MIP detection with digital SiPMs

Exploring the Potential of CMOS SPAD Arrays

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Bologna Meeting, 03 Oct 2024

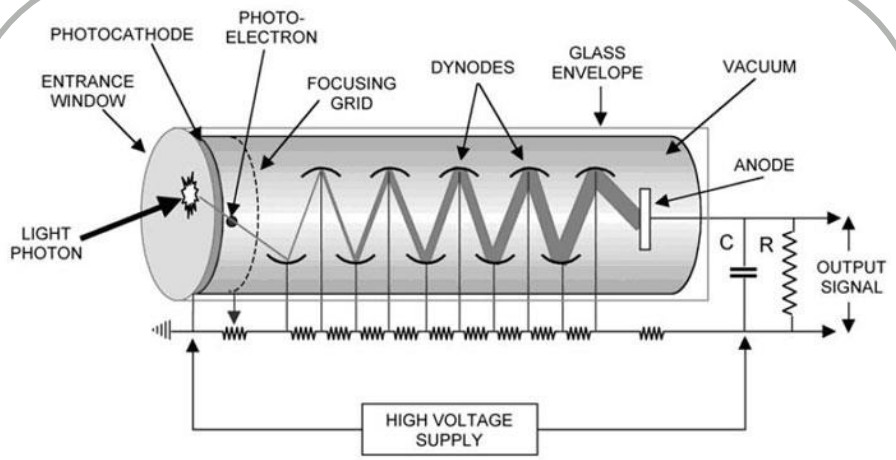
HELMHOLTZ

UNIVERSITÄT BONN

DESY.

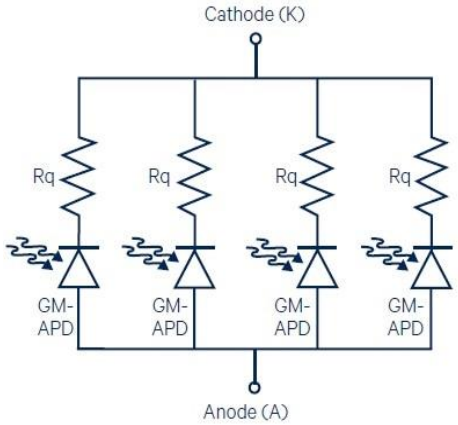
Silicon Photomultipliers

State of the Art Solid State Photodetectors

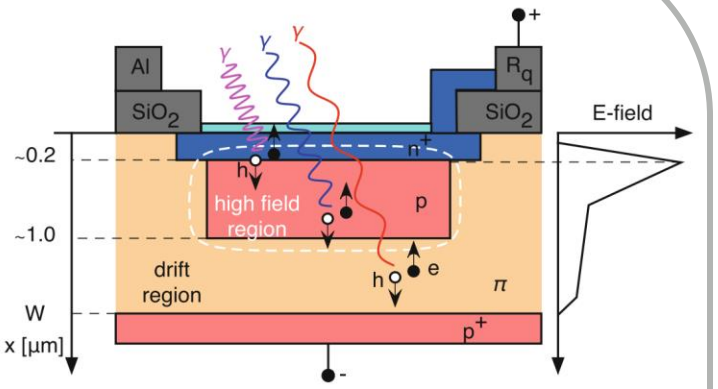


PMT working principle

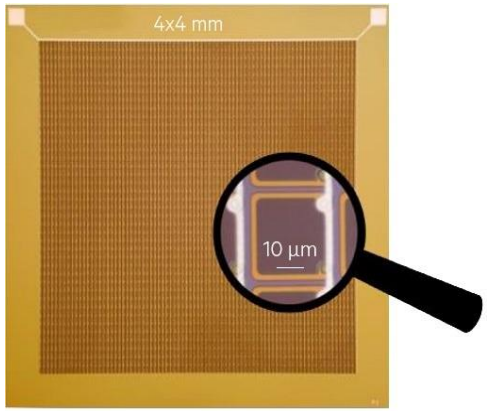
PMT Example



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
- **Can detect MIPs**

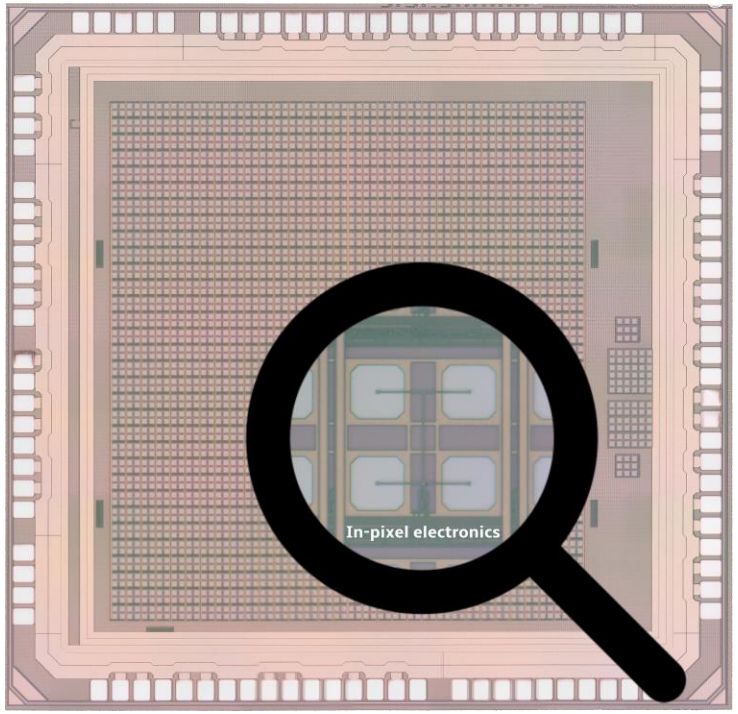
SiPM-IC Using Commercial CMOS Processes

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

DESY dSiPM Prototype

ASIC in LF 150 nm CMOS

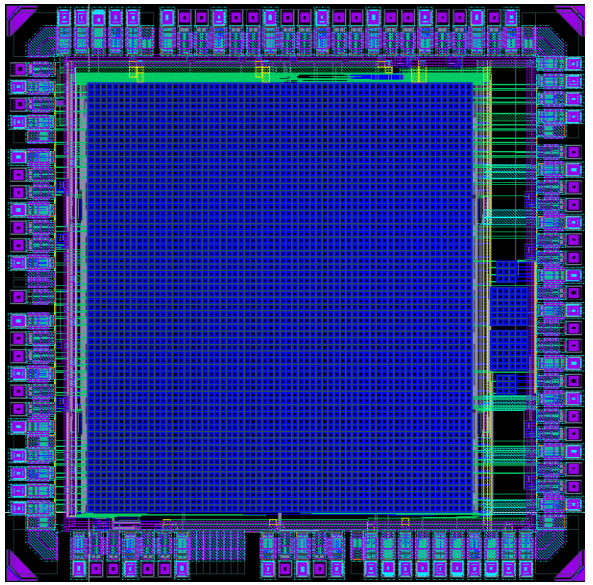
Layout

- 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

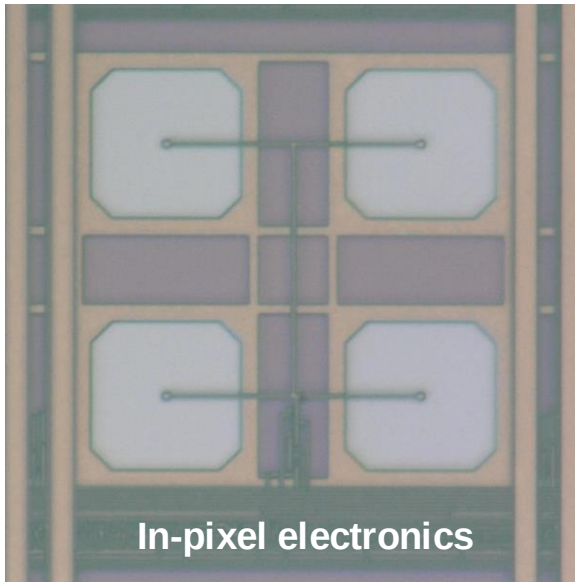
Some Features

- 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
- Caribou DAQ system is used for biasing & readout

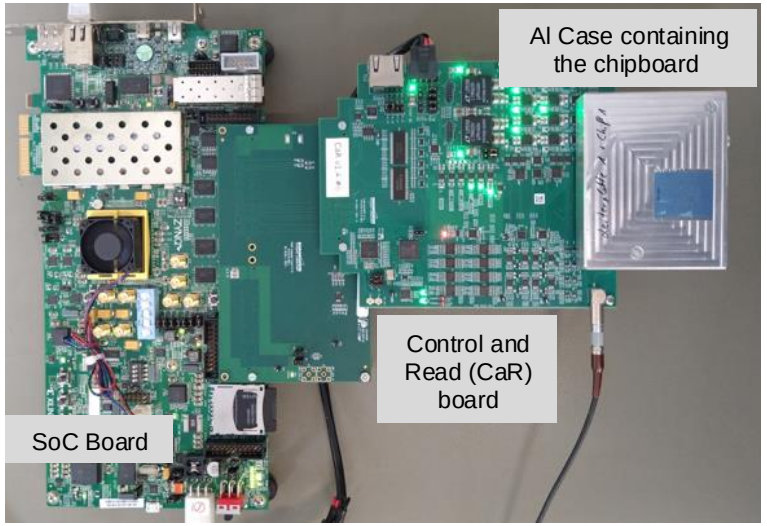
For details: I. Diehl et al 2024 JINST 19 P01020



