4D-Tracking with Digital SiPM-ICs

Exploring the Potential of CMOS SPAD Arrays

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PM2024, 28 May 2024

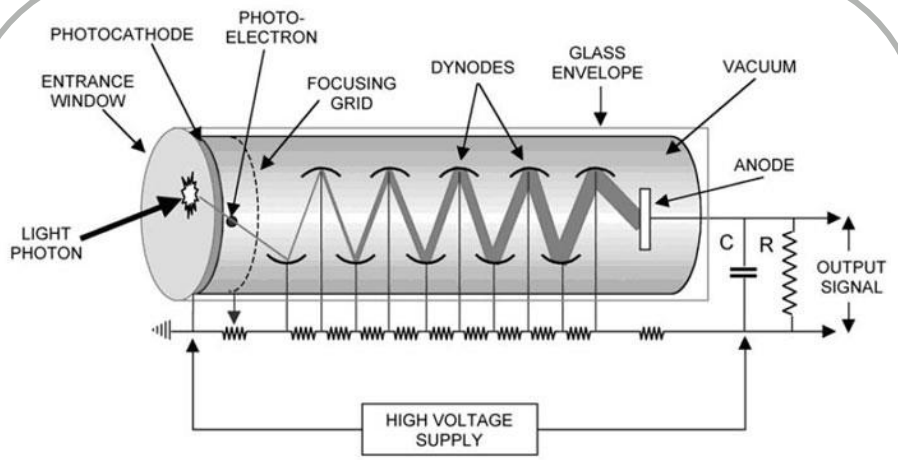
HELMHOLTZ

UNIVERSITÄT BONN

DESY.

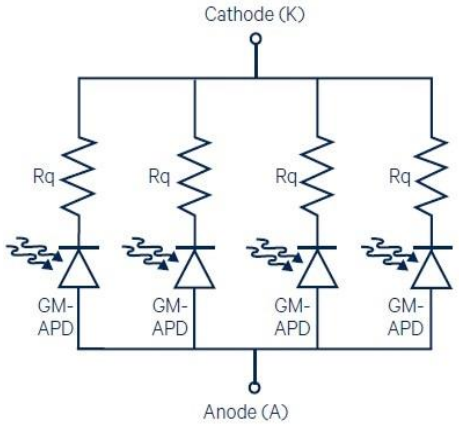
Silicon Photomultipliers

State of the Art Solid State Photodetectors

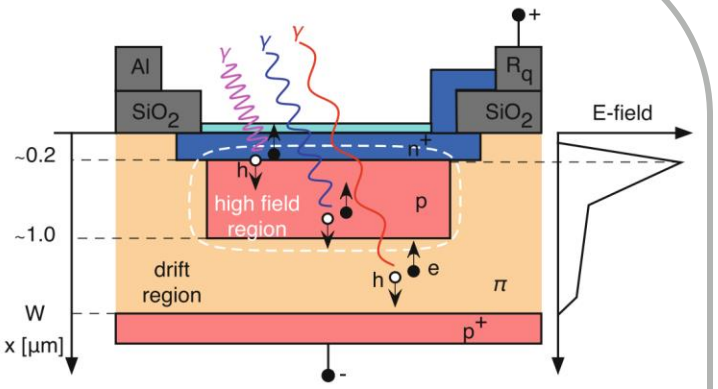


PMT working principle

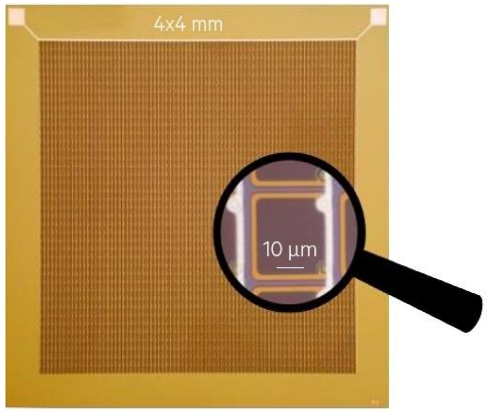
PMT Example



SiPM configuration



SPAD Structure



Example of SiPM

SiPM characteristic

- Low voltage operation
- High and stable gain
- Excellent timing performance
- High photons sensitivity
- Insensitivity to magnetic fields
- Robustness

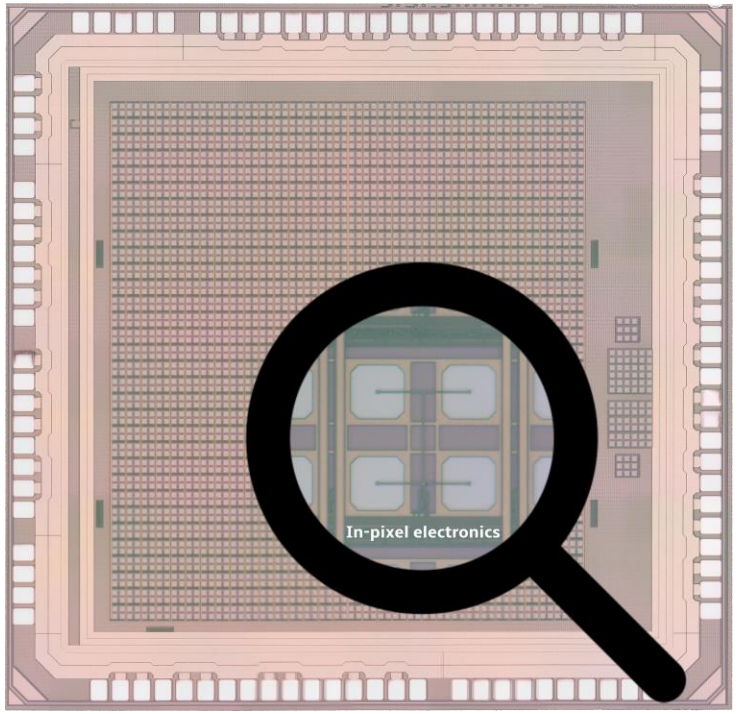
SiPM-IC Using Commercial CMOS Processes

Exploring SPADs in Foundries Process Design Kits

CMOS electronics

SPAD diodes

Digital SiPM integrated circuit (dSiPM)



DESY dSiPM in LFoundry 150 nm

Advantages

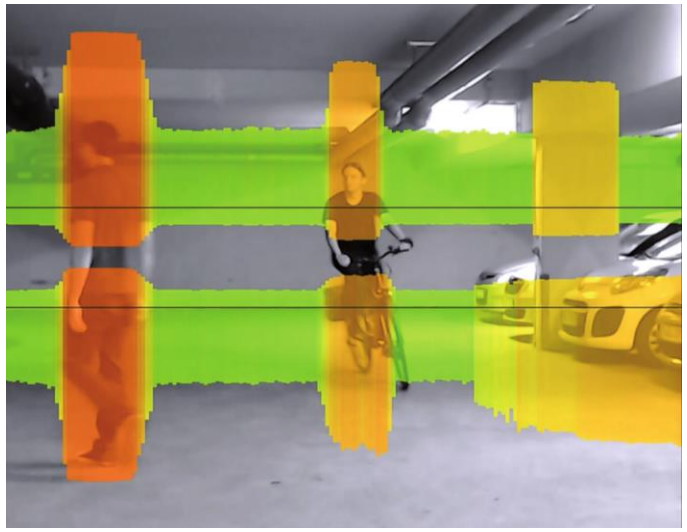
- large and fast signals
- Customized readout architectures
- Masking of noisy pixels
- Hitmap readout possible
- Simpler DAQ system
- Large volume production
- Low-cost implementation
- New possible applications

Drawbacks

- Processes not (yet) specialized
- Higher noise compared to SiPMs
- Reduced fill factor (electronics)

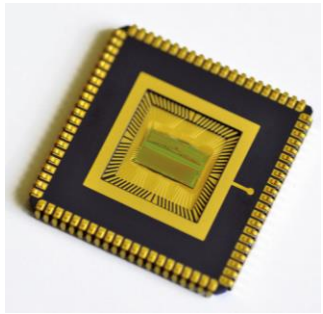
CMOS SPADs Applications

Commercial and HEP Examples

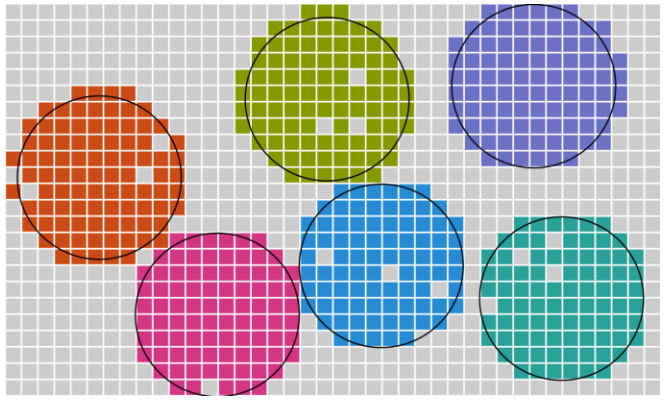


LIDAR & 4D-imaging

- Automotive
- Industry
- Security

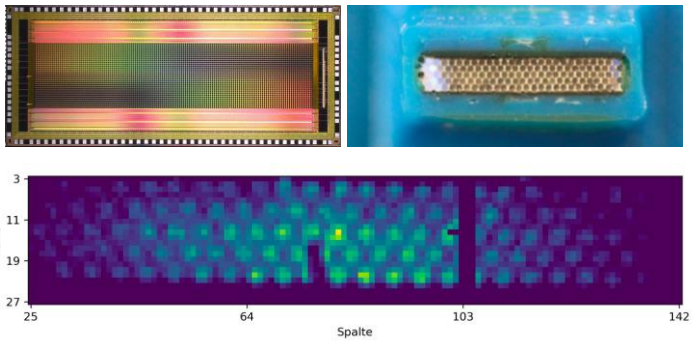


Images from: Fraunhofer IMS

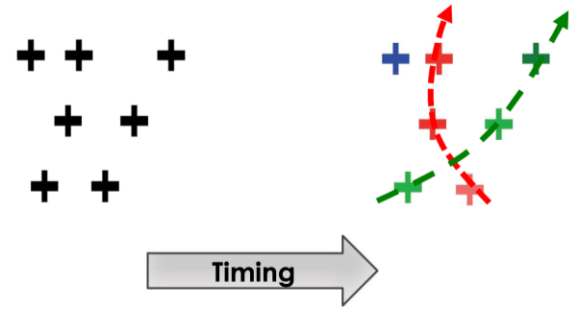


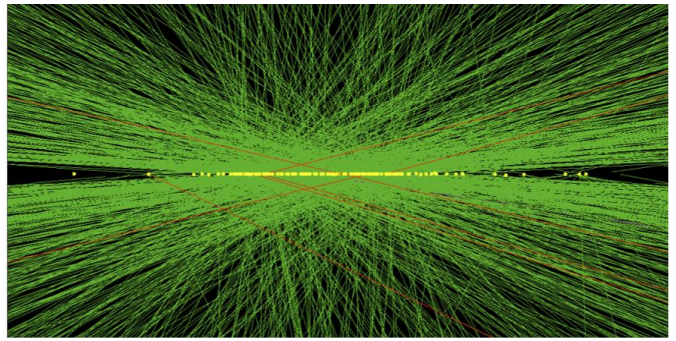
Scintillating fibers readout

- Calorimetry, tracking



https://doi.org/10.1016/j.nima.2022.167033





4D-Tracking of charged particles?

