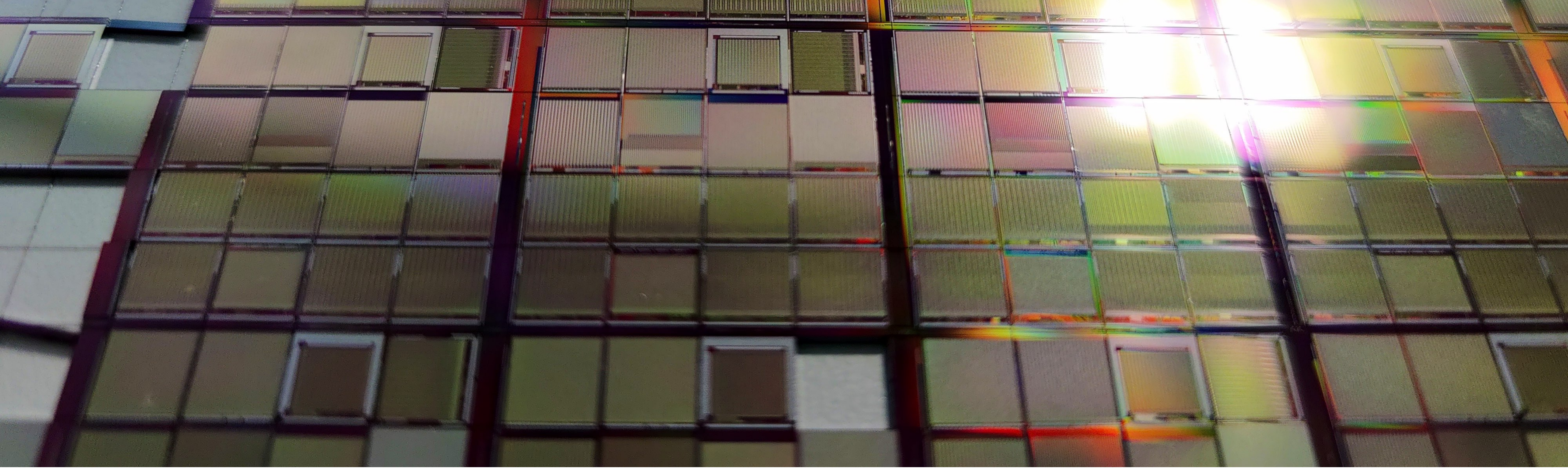


The rise of monolithic sensors

From a few pixels to an experiment

Lennart Huth

Silicon Detector Colloquium, DESY Hamburg, 21.11.2022

HELMHOLTZ

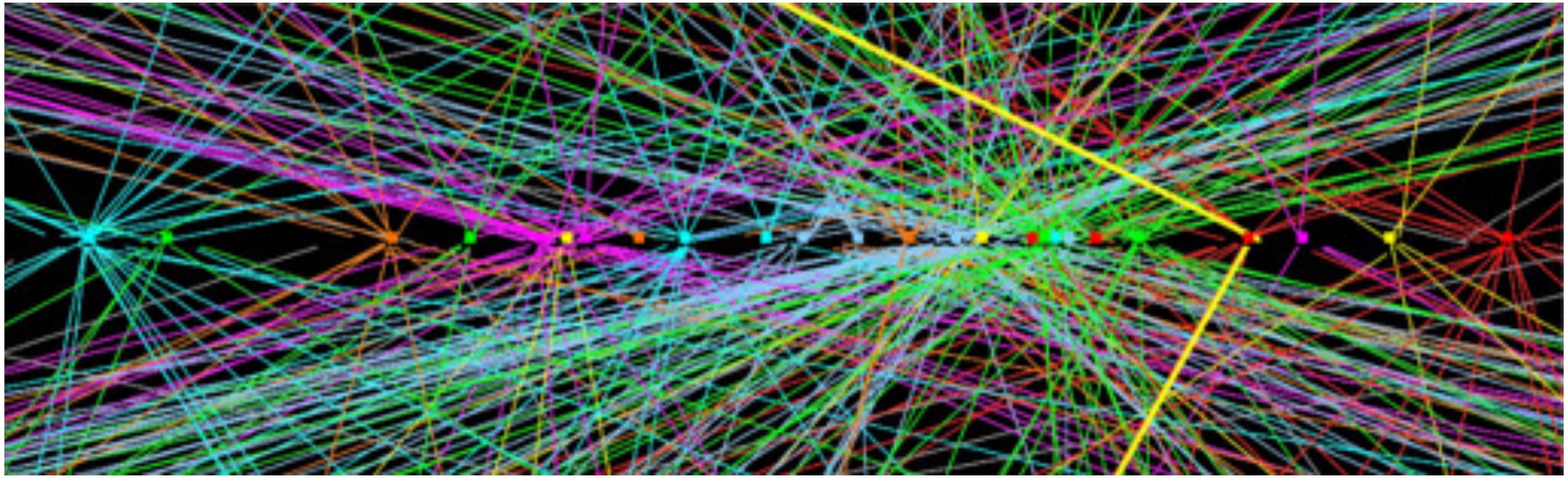
F·T·X

DESY TEST BEAM.

DESY.

Why do we need silicon detectors?