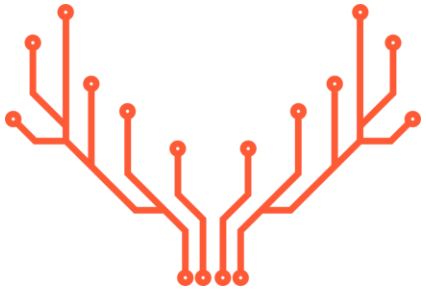
ASIC design of the DESY dSiPM



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



DAQ System

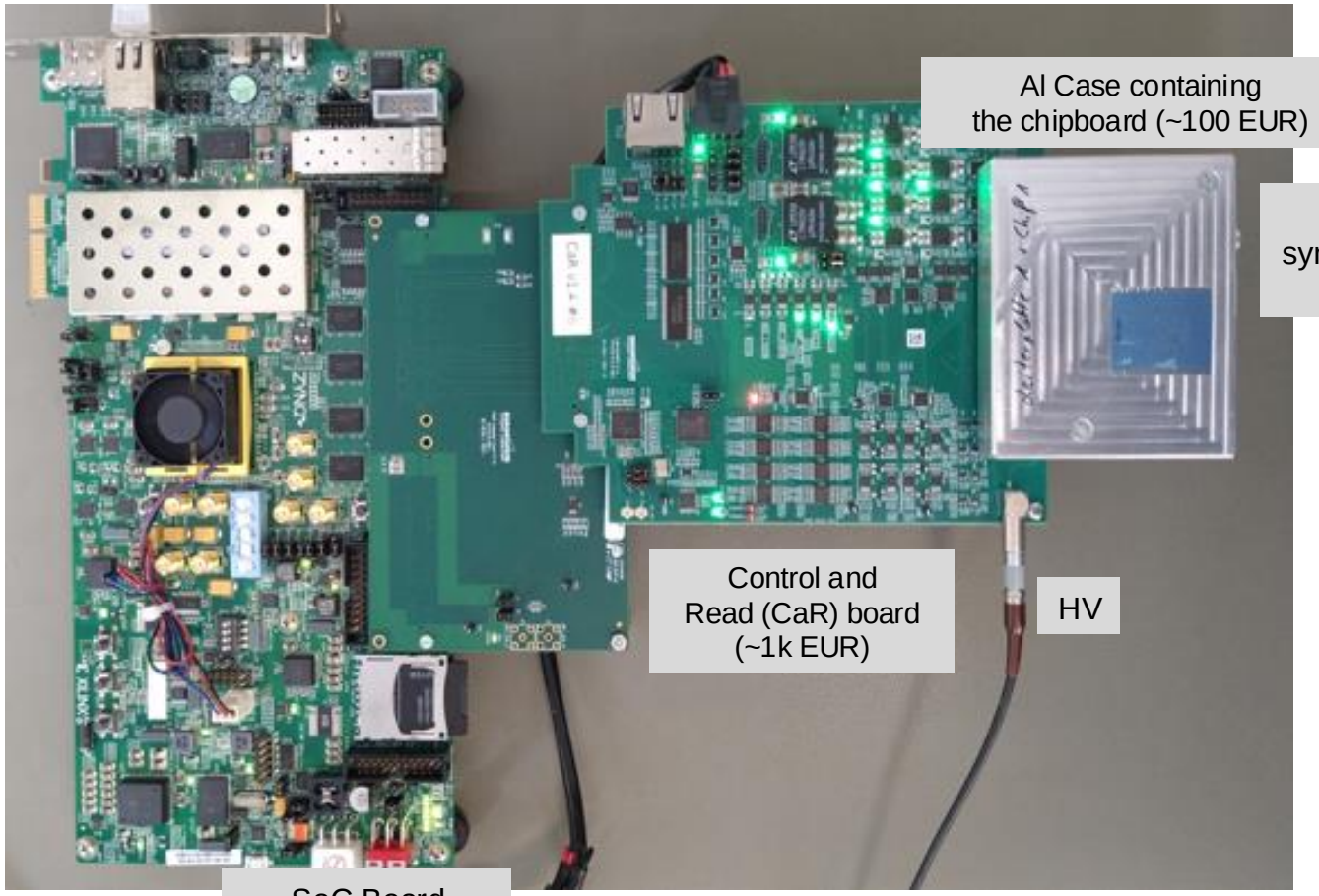


Caribou DAQ system
Fast & low-cost implementation of solid-state detector prototypes
http://dx.doi.org/10.22323/1.370.0100
https://gitlab.cern.ch/Caribou/

DESY dSiPM Prototype

Extremely Easy To Operate,

- ssh into the SoC board (linux system)
- Run the control software
- Provide a txt configuration file and a mask file
- Set trigger (Self-external-Laser)
- Bias the chip (external HV)
- Get hit-data in txt or binary file



Caribou DAQ system

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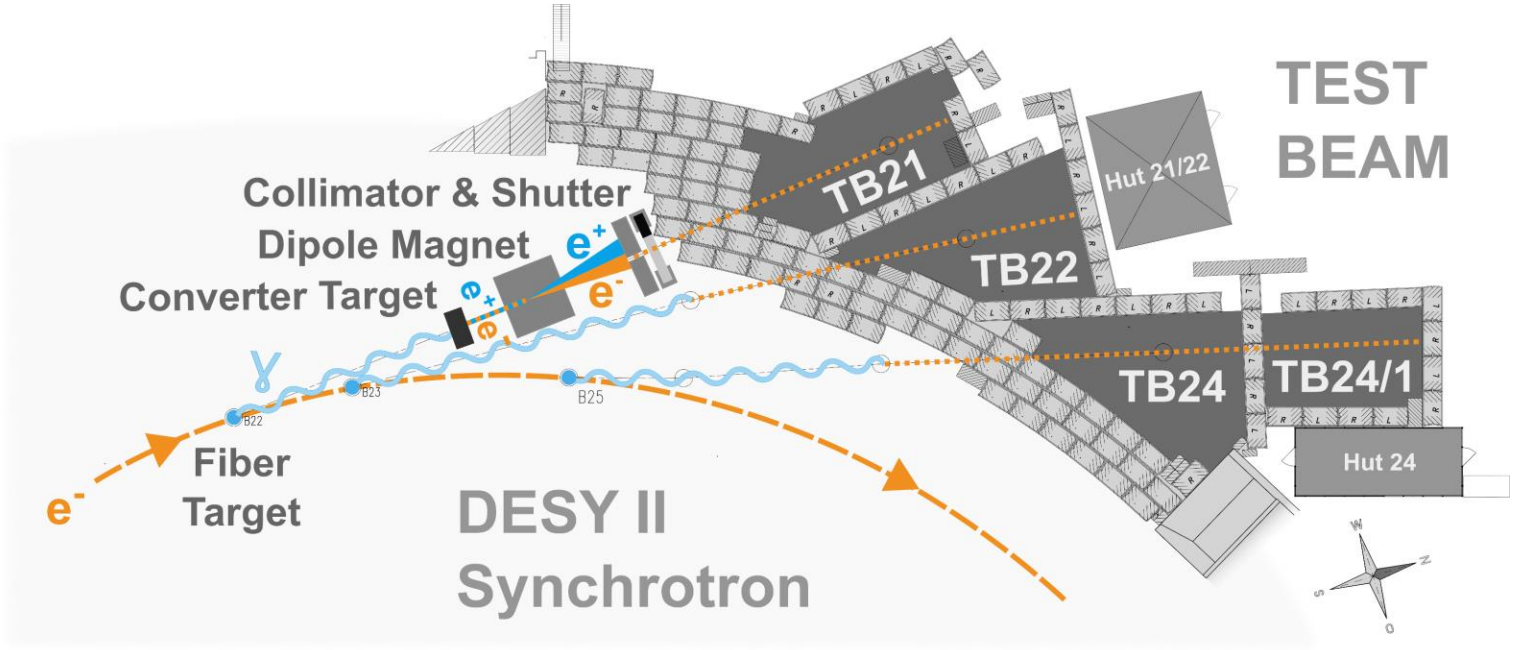
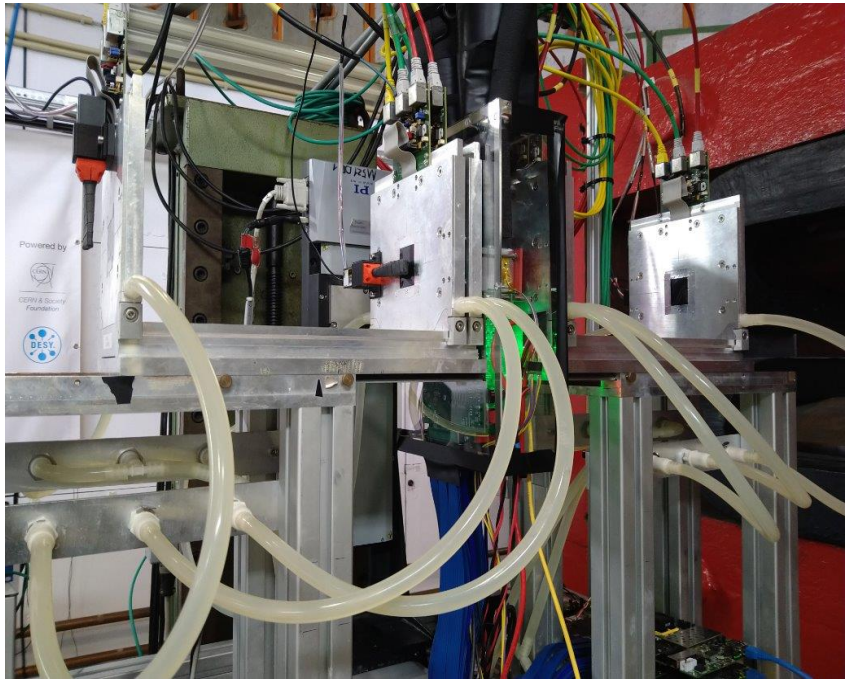
DESY dSiPM Test Beam