- MIPs tracking and timing

https://dx.doi.org/10.1088/1361-6633/aa94d3

dSiPM as Possible 4D-Tracker Candidate

Beyond Photon Detection Applications

MIP detection with analog devices

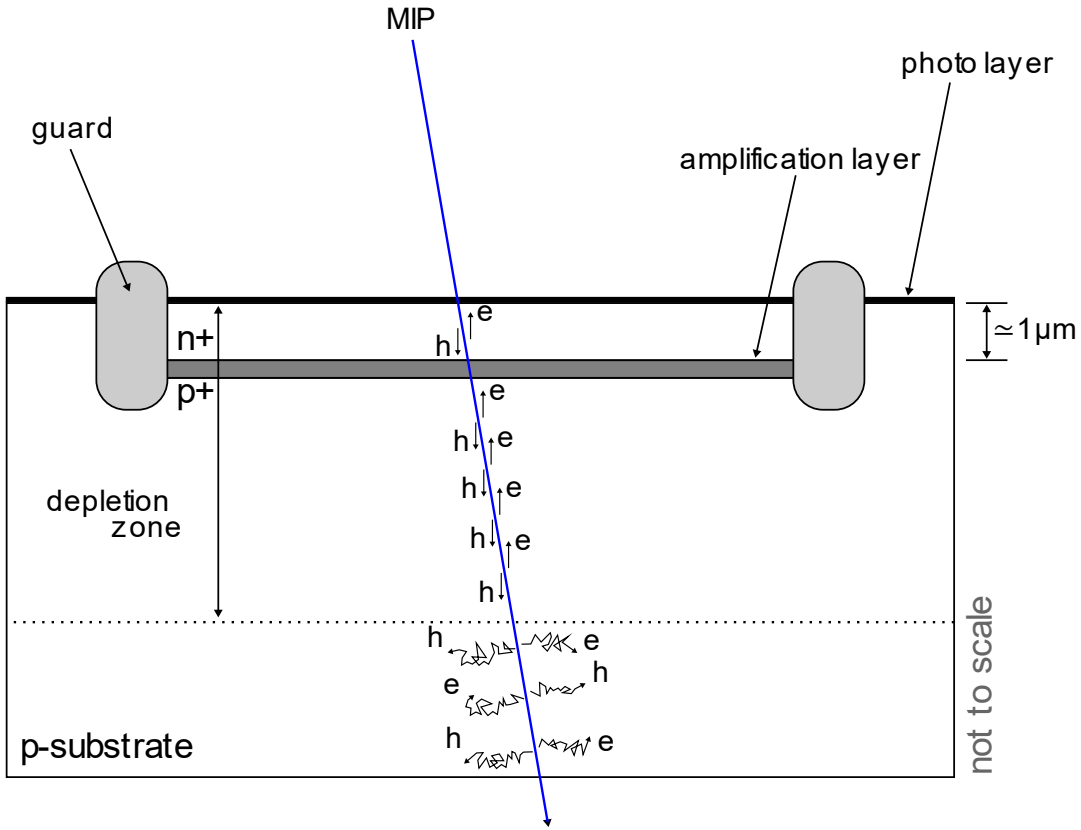
- SPAD/SiPMs already proved to be good MIPs detectors [1] [2]
- Excellent instrinsic timing performance O(10 ps)
- Photon detection is still possible (multipurpose detector)

Using CMOS dSiPM

- On-chip data processing and digitalization
- Tracking-like detector architecture possible
- High granularity with O(10 µm) spatial resolution
- Large area/volume production possible

Drawbacks

- Efficiency is limited by the fill factor
- High DCR compared to standard pixel detectors
- No distinction between signal and noise



MIP interaction in a SPAD

DESY dSiPM Prototype

ASIC in LF 150 nm CMOS

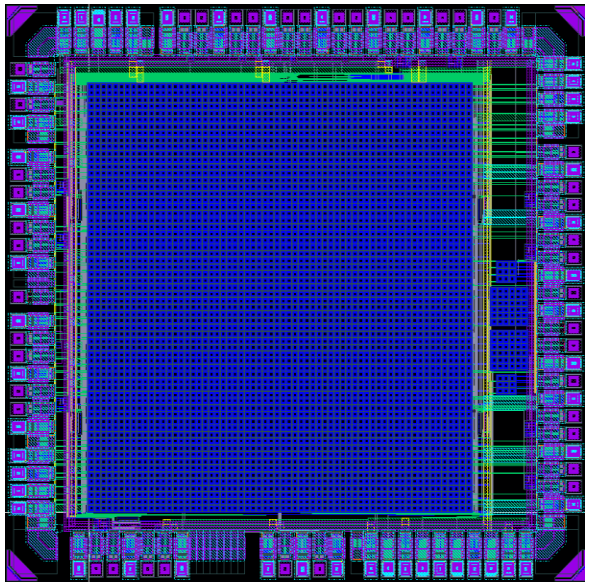
Layout

- In LFoundry 150 nm CMOS technology
- Main matrix: 32 x 32 pixels (4 SPADs per pixel)
- Sensor area: 2.2 x 2.4 mm^2
- Test structures in the chip periphery

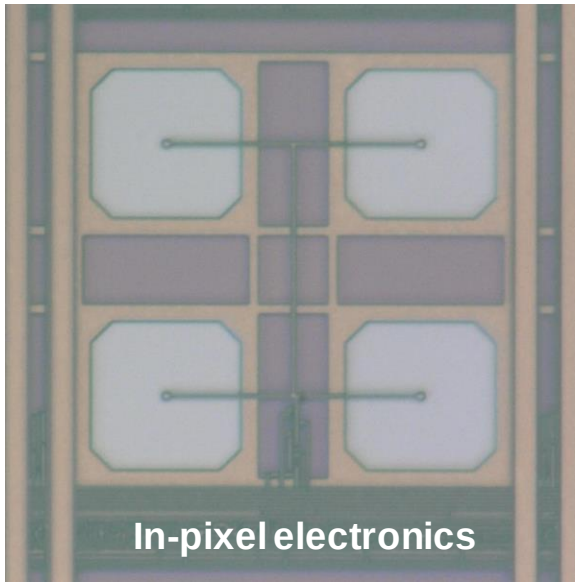
Features

- Full hit matrix readout and timing measurements
- 4 x 12-bit Time to Digital Converters with ~95 ps bins
- Pixel masking & 2-bit in-pixel hit counting
- Quenching can be tuned (quenching transistor)
- In chip trigger logic
- Readout is frame-based (3 MHz frame rate)
- Versatile Caribou DAQ system is used for biasing & readout

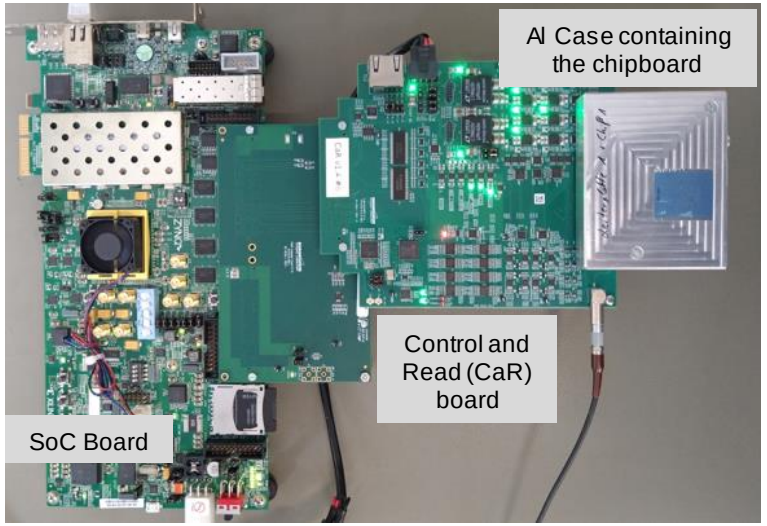
For details: I. Diehl et al 2024 JINST 19 P01020



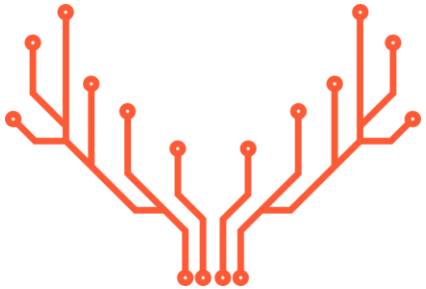
ASIC design of the DESY dSiPM



DESY dSiPM pixel picture (69.6 x 76 μm^2)



DAQ System



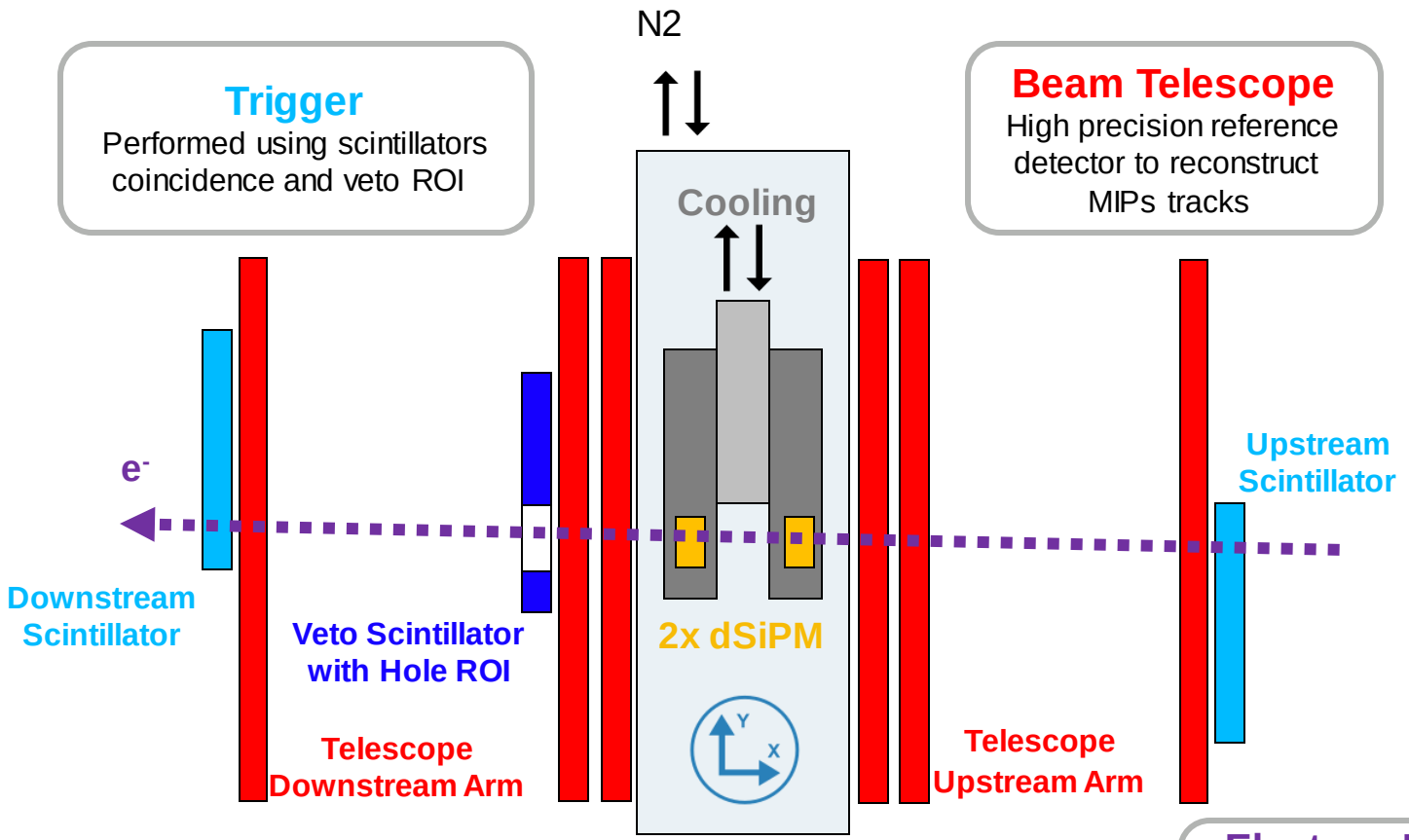
Caribou DAQ system
Fast & low cost implementation of solid state detector prototypes
http://dx.doi.org/10.22323/1.370.0100
https://gitlab.cern.ch/Caribou/

DESY dSiPM Test Beam

Device Treated as a Particle Detector

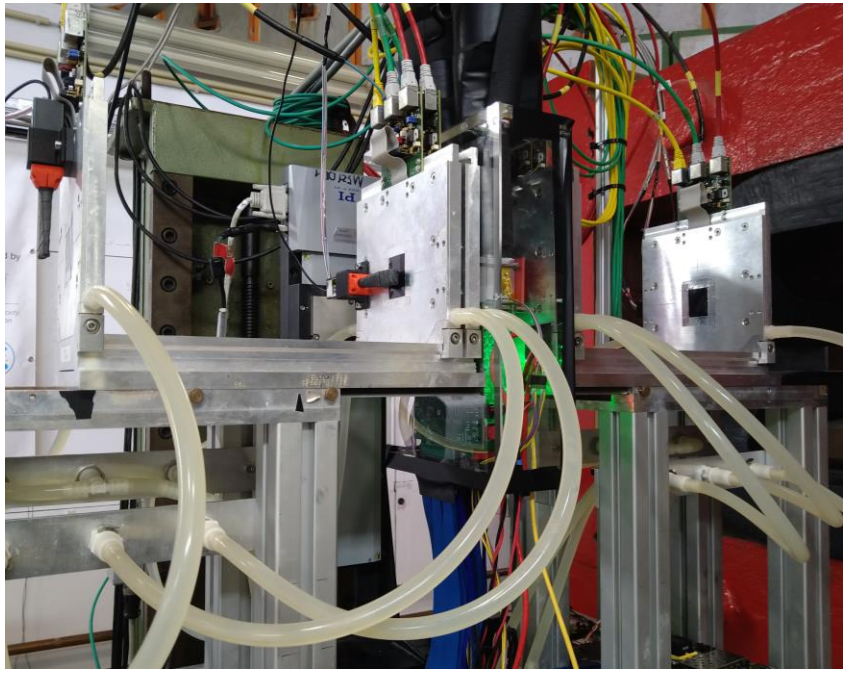
Trigger
Performed using scintillators coincidence and veto ROI

