - **8 V OV = 17%**

Gain and cross-talk

Gain

- No gain variation expected after adding flat or microlens coating
- Measurements show a **small increase** for coated SiPMs, but no difference between flat and microlenses → hypothesis: **capacitive coupling**





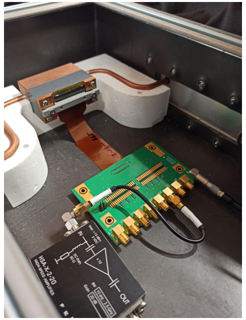
Correlated noise

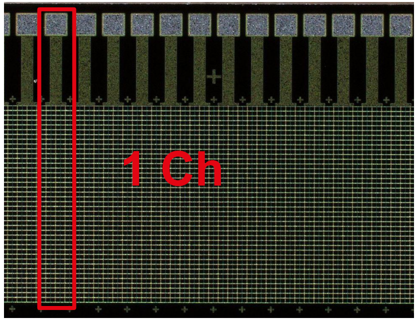
- Expected increase in optical cross-talk for flat coating with respect to bare silicon
- **Cross-talk reduced by 40%** for microlens-enhanced SiPMs with respect to flat coated ones

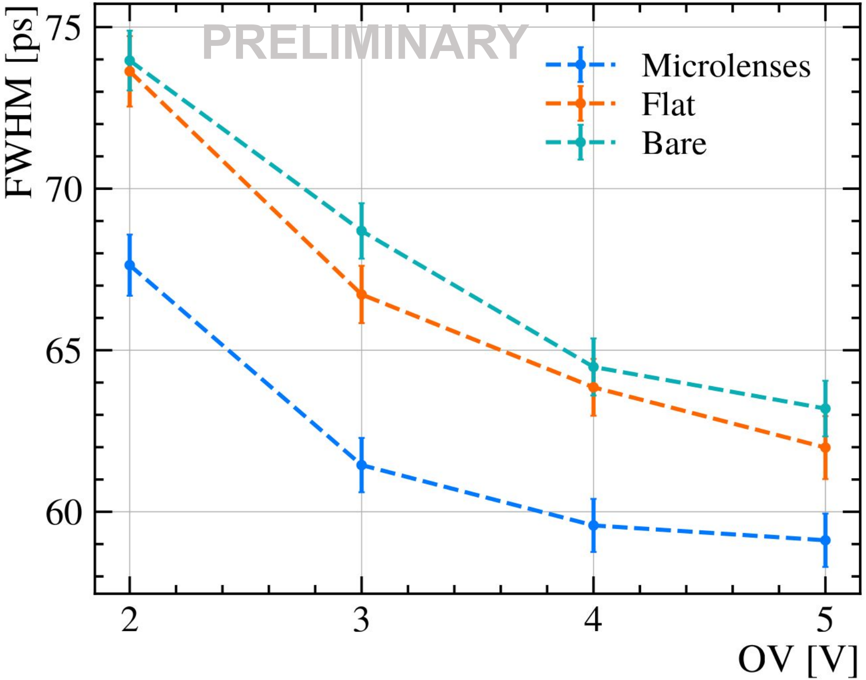
→ microlens traps, defocuses or focuses back emitted photons generated in the avalanche

Timing: SPTR

- Laser source and oscilloscope readout
  - Laser jitter ~ 56ps
- Three **FBK detectors** with different coating
- **1 channel** readout: $A_{SiPMch} = 0.4mm^2$
- **Noise and laser jitter** subtracted
- Value calculated for the **best threshold** in % of single photon amplitude
- Microlenses ~ 10% better