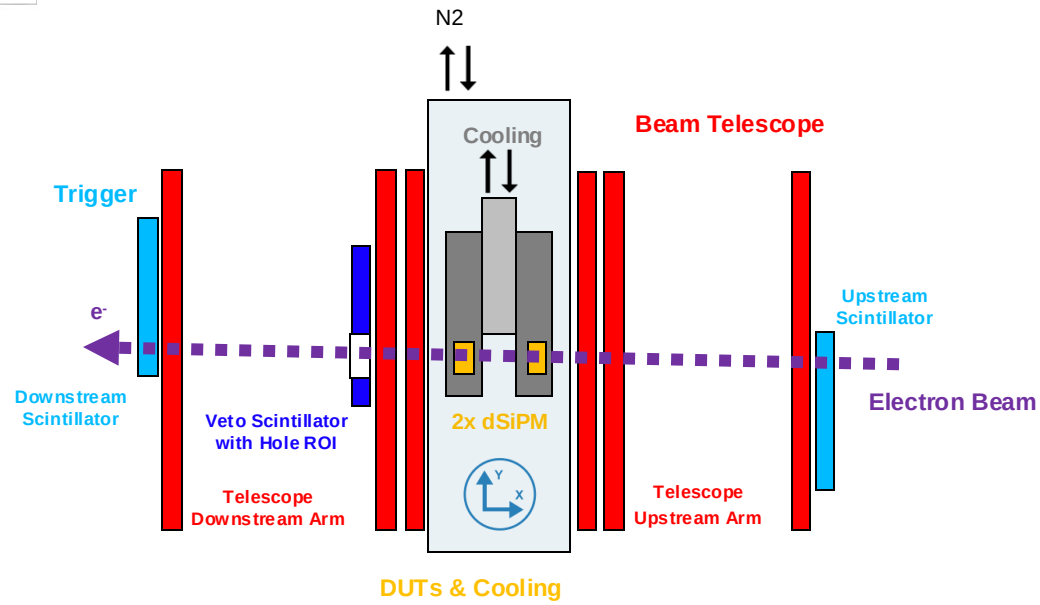
Device Treated as a Particle Detector





https://particle-physics.desy.de/test_beams_at_desy/

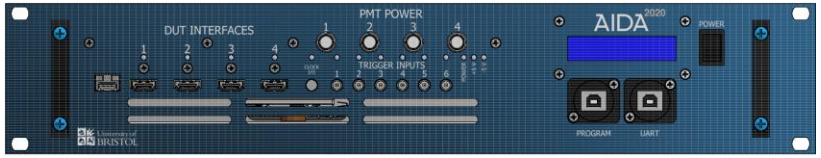
- Electron/positron beam 1-6 GeV
- High rate, very reliable and continuous beam (no spills)
- Planned to be in operation till 2029 (at least)
- During CERN shutdown (LS3) it will be the main TB facility in Europe
- Beam Telescope available in all beam areas with local support to users



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

TELESCOPE
6 x high granularity pixel reference detectors

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

Event Timestamp & Trigger ID

dSiPM Hitmap & Timestamp

Telescope Hitmap

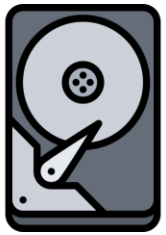
EUDAQ

https://github.com/eudaq

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

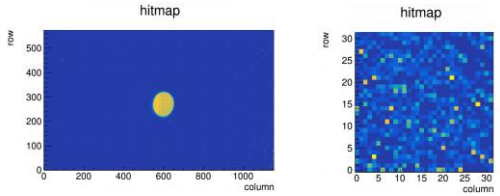
Analysis Chain

Using Corryvreckan



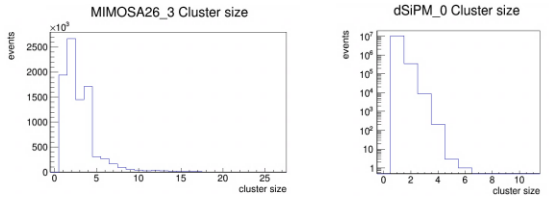
Data Decoding

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



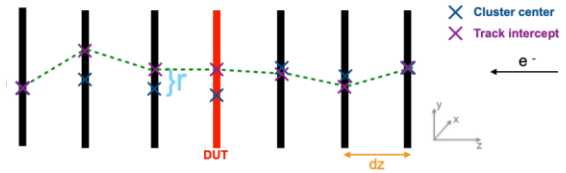
Clustering

Clusters of hits in the reference telescope and DUT are identified



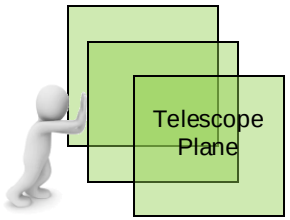
Tracking *

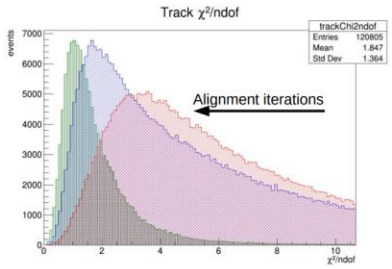
Tracks are reconstructed using telescope clusters + spatial & temporal cuts



* **Telescope Alignment**

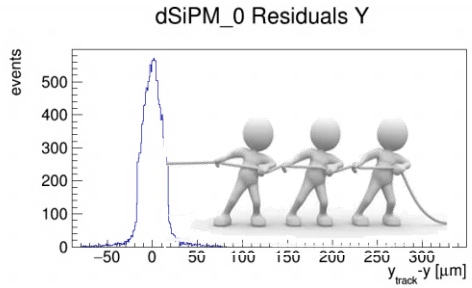
Software **translations and rotations** of the **telescope planes** are performed