Beam Telescope
High precision reference detector to reconstruct MIPs tracks



DUTs & Cooling
Two DESY dSiPMs aligned to study coincidences. Active cooling down to 0 °C on Chip for stable operations

Electron Beam
Extracted from DESY II synchrotron with an energy of 1-6 GeV



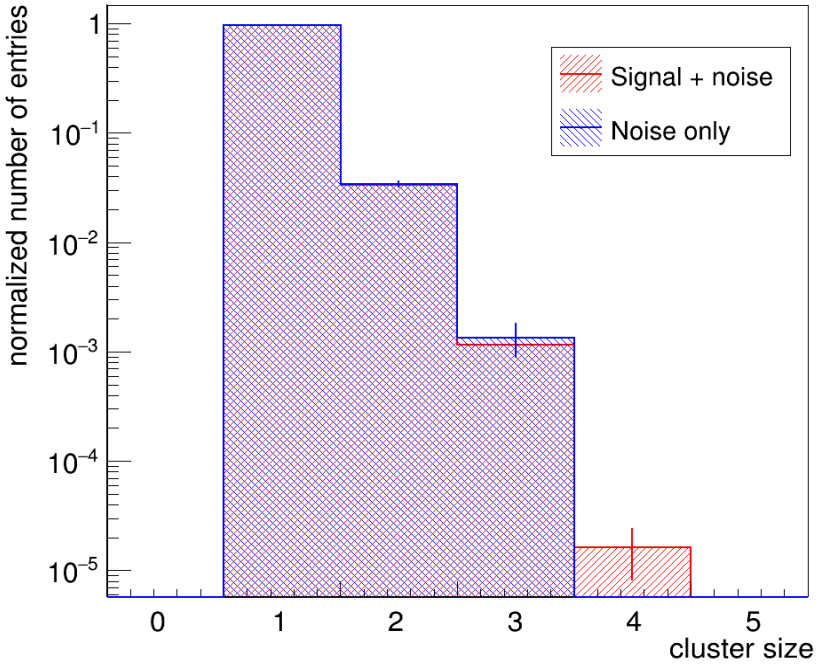
DESY dSiPM test beam setup

- **EUDAQ** framework and AIDA TLU used for data acquisition and synchronization of devices.
- **Corryvreckan** Framework used for test beam data reconstruction and analysis

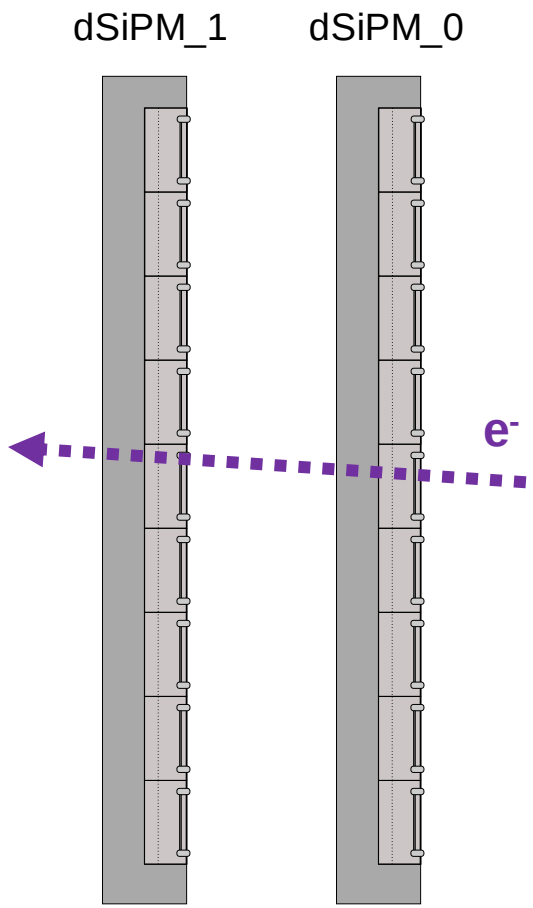
DESY dSiPM Spatial Properties

Direct MIP Detection (Only Silicon)

Associated cluster size

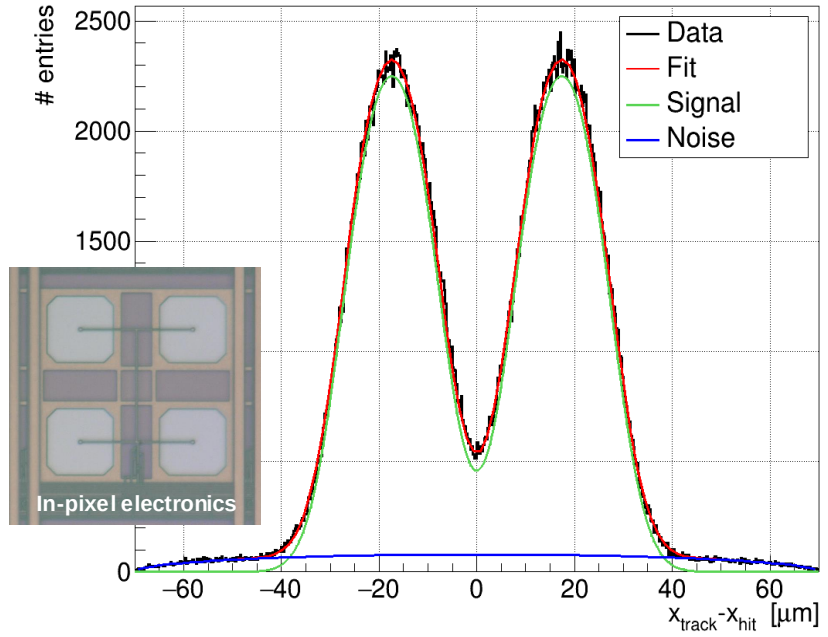


- Cluster size mainly one (log scale in figure)
- Signal and noise have the same cluster size
- Events with larger clusters due to crosstalk



MIP detection with bare silicon

Spatial Residuals

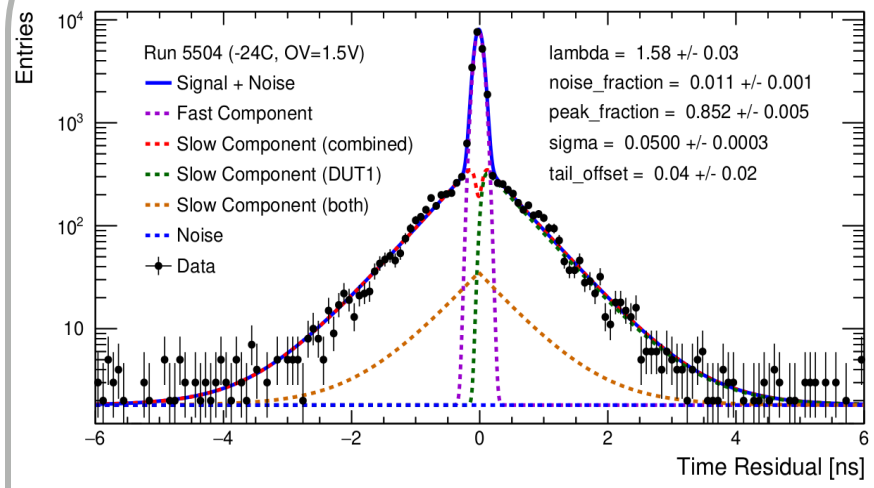


- Distance between dSiPM hit and track
- Shape due to in-pixel 4 SPADs structure
- Spatial resolution O(20 µm)

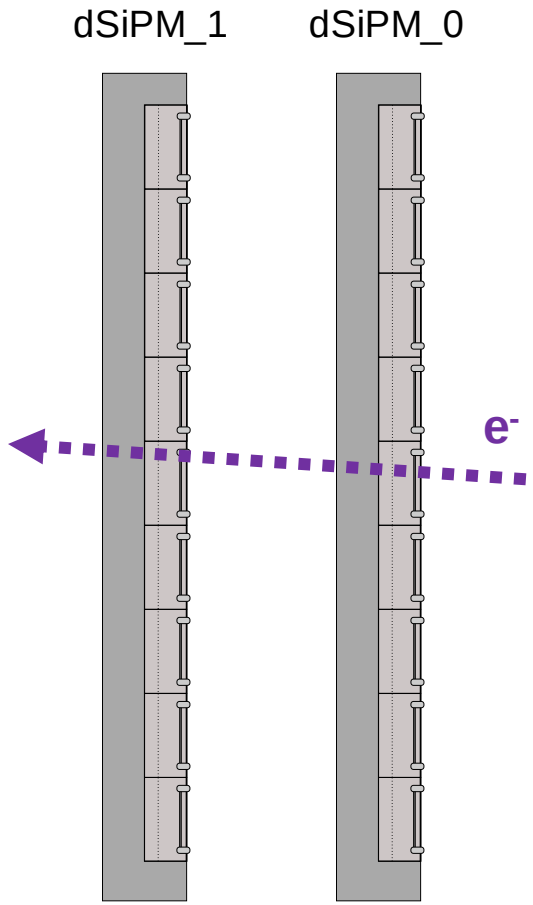
DESY dSiPM Timing

Direct MIP Detection (Only Silicon)

Time Residuals



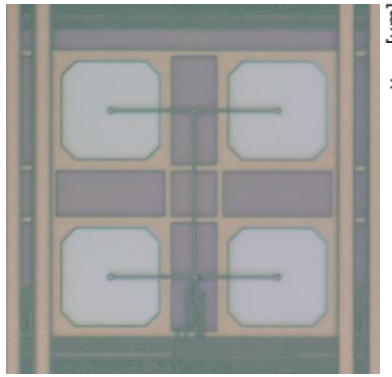
- Defined as difference of DUTs timestamps
- Model fitted to data to extract time resolution
- Fast component, 85% of entries ~50ps
- Slow component, 15% of entries O(ns)
- Timing limited by TDC resolution (~95 bins)



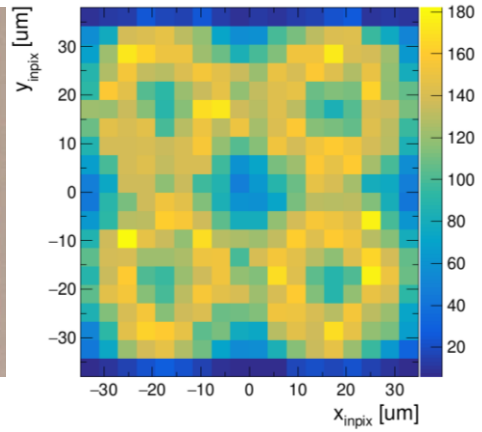
MIP detection with bare silicon

Slow component

dSiPM pixel



Hit position of "slow" events

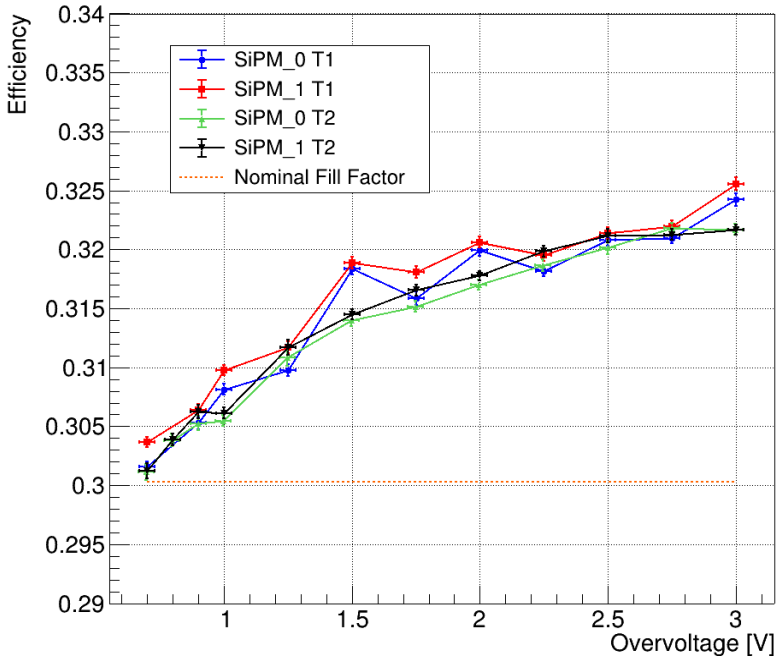


- Tracking allows spatial resolution O(5 µm)
- Selected "slow" events cutting on residuals
- In pixel "ring" shape visible
- Slow events come from SPAD edges
- Probably due to drift in low E-field regions