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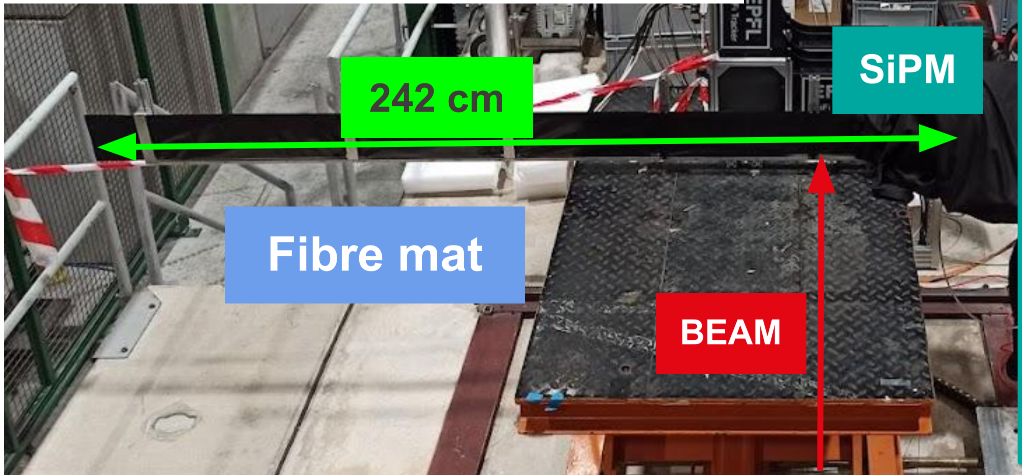
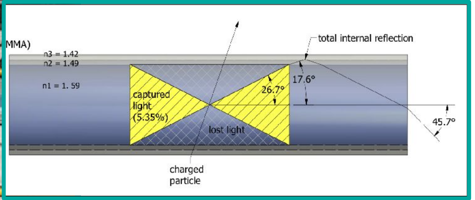
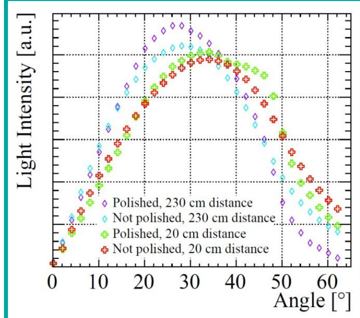
Light Yield improvement

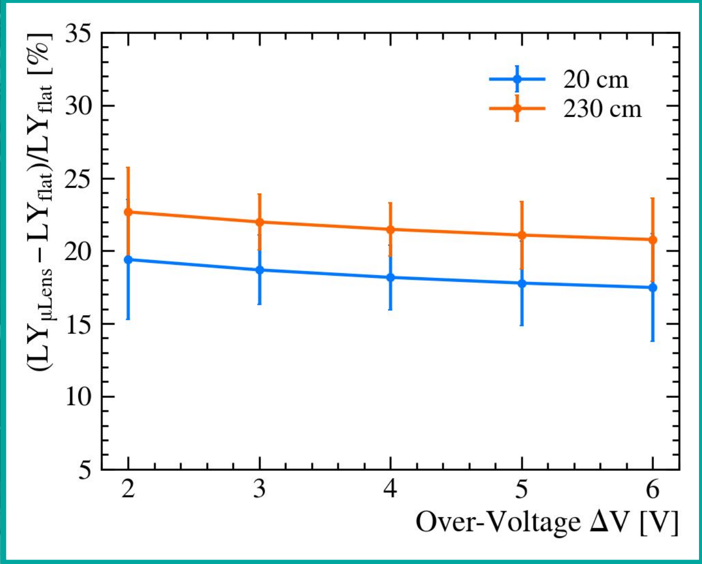
- **LY measurement** with **SciFi mat** coupled with microlens and flat FBK SiPMs
- **Testbeam** with hadrons @ 180 GeV at the CERN SPS
- LY measured at **different injection points** along the mat from the SiPMs
- Larger increase when light travels more in the fibre → **exit angle distribution** more similar to narrow one (like PDE setup)