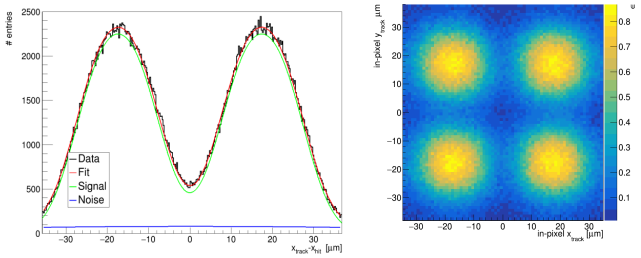
dSiPM Alignment

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



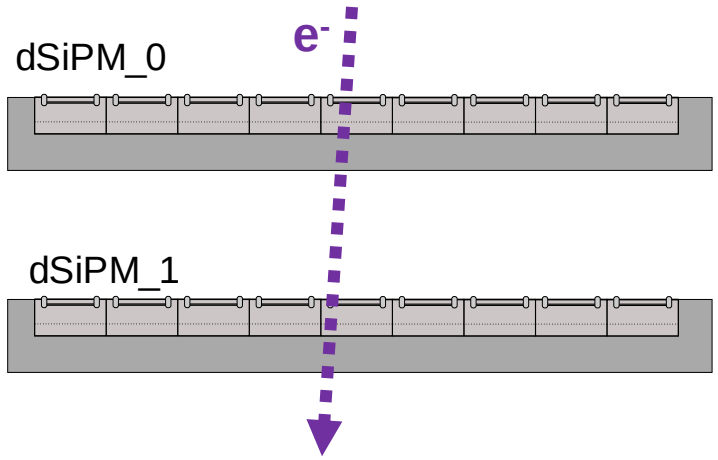
DUT Association & analysis

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



DESY dSiPM 4D-Tracking

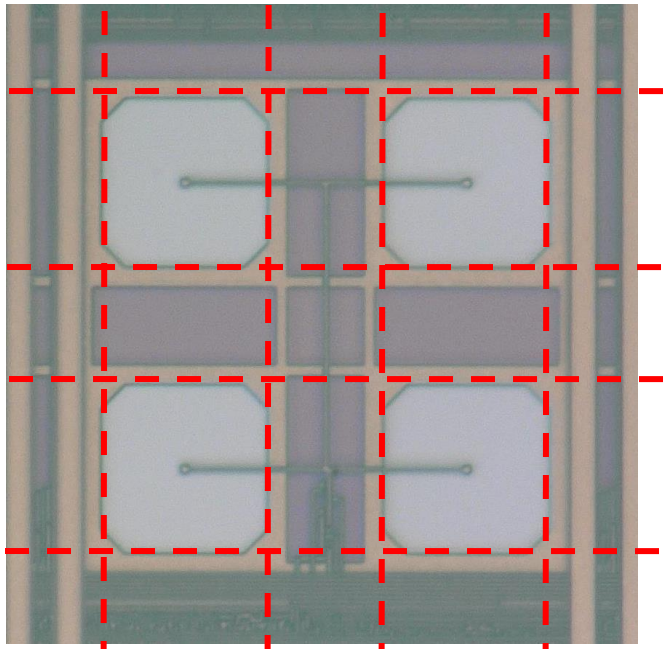
Direct MIP Detection (Only Silicon)



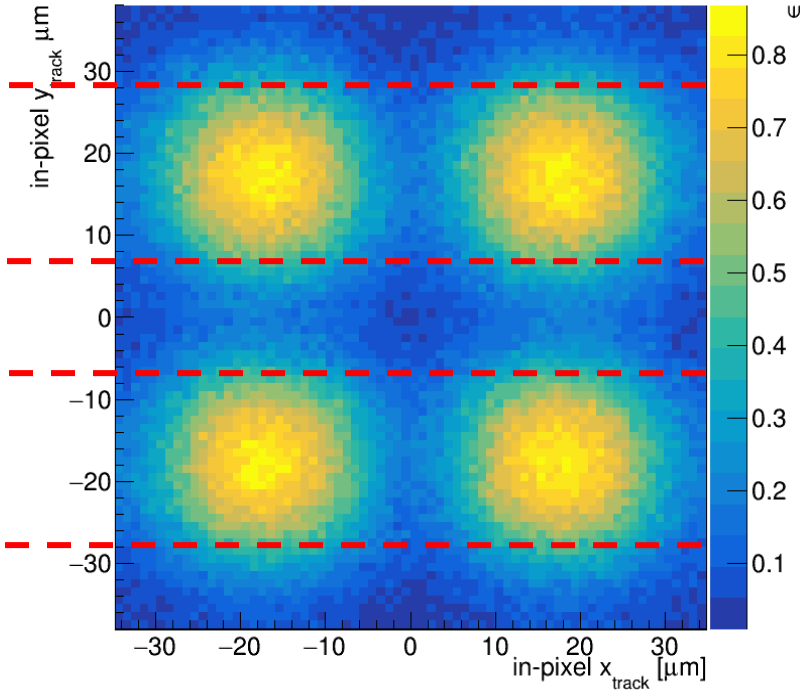
DESY dSiPM Performances

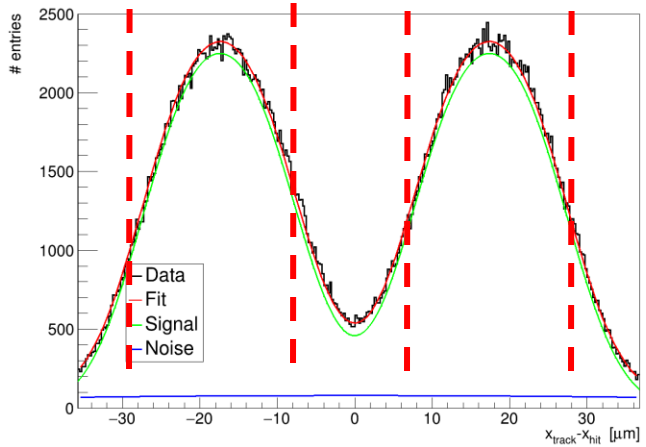
Spatial Resolution	~ 20 µm
Efficiency in MIP detection	~ 33 %
Noise Rate	O(MHz)
Time Resolution	~ 50 ps