Vertex and momentum reconstruction in particle physics experiments

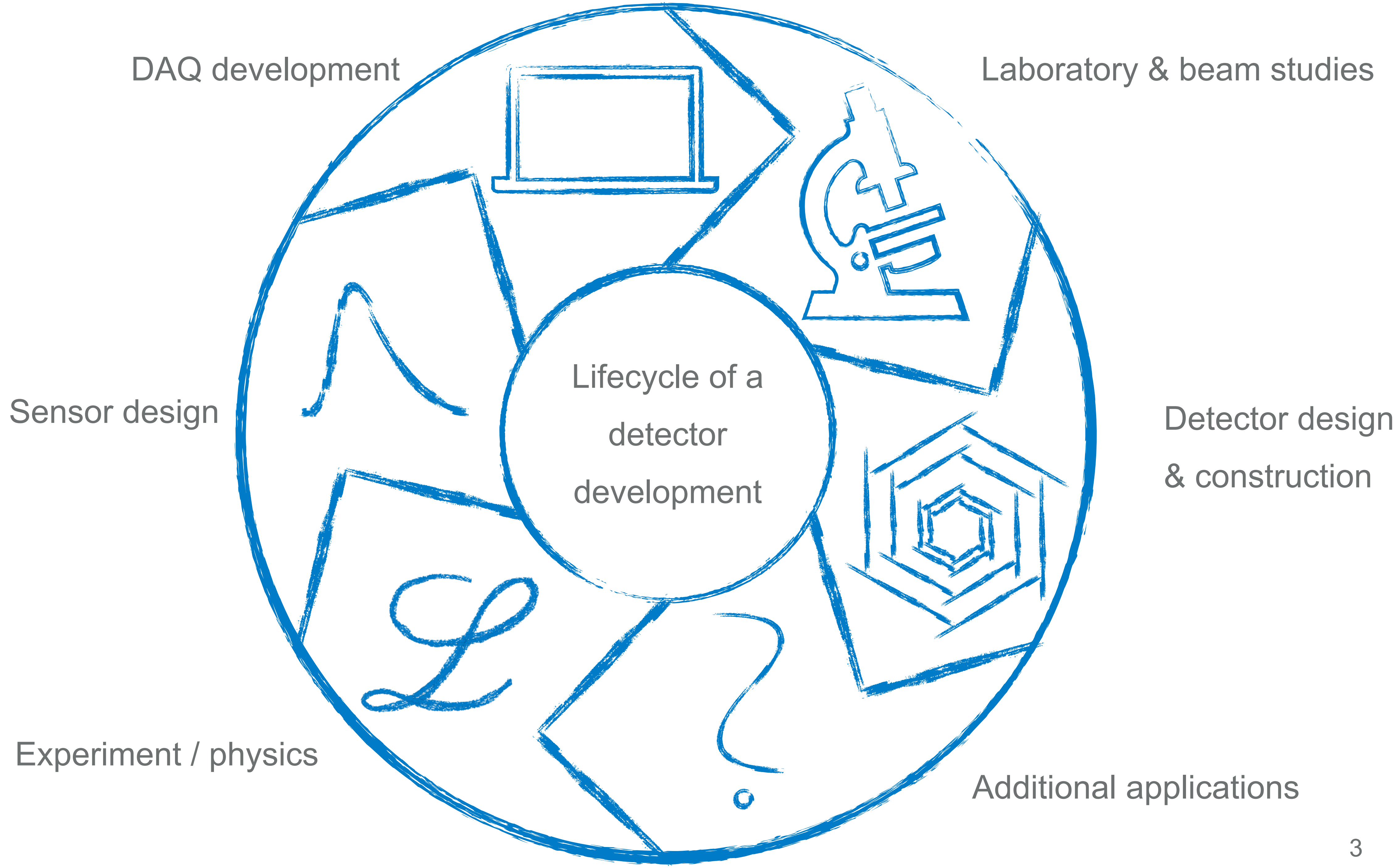


CMS

From collision to physics with silicon tracking detectors:

- Number of particles
- Vertex-position
- Momentum (in B-field)

	HL-LHC	Lepton collider
x/X_0	10 %	<1 %
Time resolution	25 ns	< ns