Fibre light exit angle distribution







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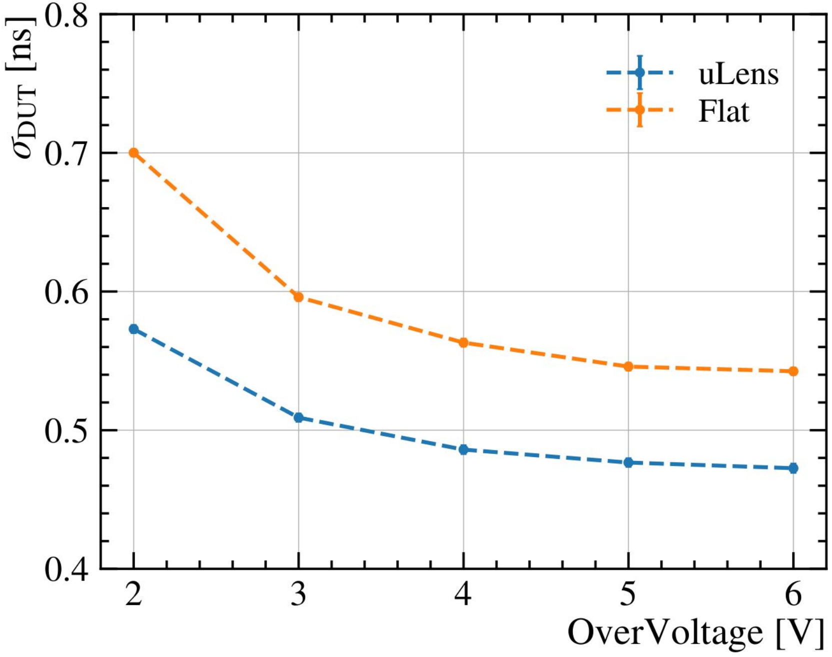
Timing: SciFi



- Testbeam measurements at the CERN SPS
- Non-irradiated **SciFi mat** readout by FBK SiPMs
- Injection point at **230 cm from the SiPMs** → smallest amount of light
- **Increased light yield** due to microlenses leads to **better time resolution**
- Time resolution **dominated by scintillator** decay time
- @ 4V OV → σ ~ 0.480 ns

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Conclusions and prospects

- 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 show **promising performance**:
    - increase in SiPM PDE up to 22%
    - 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.

- New SiPMs from different manufacturers in production
- Tests of microlens-enhanced SiPMs after irradiation in cryo

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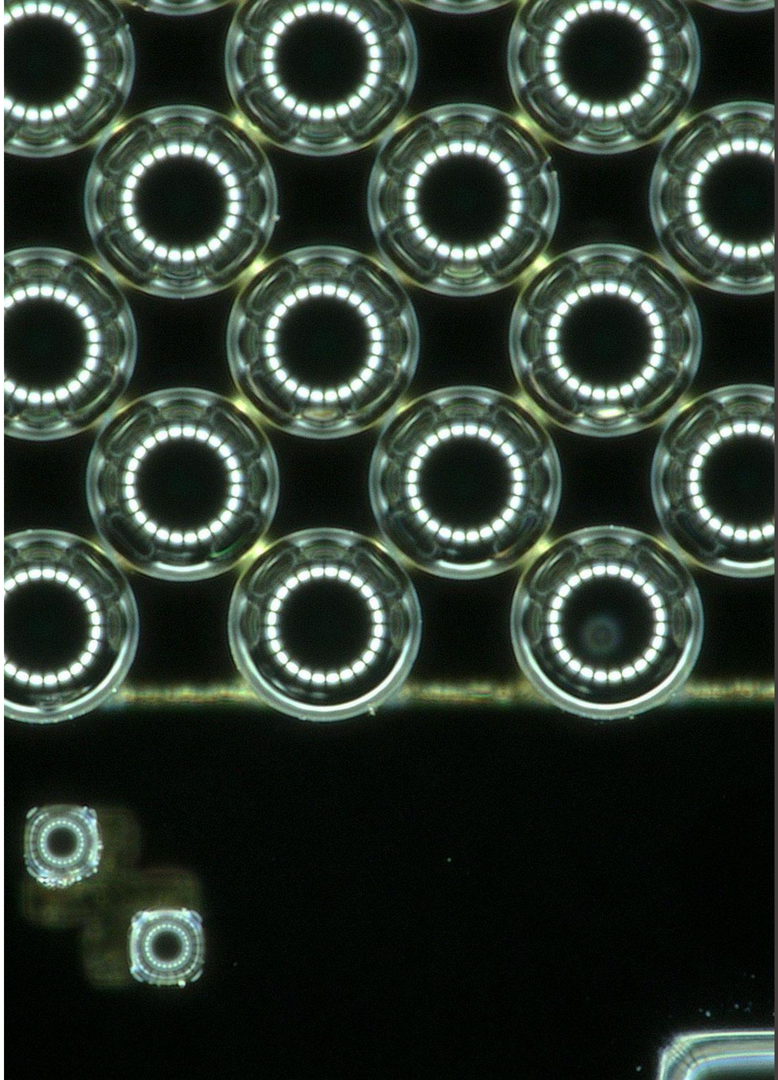

Thanks for the attention