In-Pixel Efficiency

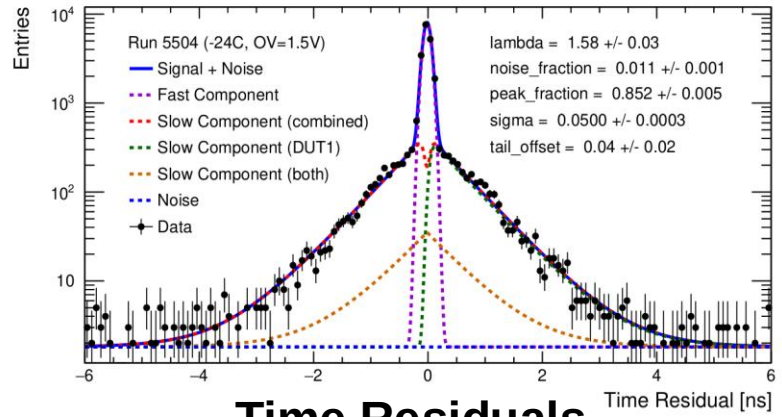


In-Pixel Efficiency





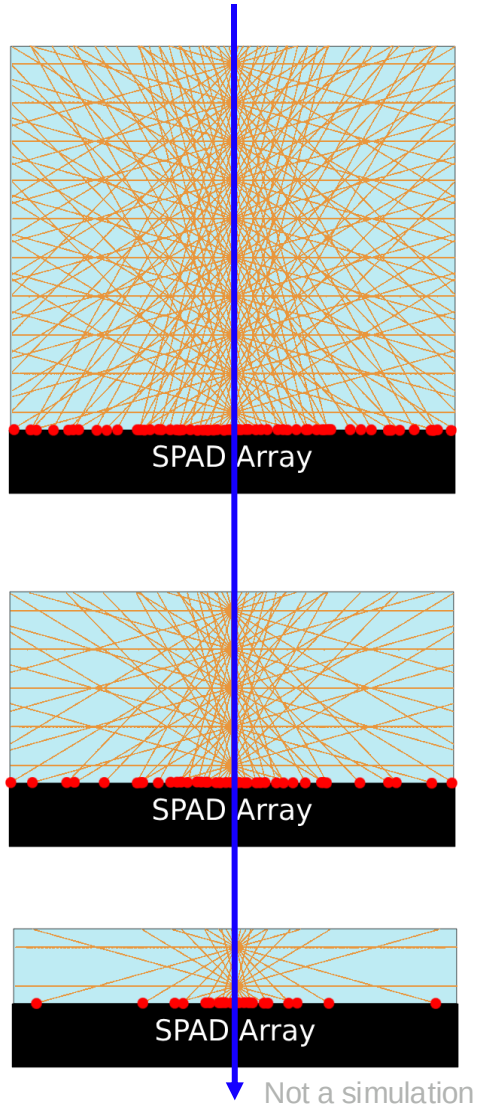
Spatial Residuals

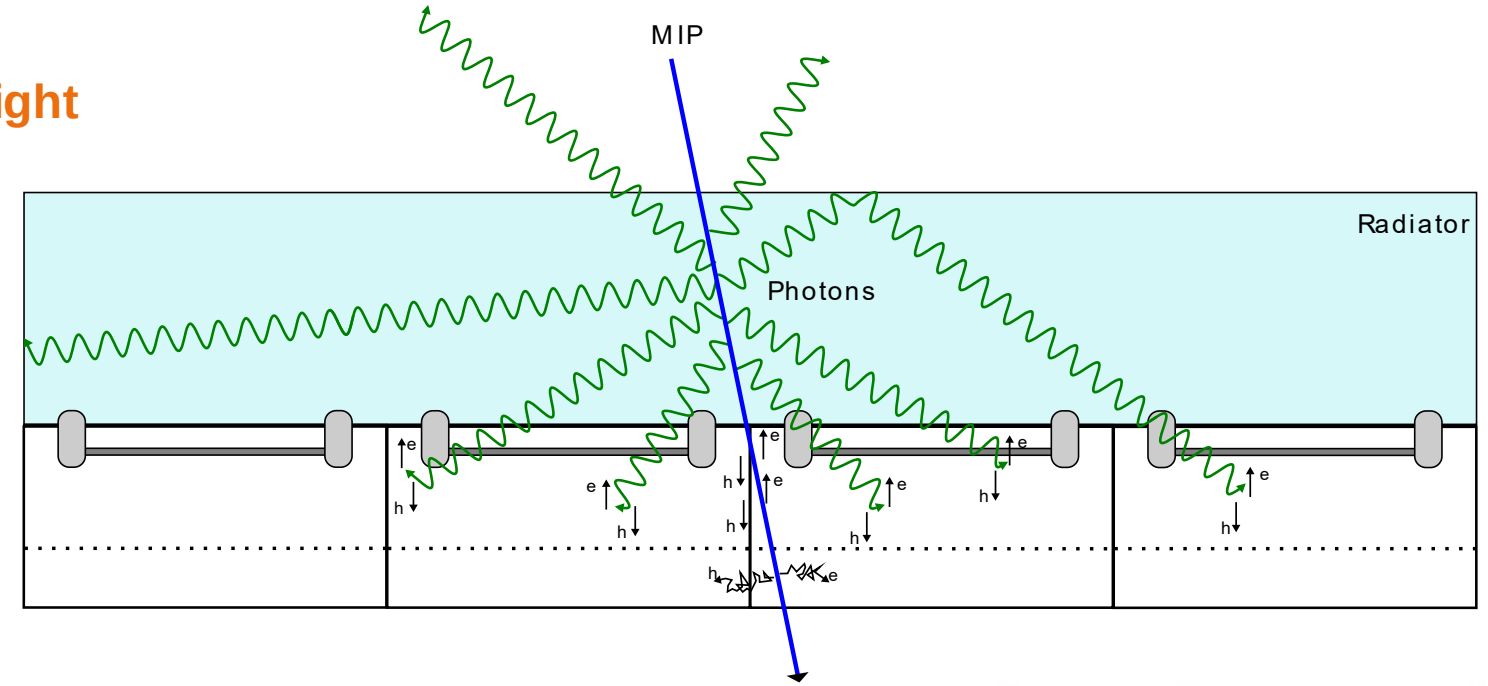


Time Residuals

Thin Radiator Concept

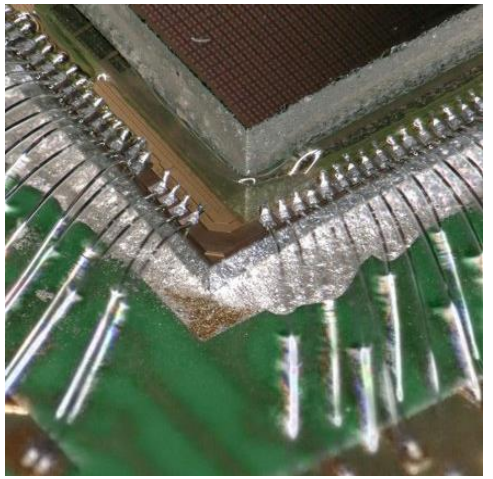
Detecting Cherenkov & Scintillation Light



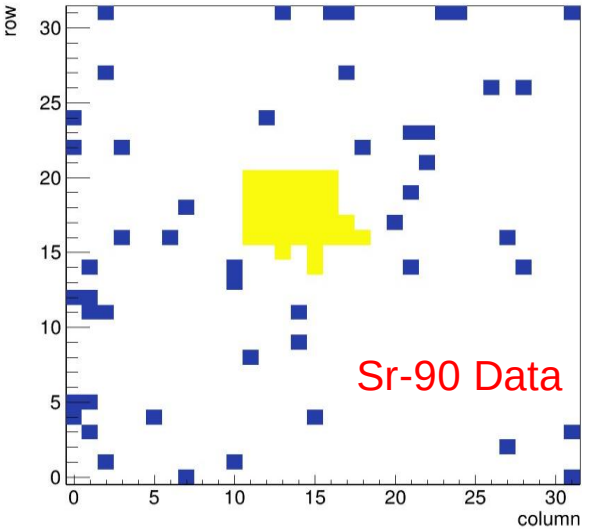


DESY dSiPM + thin LYSO

- 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 samples assembled with 100, 200 & 500 µm thick LYSO



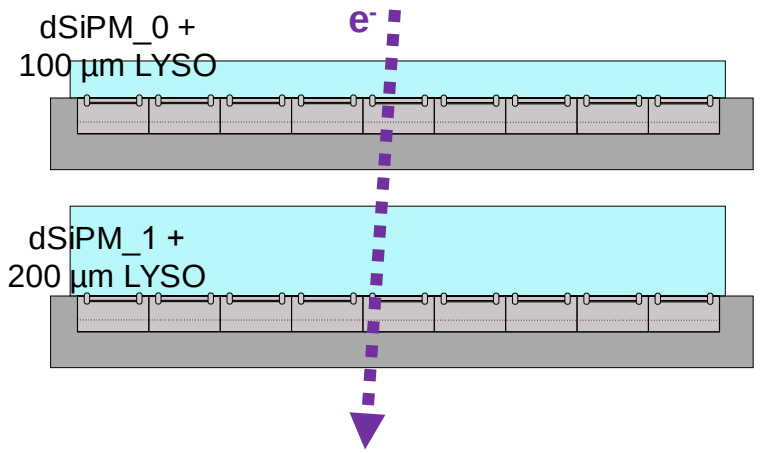
Thin LYSO glued on DESY dSiPM



dSiPM + 200µm LYSO MIP hit map

DESY dSiPM + Thin LYSO

Using Radiators to Enhance Efficiency

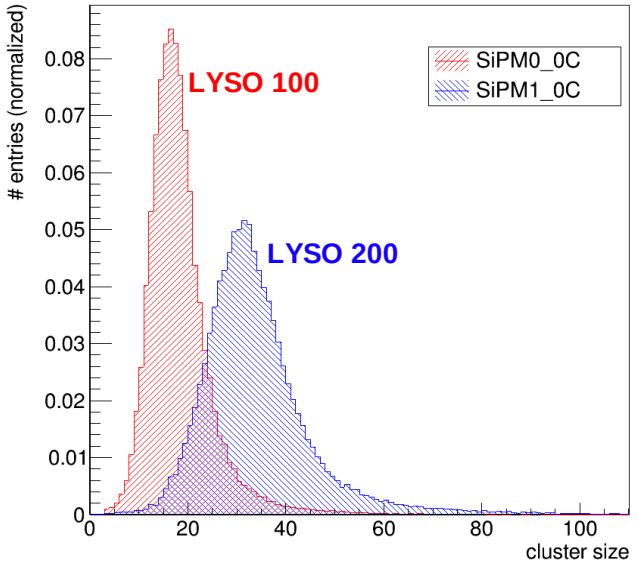


DESY dSiPM + LYSO Performances

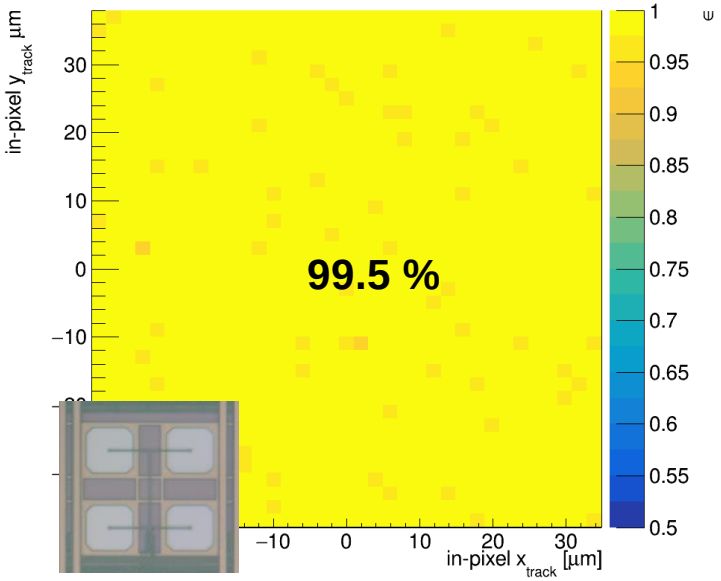
Spatial Resolution	~ 35 µm
Efficiency in MIP detection	> 99 %
Noise Rate	O(Hz)*
Time Resolution	< 1 ns**

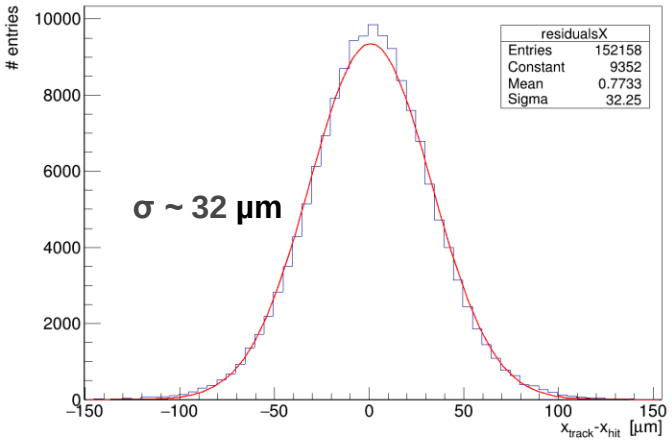
* While cutting on cluster-size
** Currently under investigation