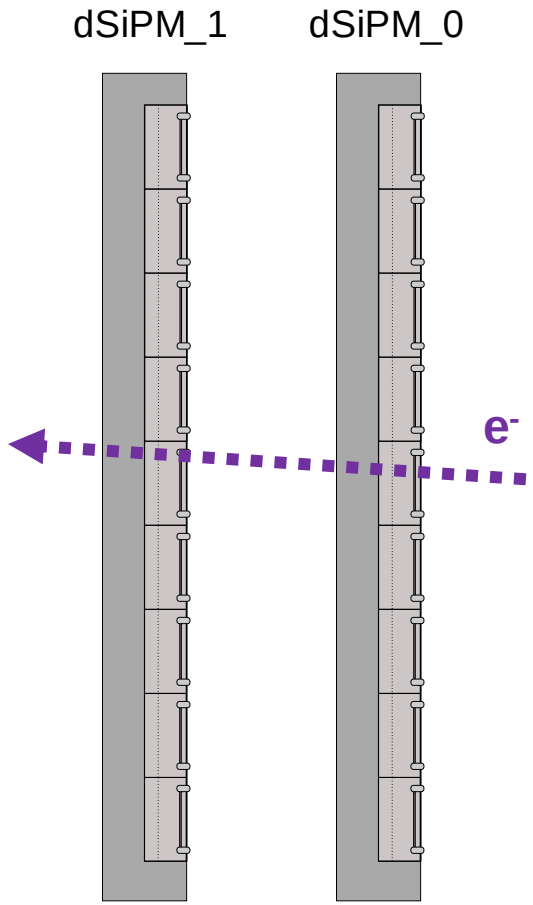
DESY dSiPM Efficiency

Direct MIP Detection (Only Silicon)

Efficiency VS overvoltage

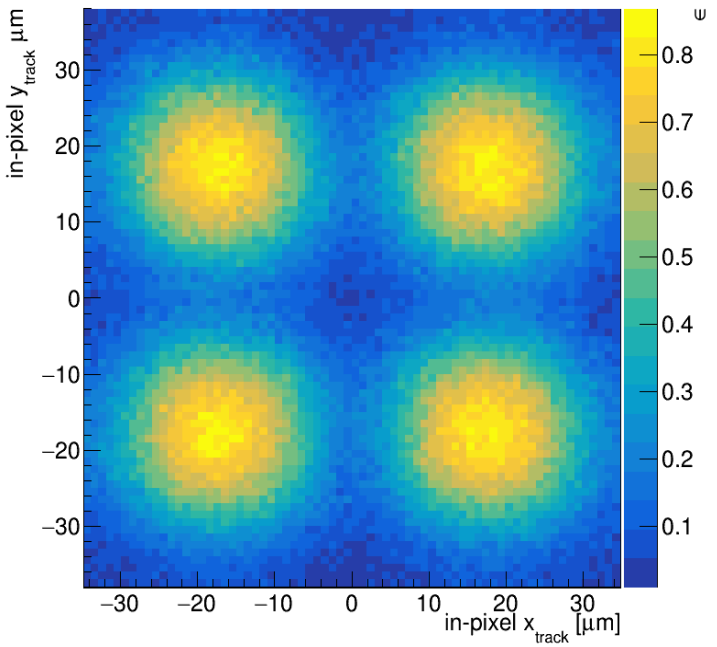


- Efficiency compatible with fill factor (~30%)
- Small overvoltage dependence
- No temperature/sample dependence



MIP detection with bare silicon

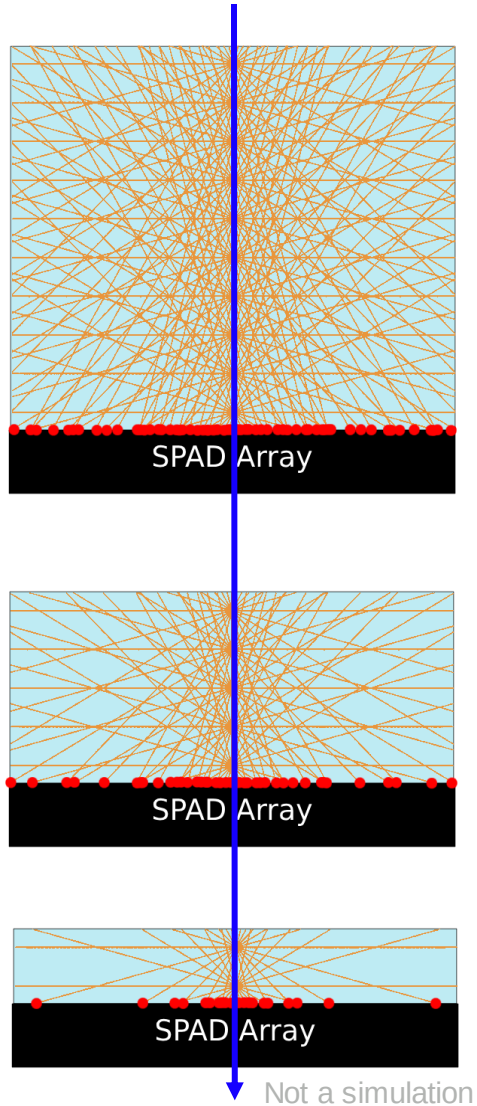
In-pixel efficiency

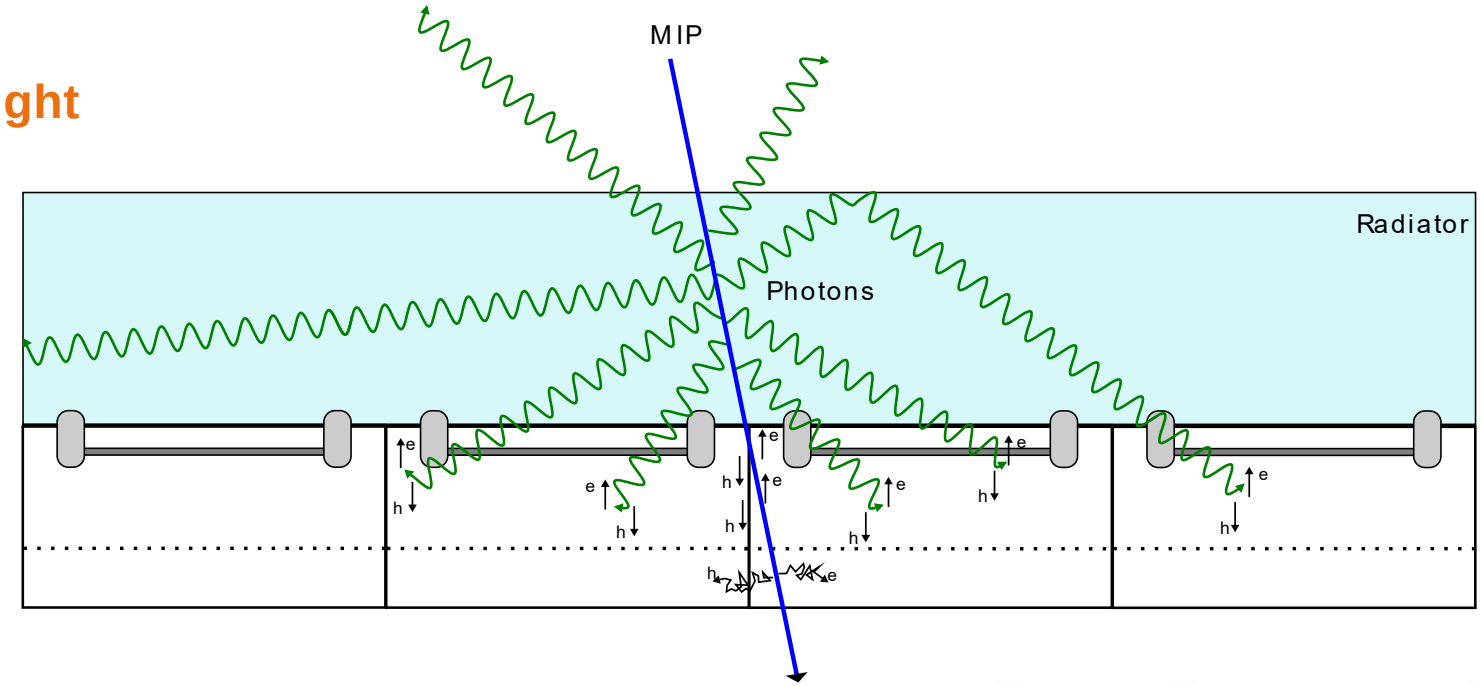


- Image resolution limited by tracking
- Maximum efficiency in the SPAD centre
- Lower efficiency in SPAD edges

Thin Radiator Concept

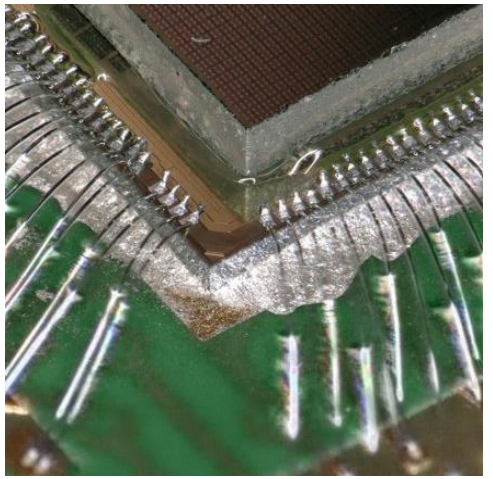
Detecting Cherenkov & Scintillation Light



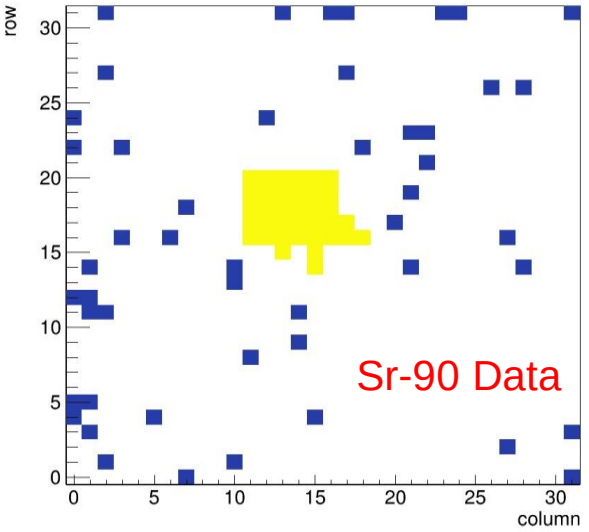


DESY dSiPM + thin LYSO

- Overcome efficiency limit
- Reduce noise contamination (large signals for MIP events)
- Preserve good spatial resolution
- Concept already explored using analog SiPM [1] [2] [3]
- Three sample assembled with 100, 200 & 500 µm thick LYSO