Events Cluster Size

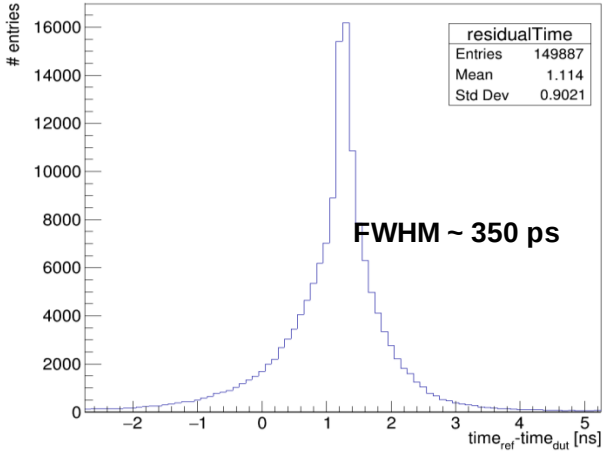


In-Pixel Efficiency





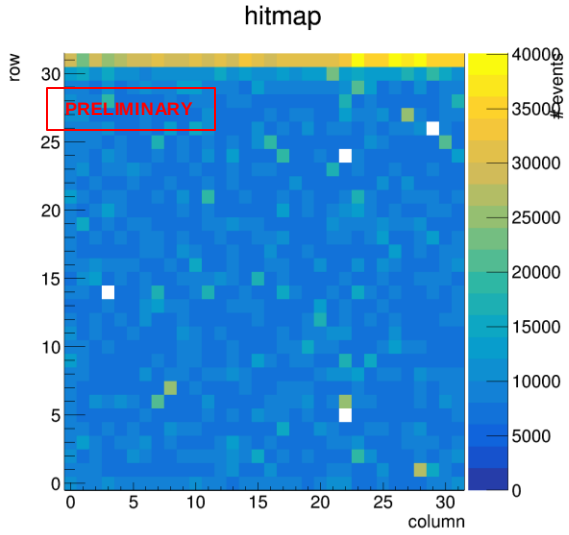
Spatial Residuals

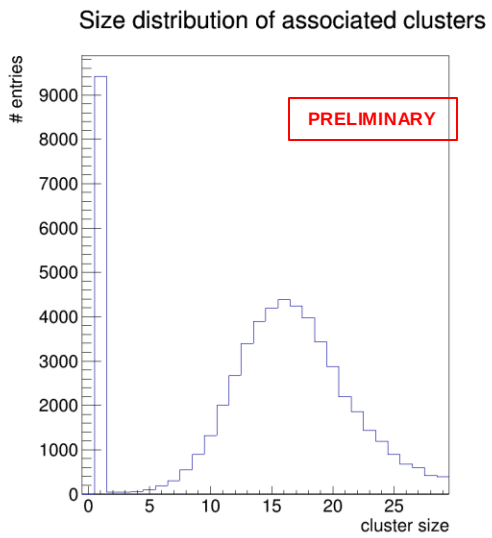


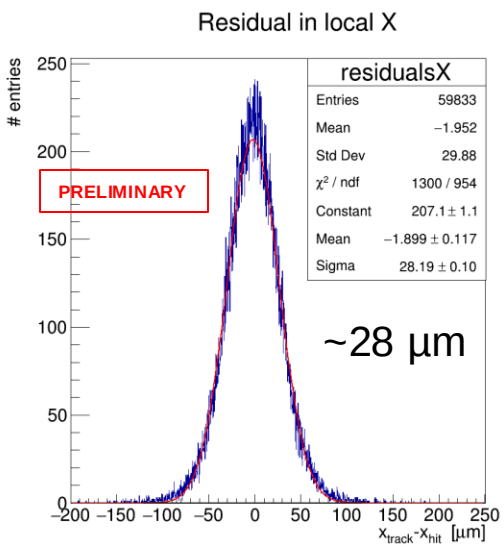
Time Residuals

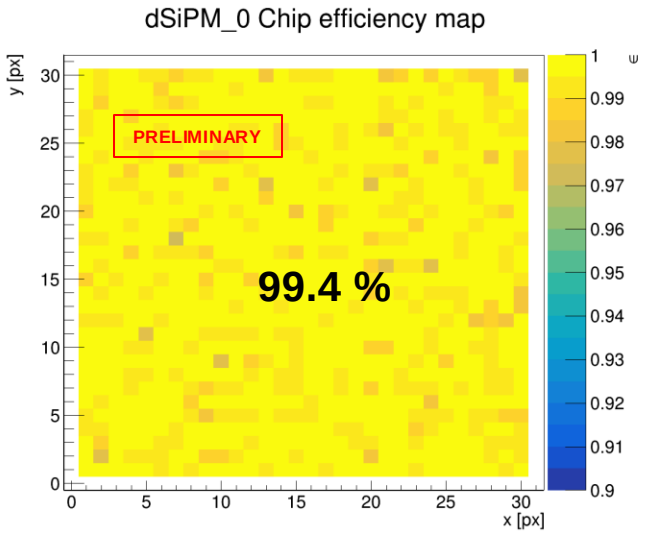
Let's Play Chess

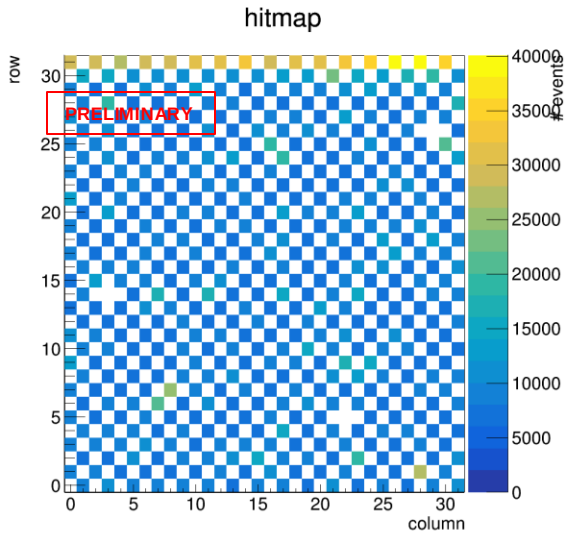
Similar Performances Whith Half Active Area!