Thin LYSO glued on DESY dSiPM

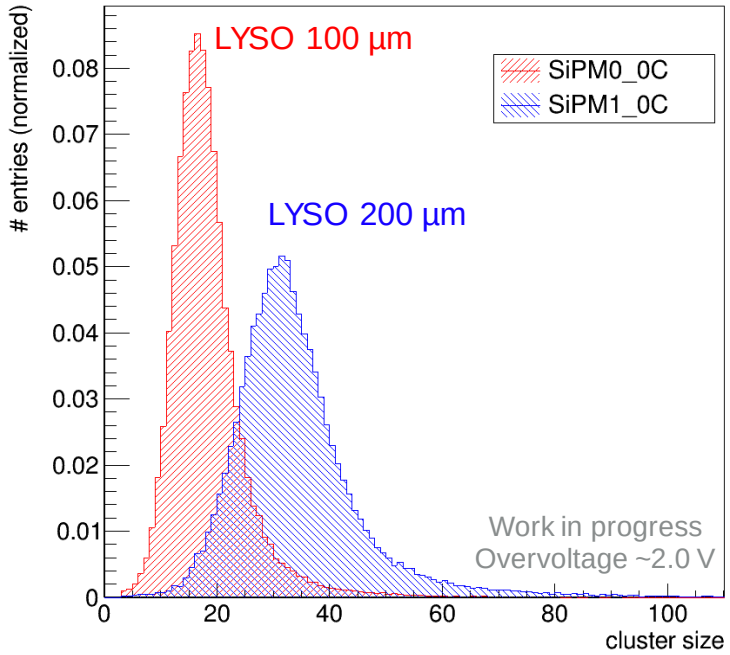


dSiPM + 200µm LYSO MIP hit map

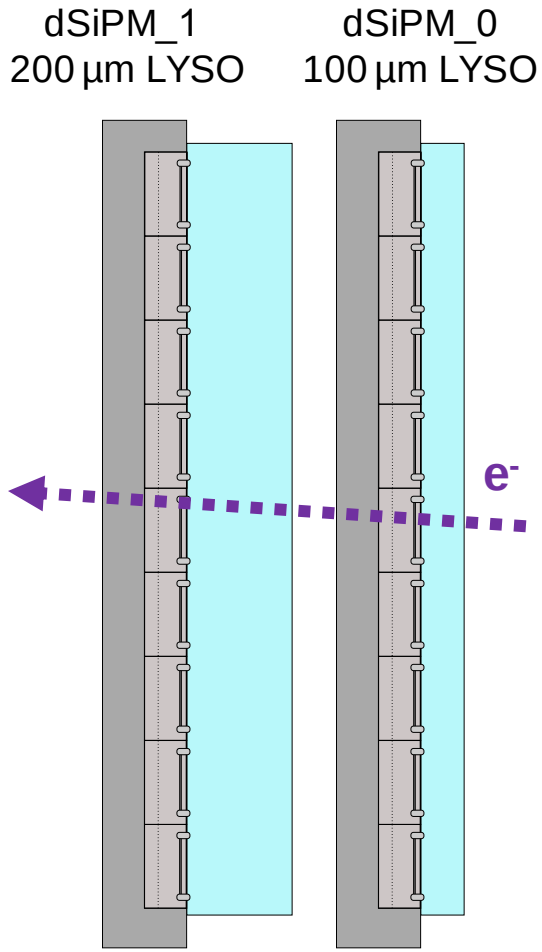
DESY dSiPM + Thin LYSO

Cluster Size, Signal & Noise with Different Tagging

MIP events cluster size

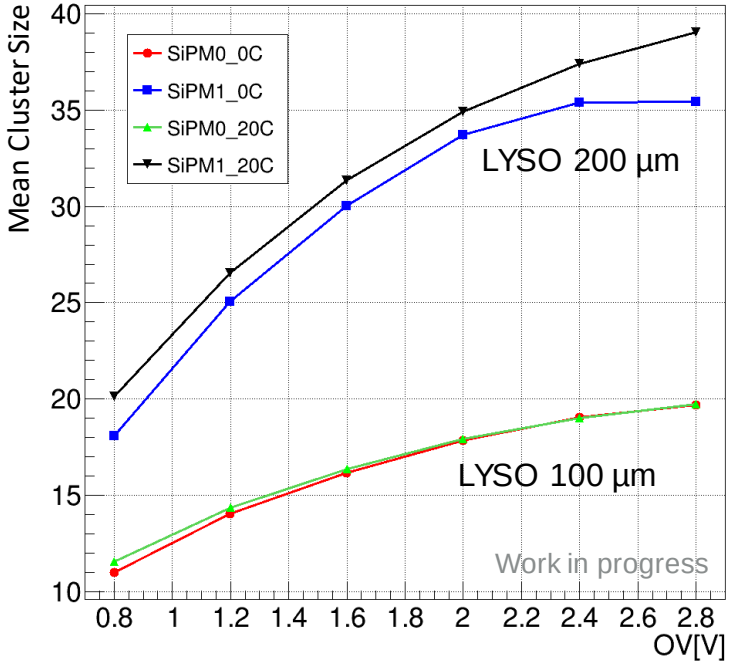


- Large cluster size for MIP events
- DCR hits (1 or 2 pixels) can be filtered
- Very low noise with threshold on clusters



MIP detection with thin radiator coupling

Cluster size VS overvoltage

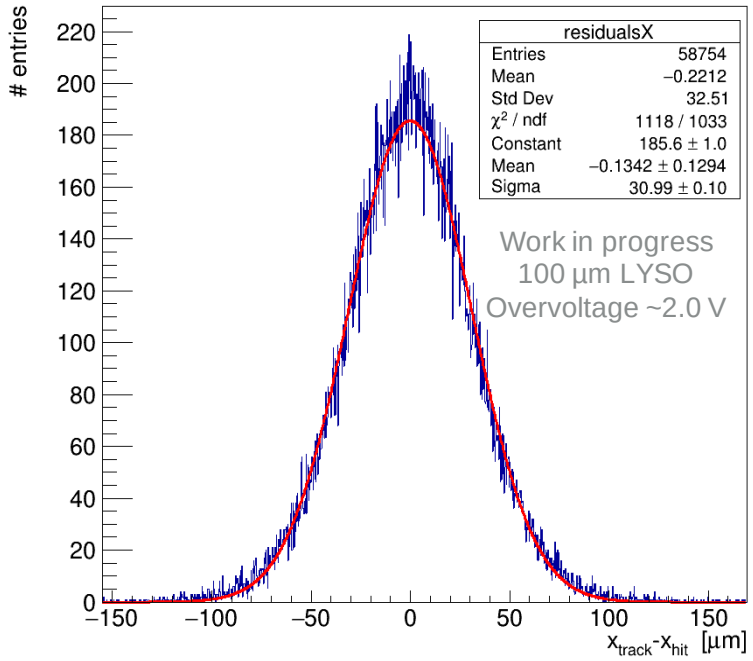


- The thicker the LYSO, the larger the cluster
- Overvoltage dependence due to PDE increase
- Small temperature (DCR) dependence

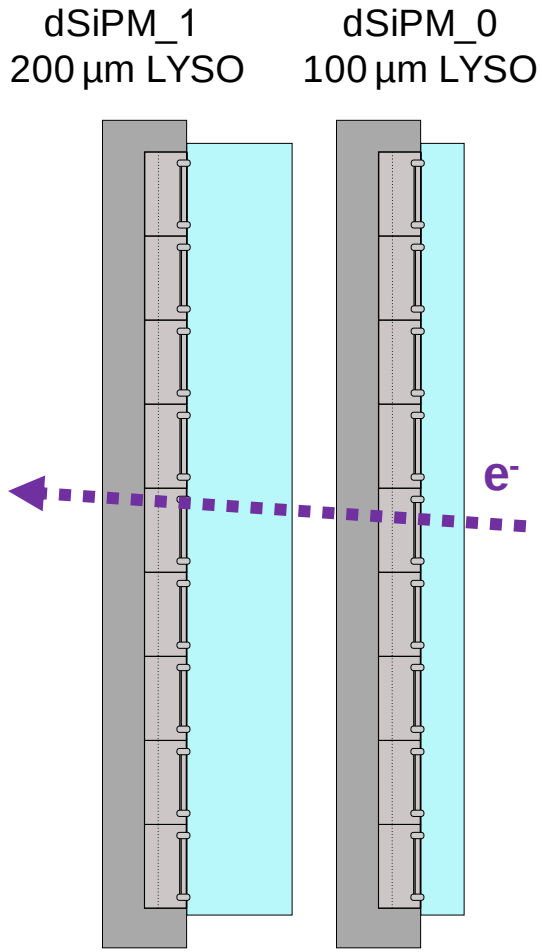
DESY dSiPM + Thin LYSO

Spatial Residuals, Good Spatial Performances Preserved

Spatial Residuals

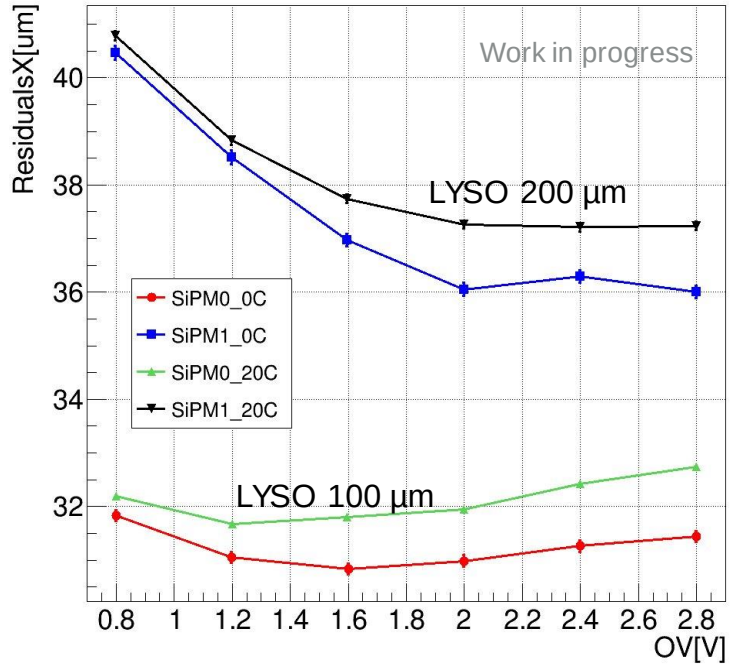


- In-pixel structure not visible
- Gaussian shape
- Good spatial resolution preserved



MIP detection with thin radiator coupling

Residuals VS overvoltage

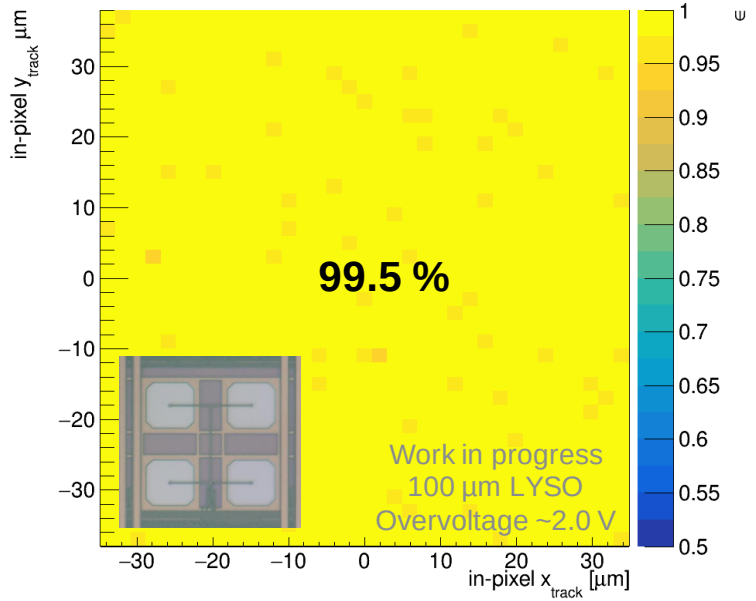


- Thinner LYSO has better spatial resolution
- Sigma ~32 µm (100µm LYSO) and ~38 µm (200µm LYSO)
- Small OV & temperature dependence

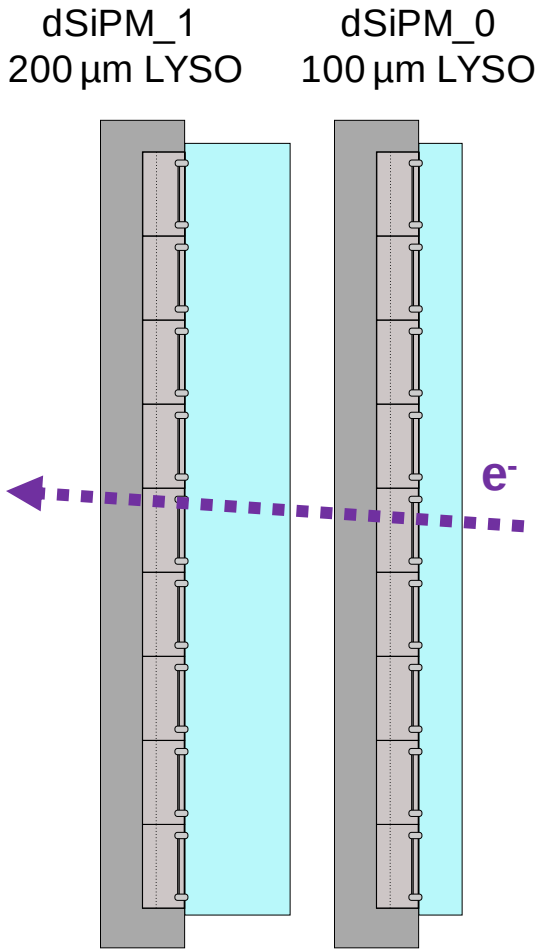
DESY dSiPM + Thin LYSO

Efficiency & Timing Performances

In-pixel Efficiency

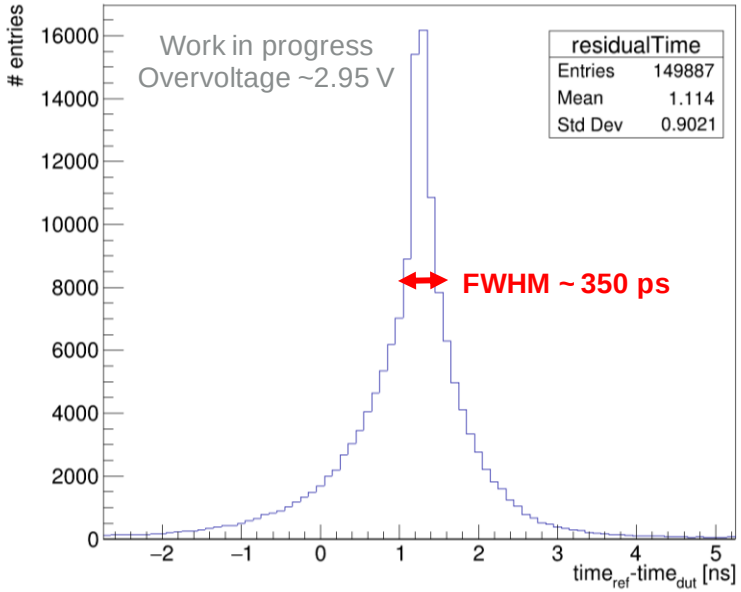


- Uniform in-pixel efficiency (SPADs position no longer visible)
- From ~33% (bare silicon) to >99% using Thin LYSO coupling
- No OV or temperature dependence