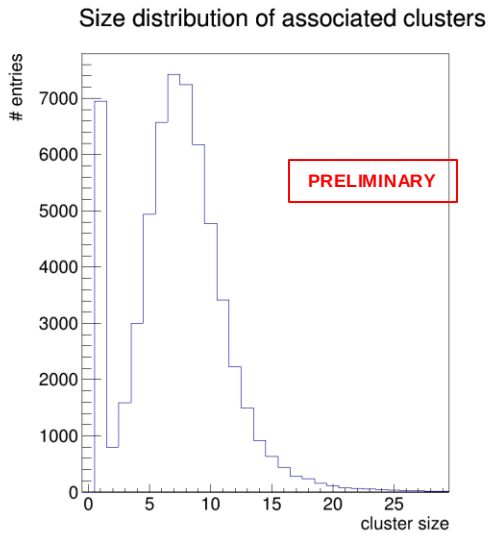


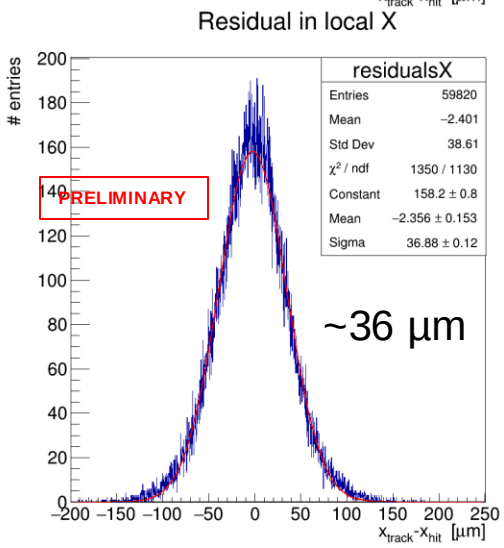


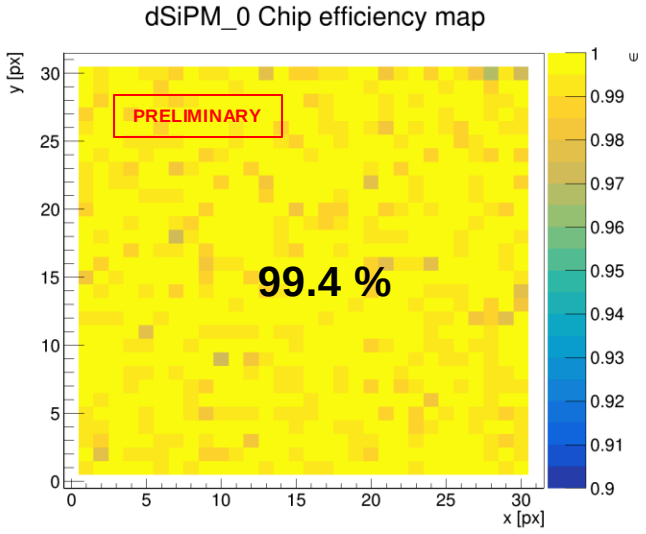












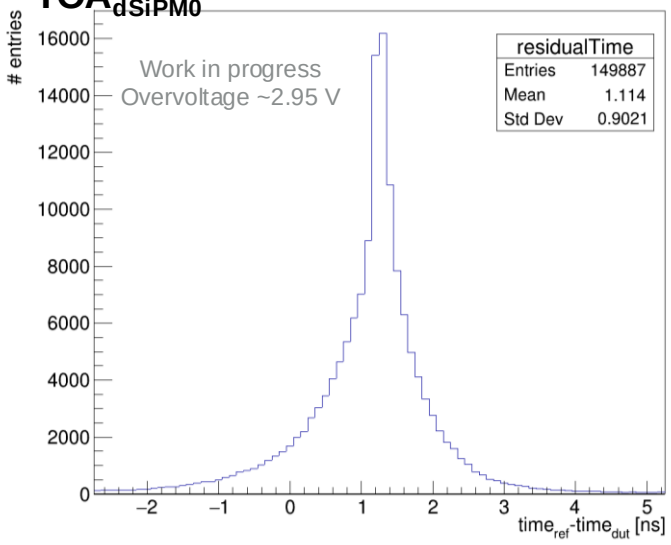
Run 1826, 2 OV chip10-100um LYSO

DESY dSiPM + Thin LYSO

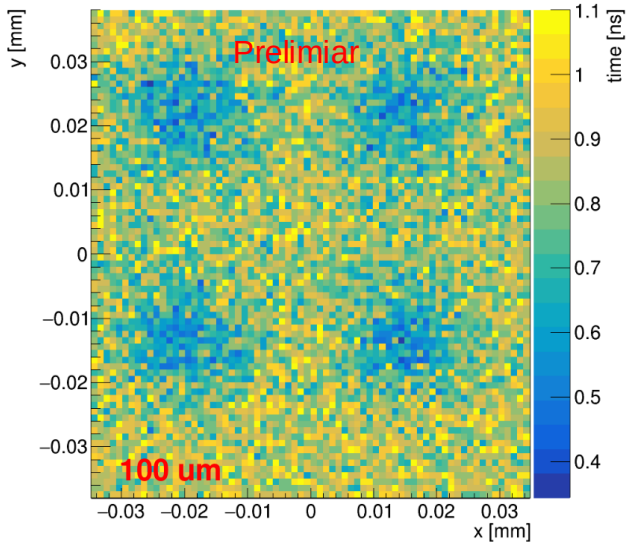
Timing Performances

- The timing is worse when the MIP does not hit the SPAD
- Tail effect attributable to the LYSO's scintillation properties and low fill-factor
- Faster radiators or designs/technology with higer sensor fill-factor will improve timing

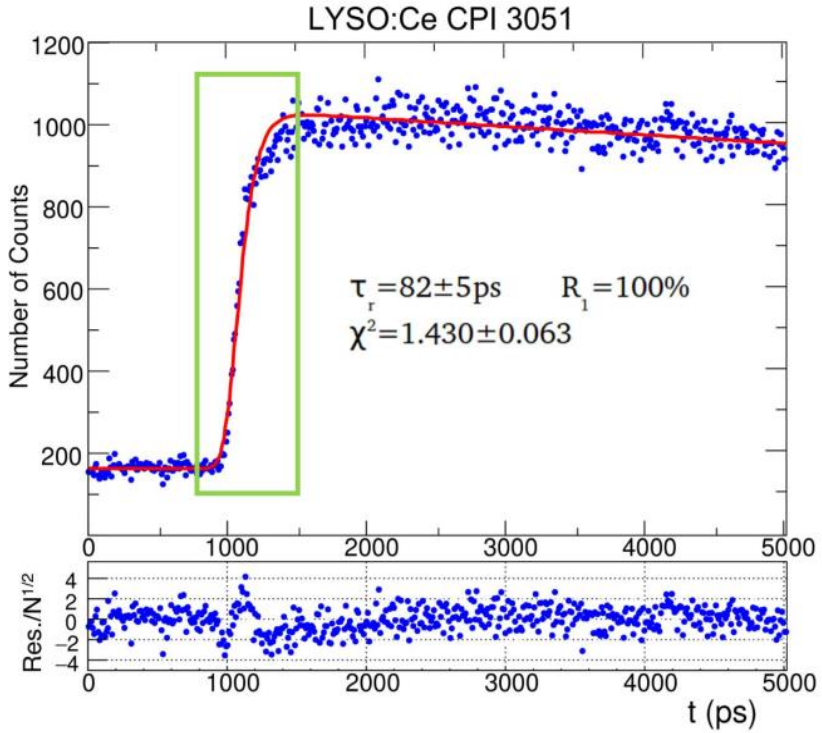
Time residuals: TOA_{dSiPM1} - TOA_{dSiPM0}



In-pixel map of time residuals Std Dev



Example of LYSO(Ce) scintillation



LYSO Timestamp: Fast if we catch one prompt ph

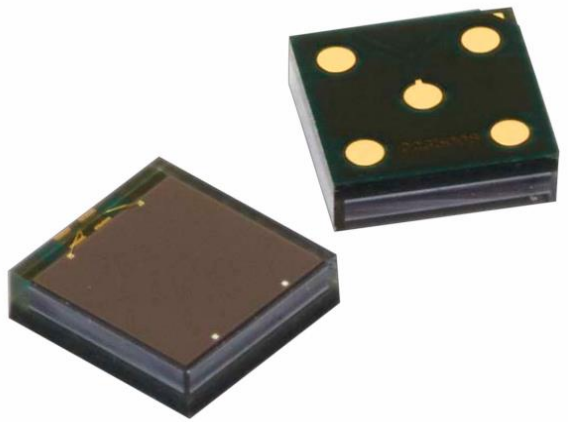
From
https://www.sciencedirect.com/science/article/pii/S0168900218302286

Not the LYSO used in the presented studies!

Analog SiPM + Thin LYSO

Confirm that Fill-Factor and Scintillator Properties Affect Timing

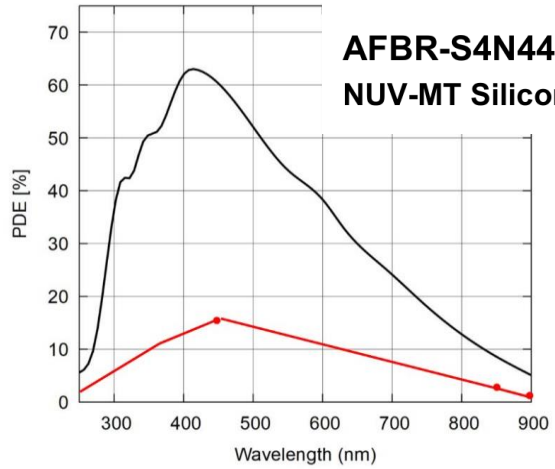
- Thin LYSOs coupled to a commercial analog SiPM
- Investigation of the effect of higher fill-factor
- With low threshold exelent timing measured