MIP detection with thin radiator coupling

Time residual distribution



- Fast time residuals core with FWHM ~350 ps
- Important fraction of event in residuals tails
- Probably due to LYSO timing property
- Faster radiators may improve timing

Summary & Outlook

dSiPM as 4D-Tracking Candidate

CMOS dSiPMs

- Combination of SPAD and CMOS electronics in the same silicon die opens new application possibilities
- Reduction of complexity & cost especially for large volumes

DESY dSiPM & MIPs 4D-Tracking

- dSiPM can be a possible candidate technology for 4D-tracking
- Spatial resolution down to ~20 µm and ~50 ps system timing
- Efficiency >99%, very low noise rate using thin LYSOs

CMOS dSiPMs R&D Potential

- dSiPM can play an important role in future HEP detector systems
- CMOS dSiPMs are a "young" technology, promising R&Ds ongoing
- Any new idea of possible HEP application is welcome

DESY dSiPM 4D-Tracking Performances

	dSiPM	dSiPM+LYSO
Signal Cluster Size	~ 1	10 – 40
Spatial Resolution	**~ 20 µm**	~ 35 µm
Efficiency in MIP detection	~ 33 %	**> 99 %**
Noise Rate	O(MHz)	**O(Hz)***
Time Resolution	**~ 50 ps**	< 1ns **

* While cutting on cluster-size
** Currently under investigation

Thank you.

References:

I. Diehl et al, Monolithic MHz-frame rate digital SiPM-IC with sub-100 ps precision and 70 µm pixel pitch
S.Lachnit, Time Resolution of a Fully-Integrated Digital Silicon Photo-Multiplier
F.Feindt et al, The DESY digital silicon photomultiplier: Device characteristics and first test-beam results

Gianpiero Vignola
gianpiero.vignola@desy.de

Deutsches Elektronen-Synchrotron DESY
Notkestraße 85, 22607 Hamburg
1C, O1.331, ATLAS

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

DESY dSiPM ASIC

More Details in Reference Publication

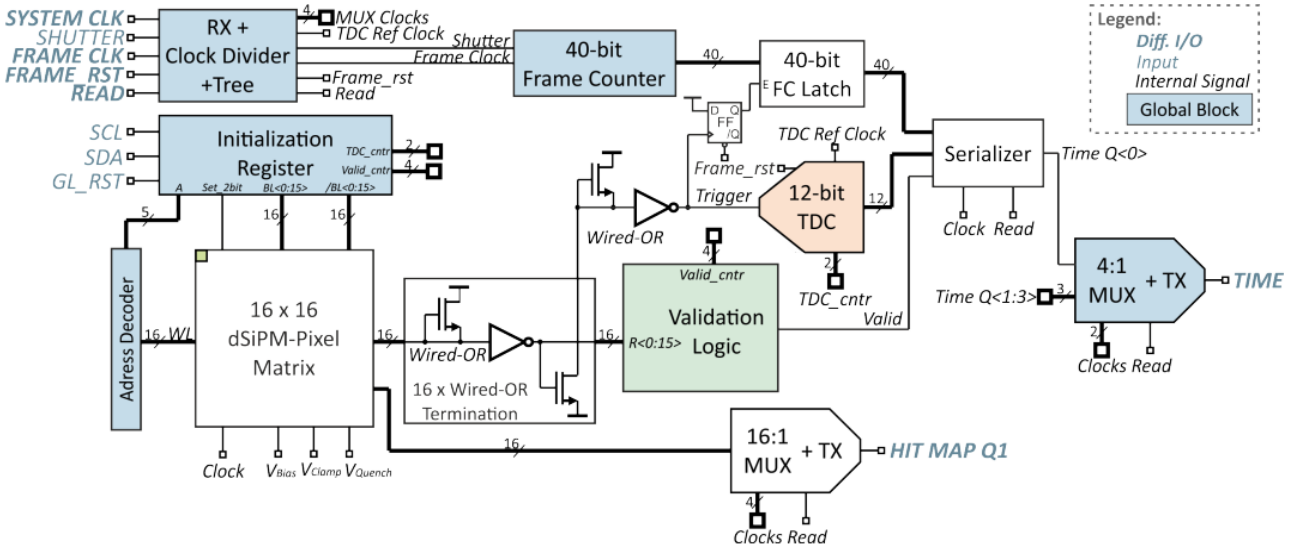


Figure 2. Quadrant block diagram.

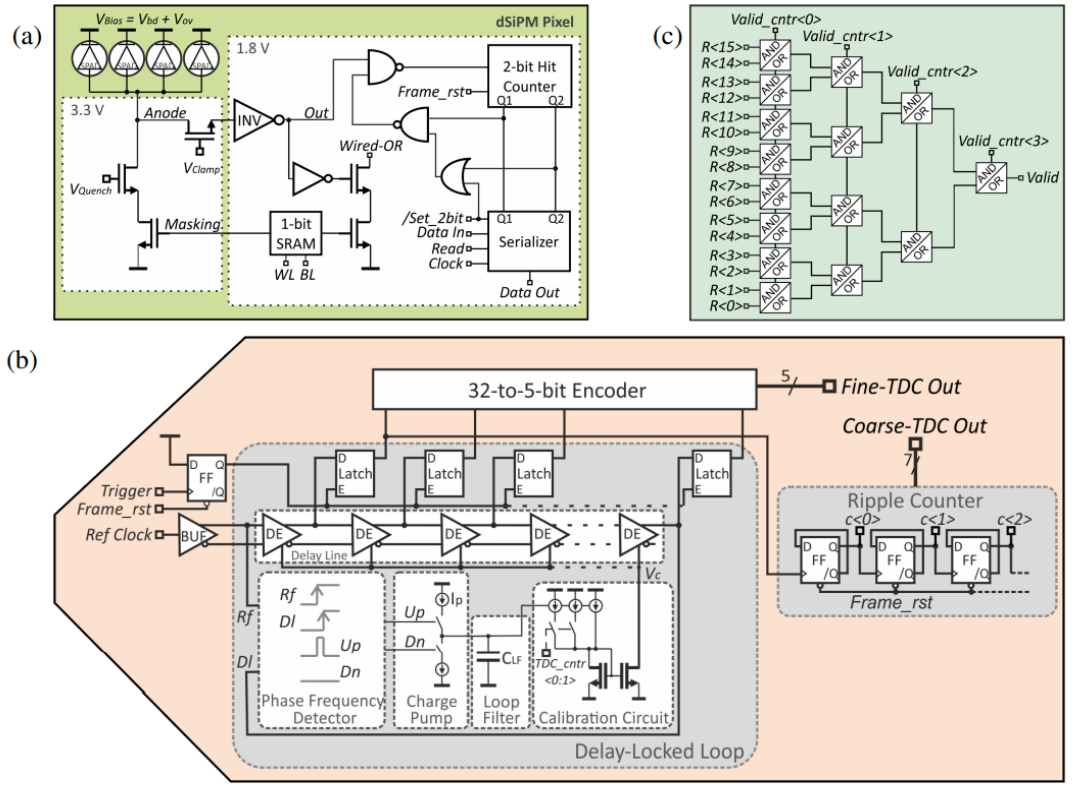


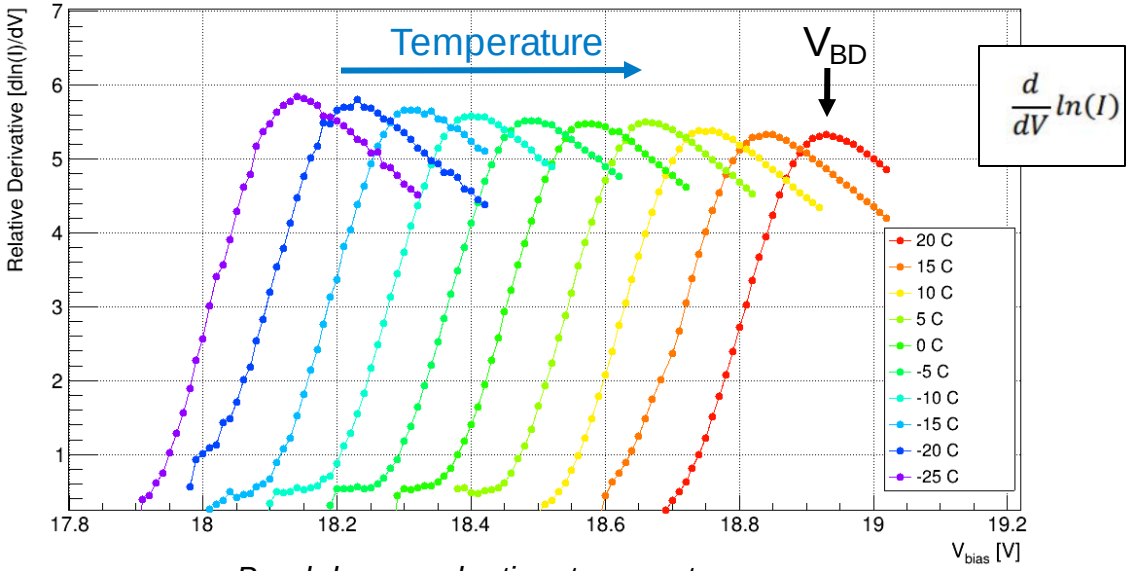
Figure 3. Simplified equivalent circuits of: (a) the dSiPM pixel, (b) the TDC, and (c) the validation logic.

From: I. Diehl et al 2024 JINST 19 P01020

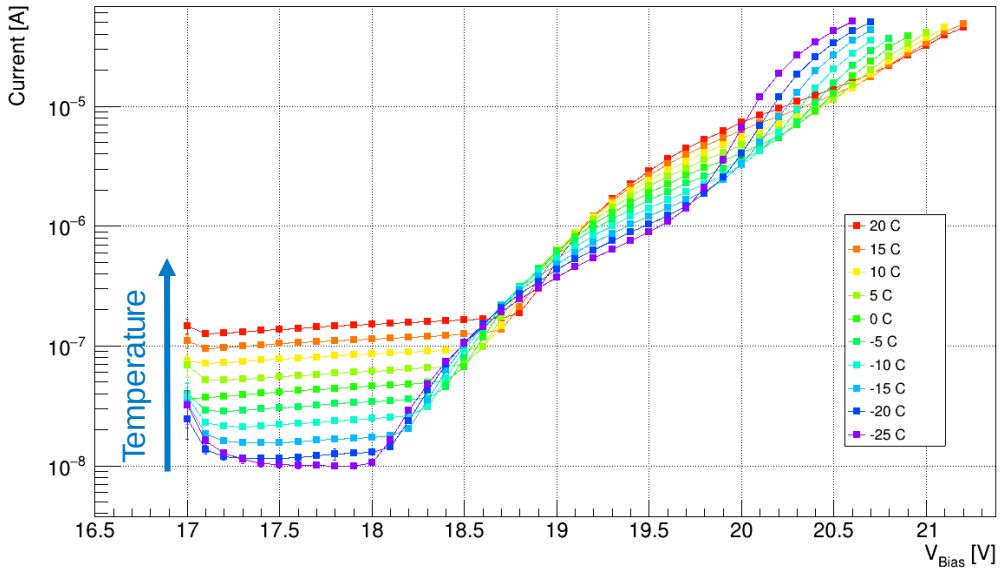
IV Curves & Dark Count Rate

Basic Chip Characterization

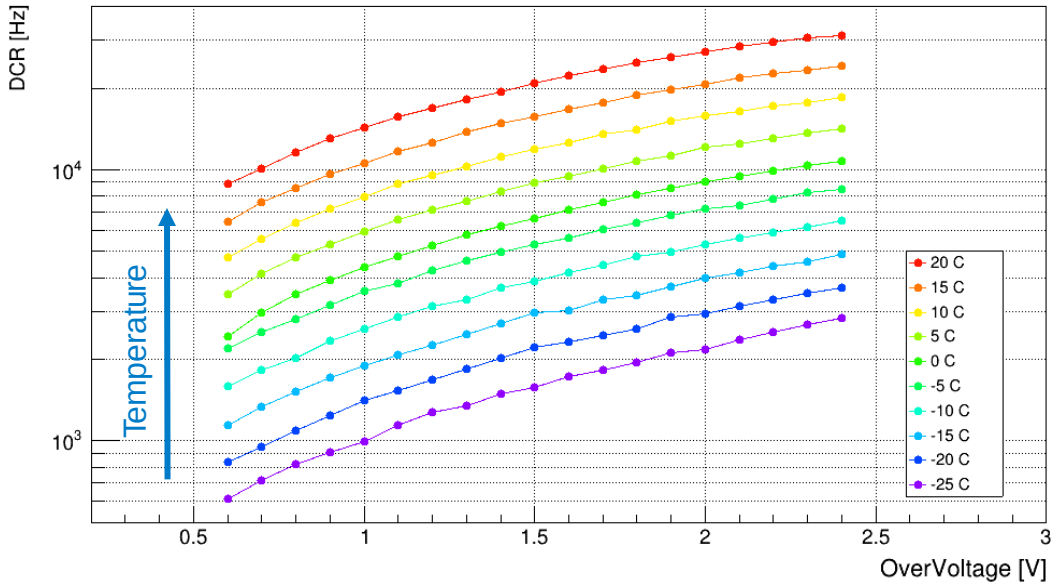
- Detailed characterization performed on several samples (Chip4 shown in figures)
- IV & Dark Count Rate studies performed with controlled **temperature** (from -25 to 20 °C) and **humidity** (~ 0 %) in a dark environment
- Measurements compatible with expectations