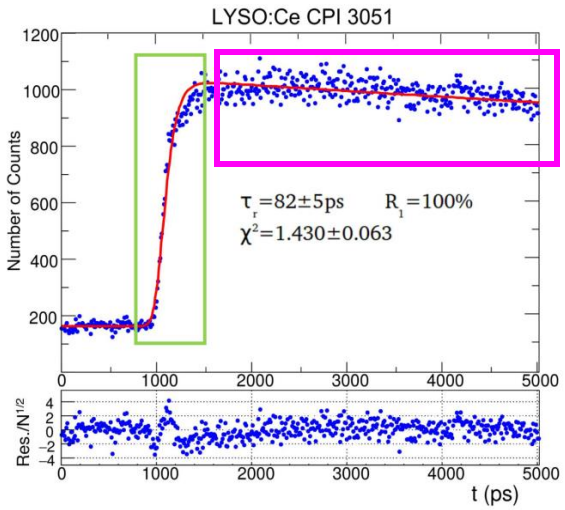


BROADCOM®

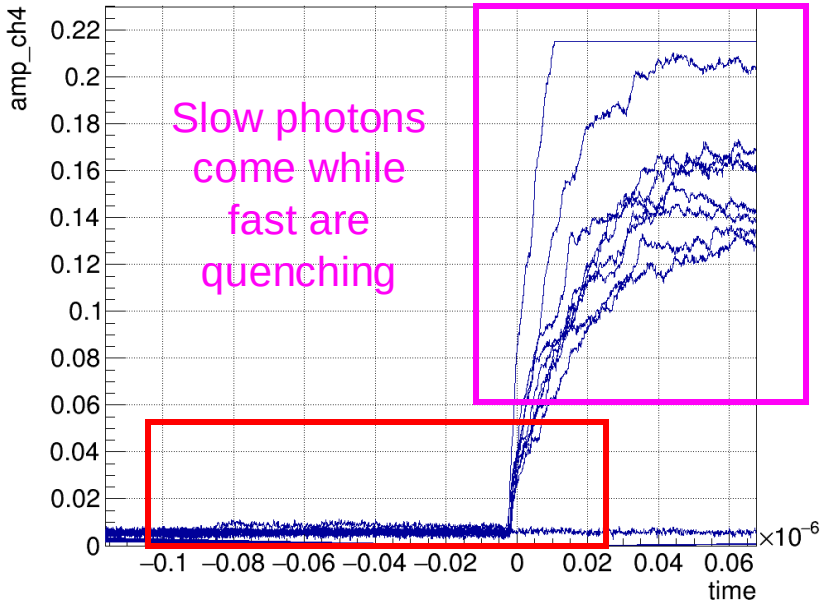
AFBR-S4N44P014M

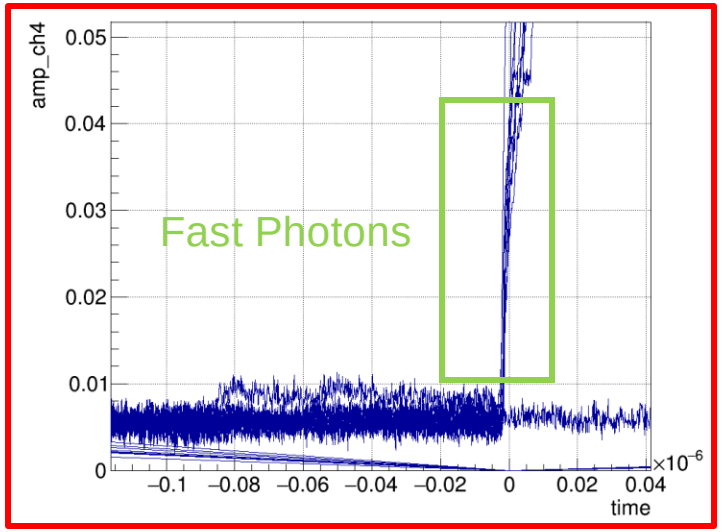
NUV-MT Silicon Photomultiplier





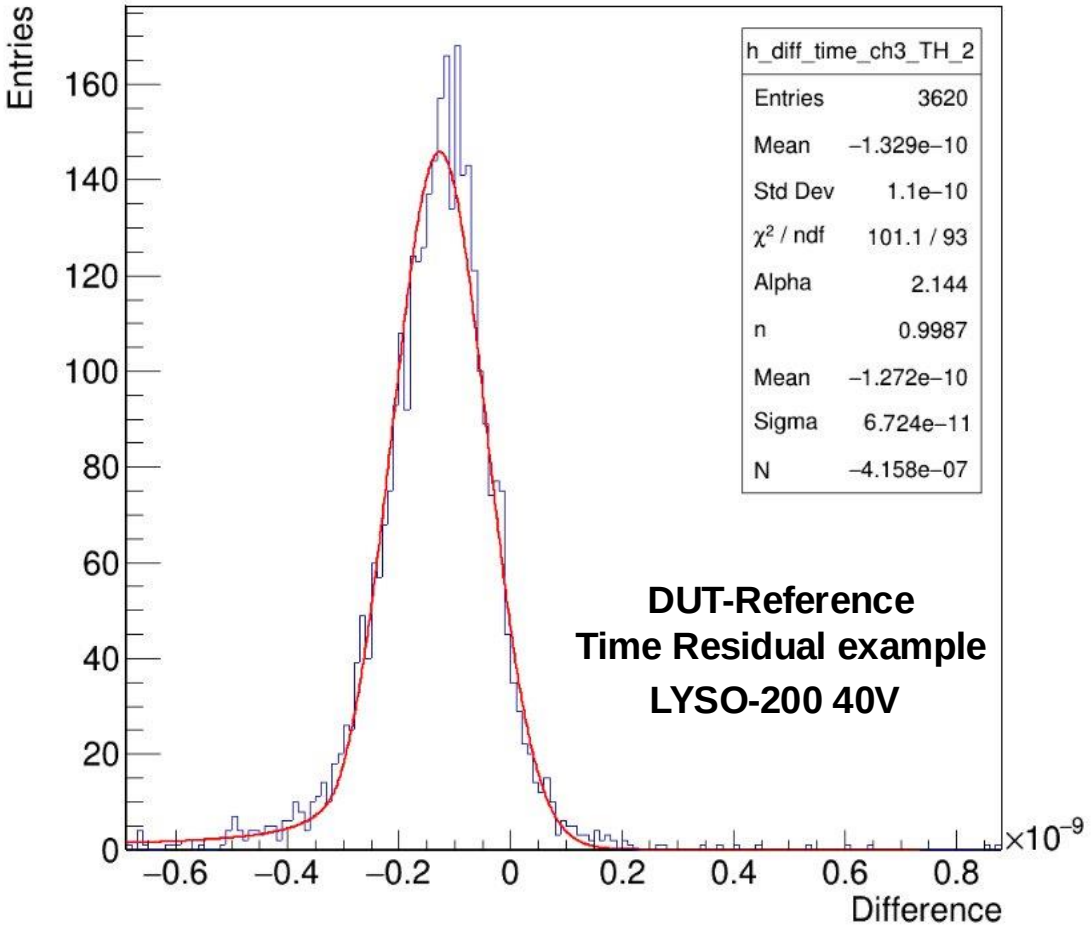
LYSO Timestamp: Fast if we catch one prompt ph

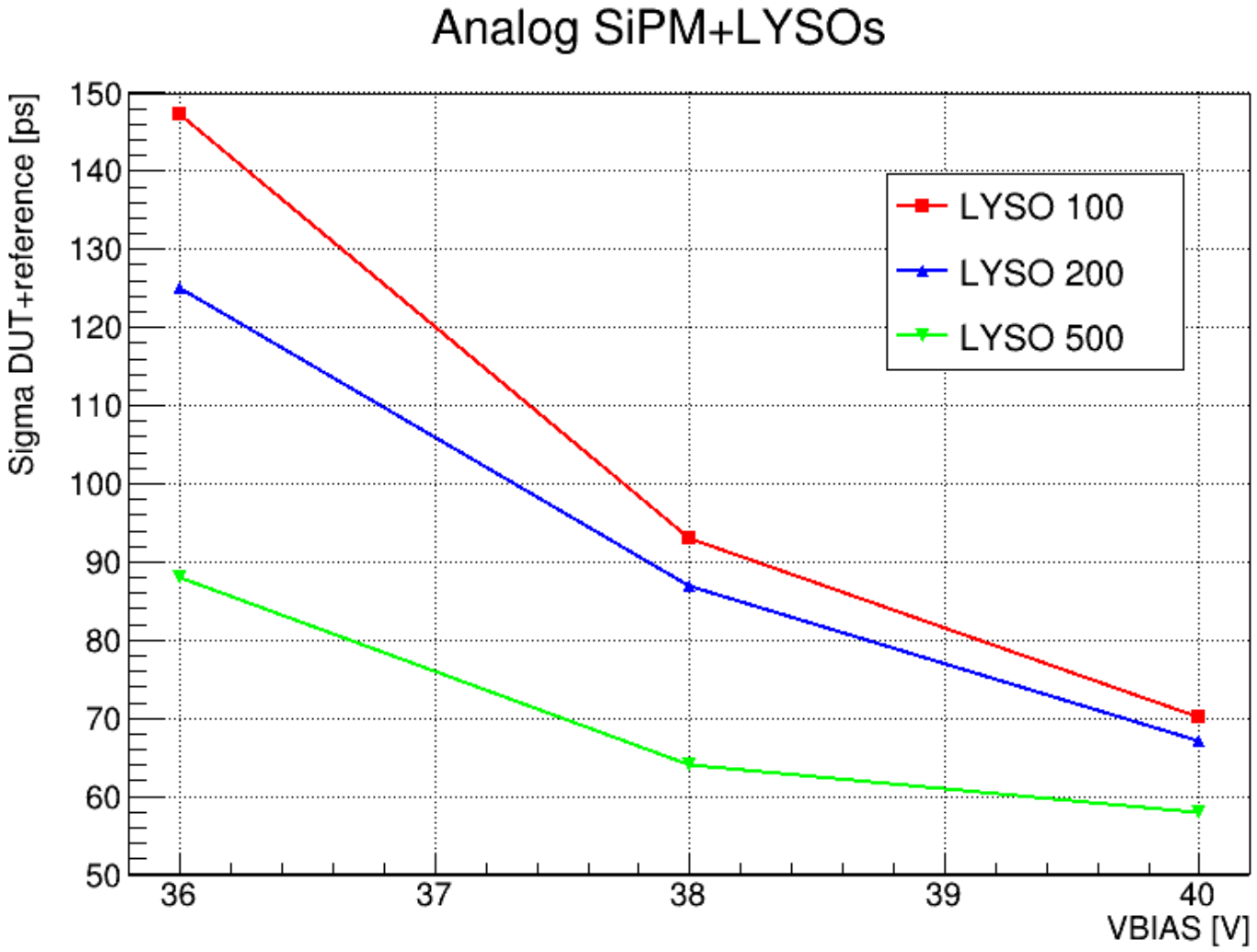




Analog SiPM + Thin LYSO

Confirm that Fill-Factor and Scintillator Properties Affect 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

- Prototype easy to use on a versatile DAQ system
- 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
- Timing with LYSO coupling limitated by the Fill-Factor
- Sensor with higher fill-factor improve timing

DESY dSiPM 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

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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).