Breakdown evaluation, temperature scan



IV curves (full matrix), temperature scan



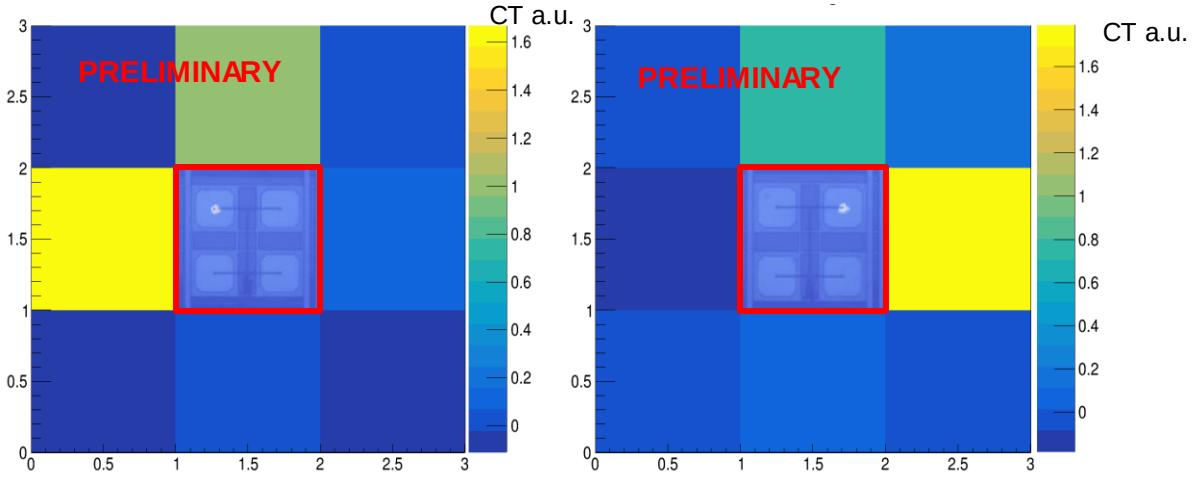
Dark Count Rate (per pixel), temperature scan

DESY dSiPM Characterisations

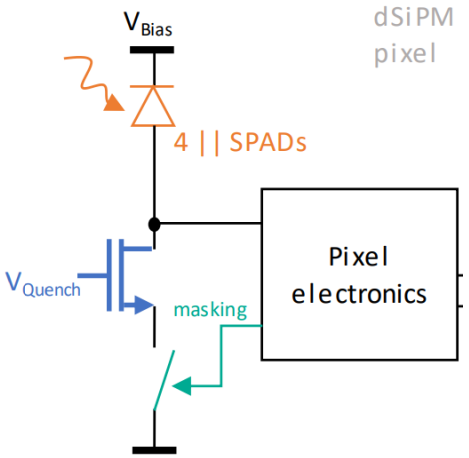
Exploring the Potential of Digital SPADs

Studies possible thanks to digital features

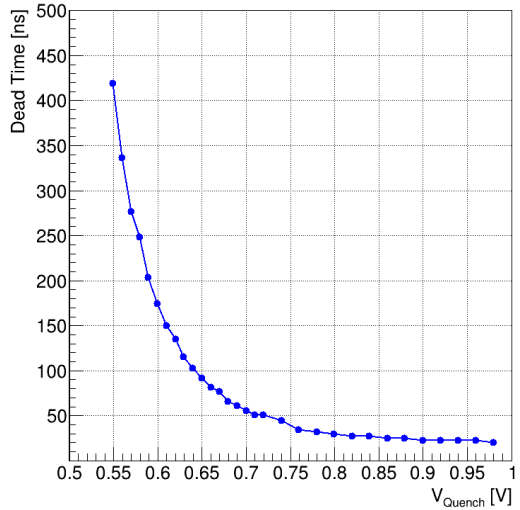
- Effect of quenching transistor tuning in senor response
- Pixel masking: effect on IV and DCR reduction
- Pixel crosstalk characterisation: studying the correlation between avalanche position and CT probability in neighbours



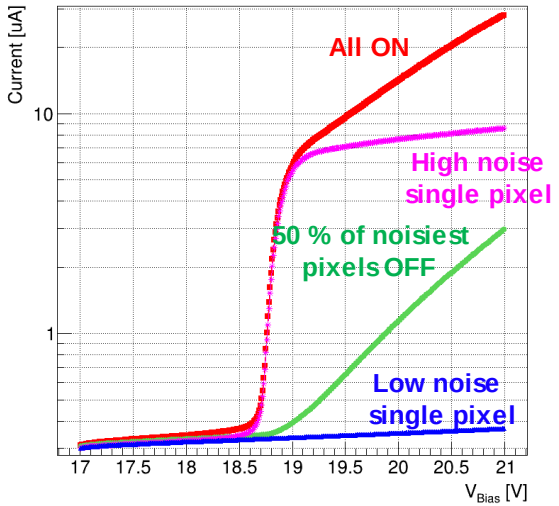
Crosstalk studies as function of avalanche position



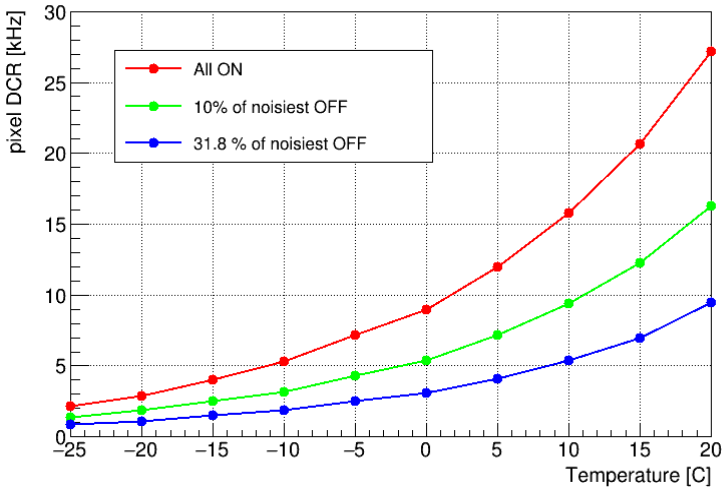
Pixel circuit



Dead time vs V_{Quench}



IVs with different masks

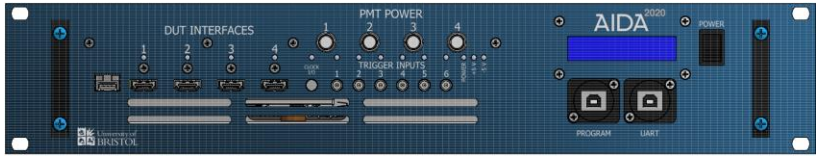


DCR with different masks (2 OverVoltage)

DAQ System in Test Beam

AIDA TLU Core

https://doi.org/10.1140/epjti/s40485-016-0033-2



https://doi.org/10.1088/1748-0221/14/09/P09019

Scintillators & PMTs

NIM Logic

Trigger IN

EUDET TELESCOPE (6 x Mimosa 26)

BUSY

Trigger ID

AIDA Trigger Logic Unit "Aida Mode"

Clock, t0

Trigger OUT

BUSY

Caribou DAQ

Clock

LVDS

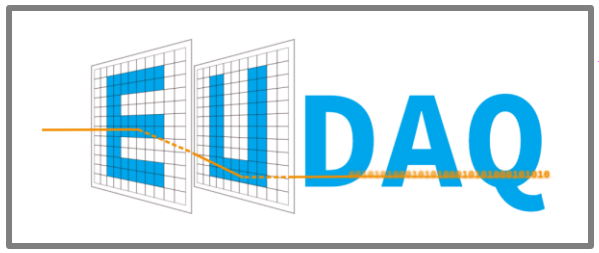
dSiPM

http://dx.doi.org/10.22323/1.370.0100

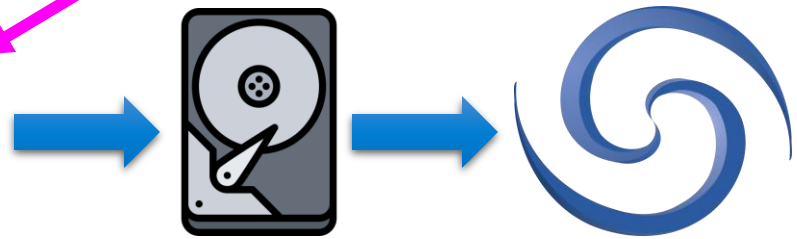
Telescope Hitmap

Event Timestamp & Trigger ID

dSiPM Hitmap & Timestamp



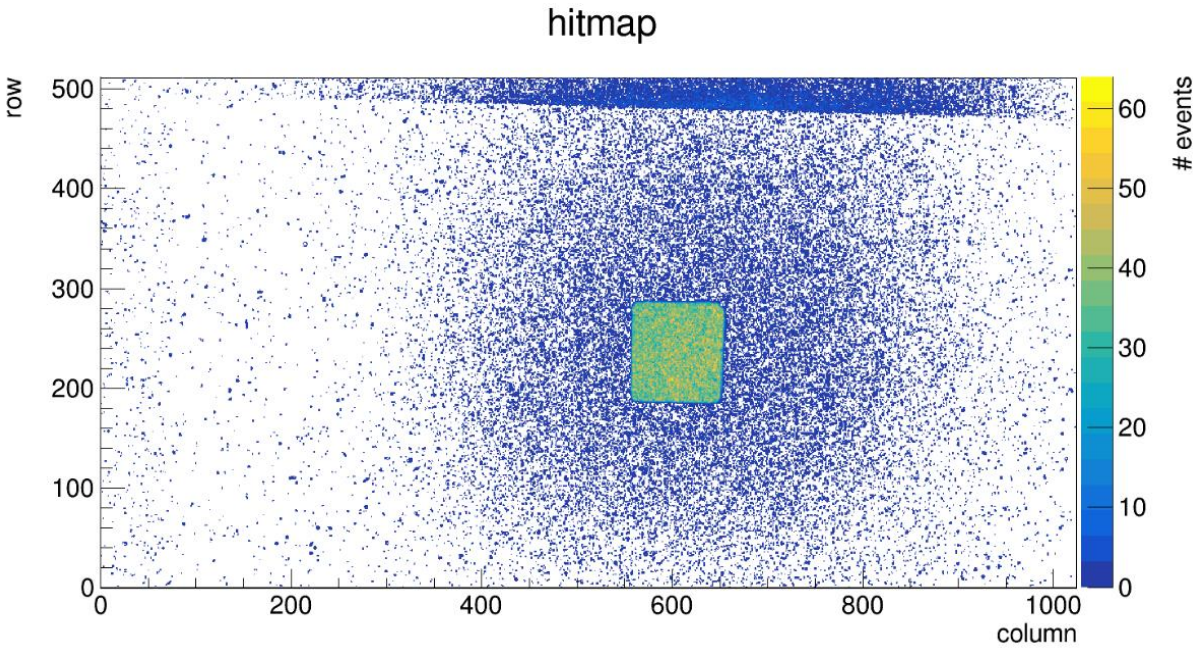
https://github.com/eudaq

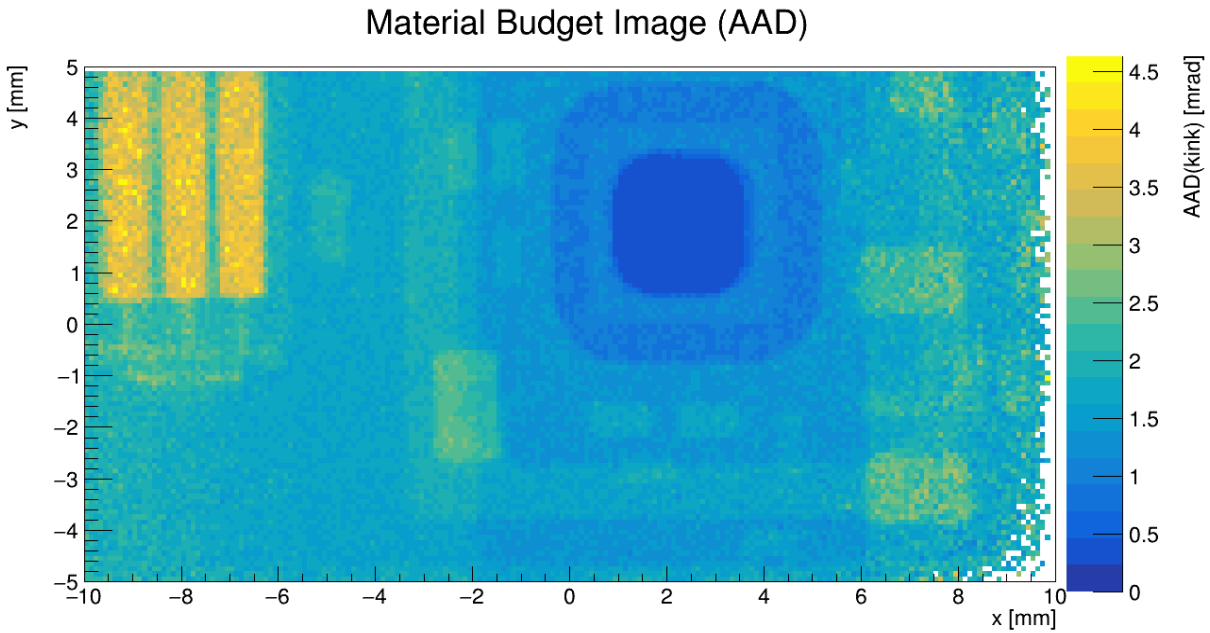


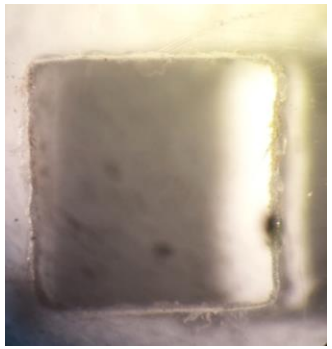
https://gitlab.cern.ch/corryvreckan/corryvreckan

DESY II Test Beam Setup

MBI for Alignment to the VETO Area

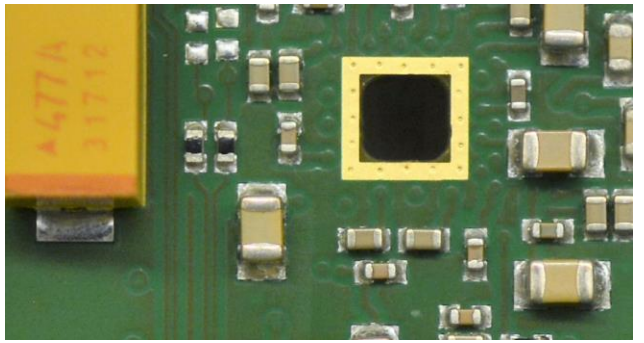






Plastic scintillator with a hole used as VETO for Trigger

- Anticoincidence with other scintillators
- Trigger only in a ROI slightly larger than DUT
- Allows to save disk space and maximize yeld

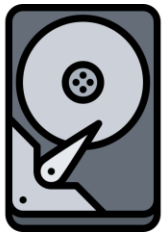


Material budget image for DUT alignment

Corryvreckan modules:
[TrackingMultiplets]
[AnalysisMaterialBudget]

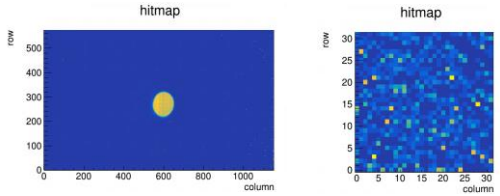
Analysis Chain

Using Corryvreckan



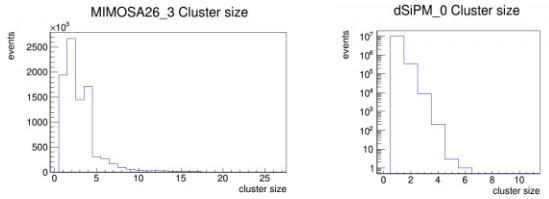
Data Decoding

Raw Telescope & dSiPM **data** are **decoded** into an accessible format



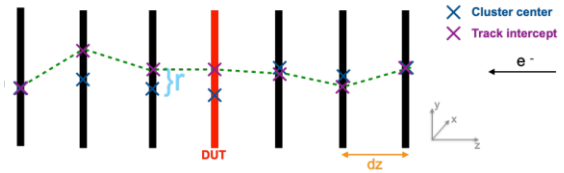
Clustering

Clusters of hits in the reference telescope and DUT are identified



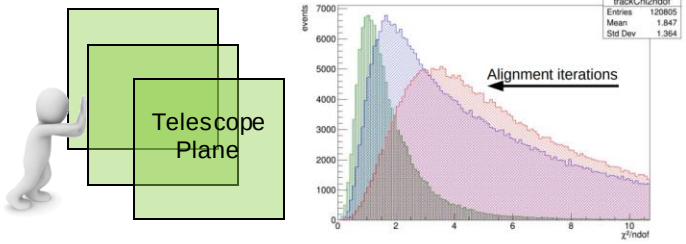
Tracking *

Tracks are reconstructed using telescope clusters + spatial & temporal cuts



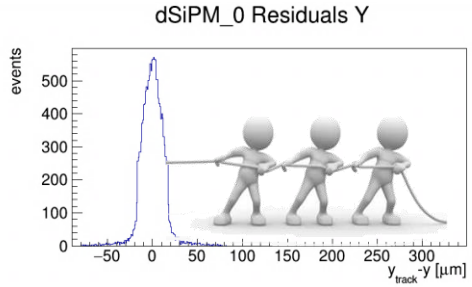
* **Telescope Alignment**

Software **translations and rotations** of the **telescope planes** are performed



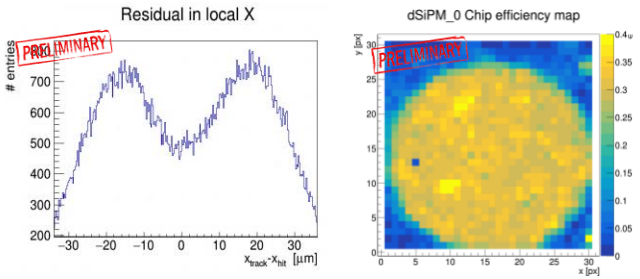
dSiPM Alignment

Translations and rotations of the **DUT** are performed to minimize unbiased residuals



DUT Association & analysis

DUT clusters are associated with tracks & its **MIP detection response** is analyzed

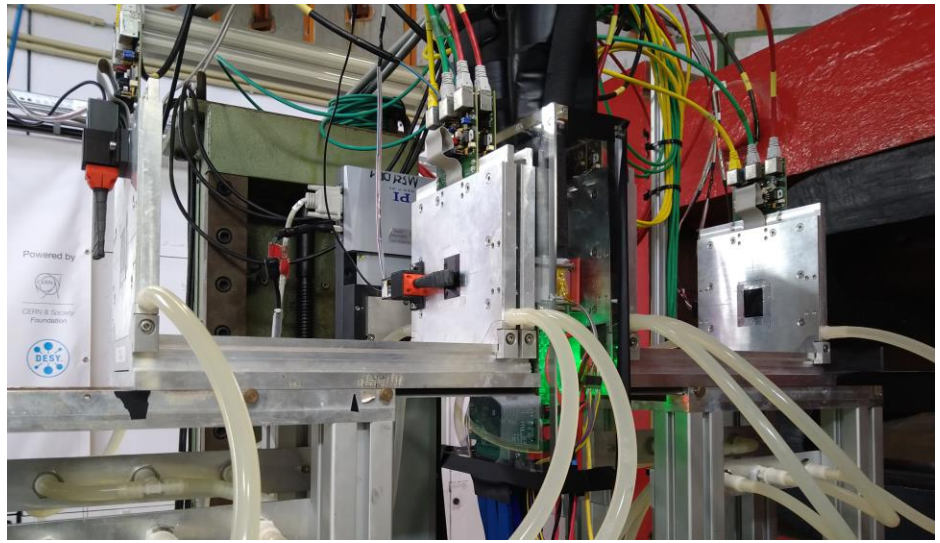


TestBeam data reconstruction

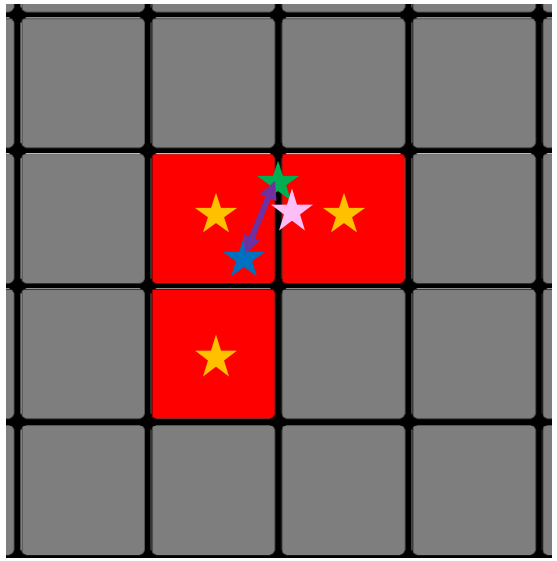
Using Corryvreckan Framework

- Corryvreckan use hit ⯎ (pixels above threshold) and Clusters □ (groups of adjacent hits) to reconstruct particle trajectories.

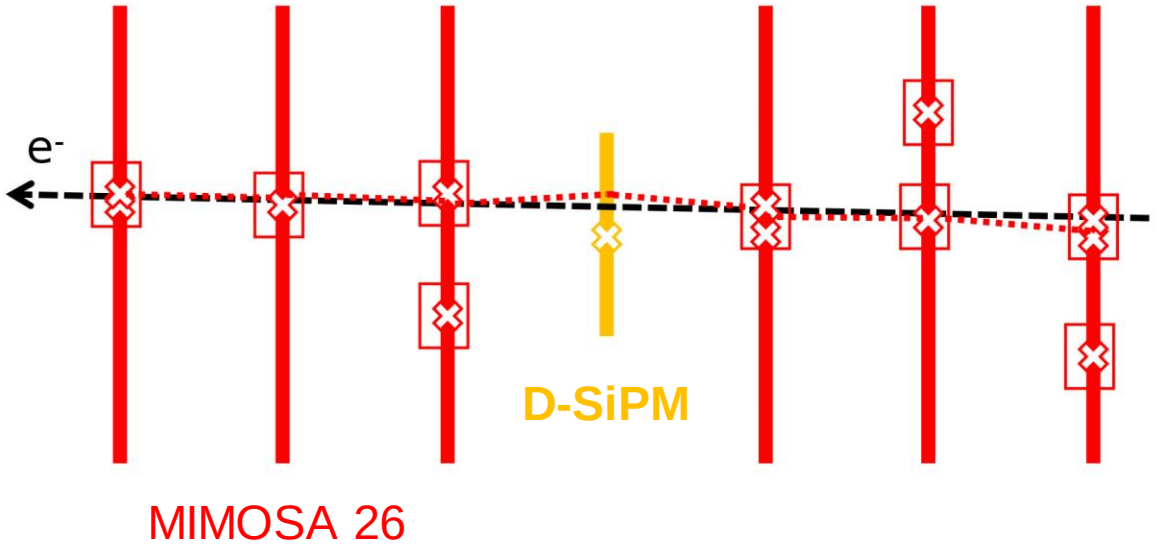
- DUT response is then investigated on associated events



SiPM-IC tesbeam setup



- Real Track
- Hit
- Cluster
- Cluster center
- Reconstructed Track
- Residuals



http://cern.ch/corryvreckan

dSiPM + LYSO Sr-90 Data

Random Selection (100, 200, 500 from the top)

Overvoltage ~1.5

Temperature on Chip ~25C