Pitch	50 µm	< 25 µm
Point resolution	15 µm	3 µm
n_{eq} / cm^2	10^{16}	10^{11}

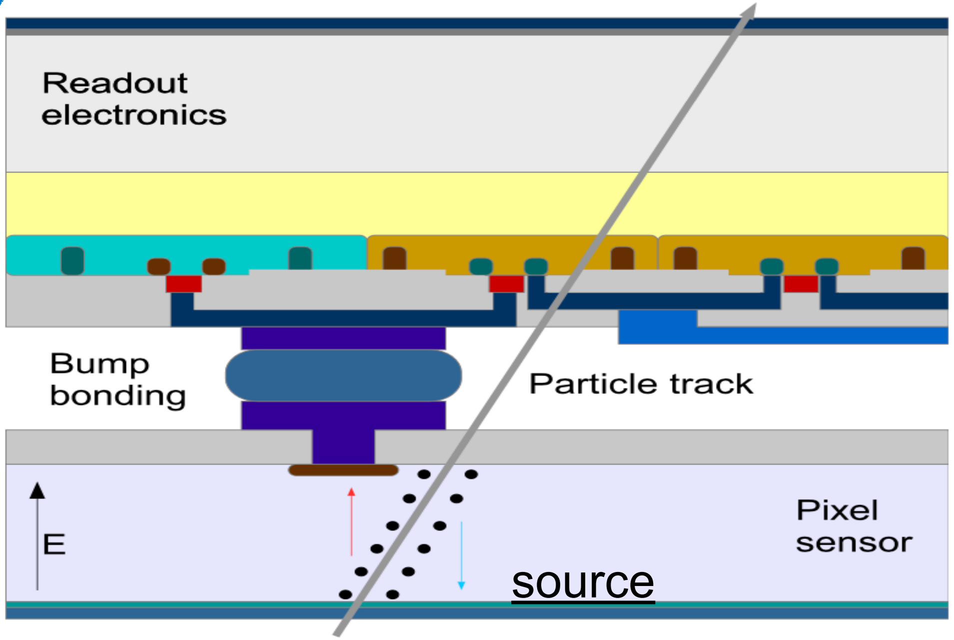

DAQ development
Laboratory & beam studies
Sensor design
Lifecycle of a
detector
development
Detector design
& construction
Experiment / physics
Additional applications

DESY.

Sensor design

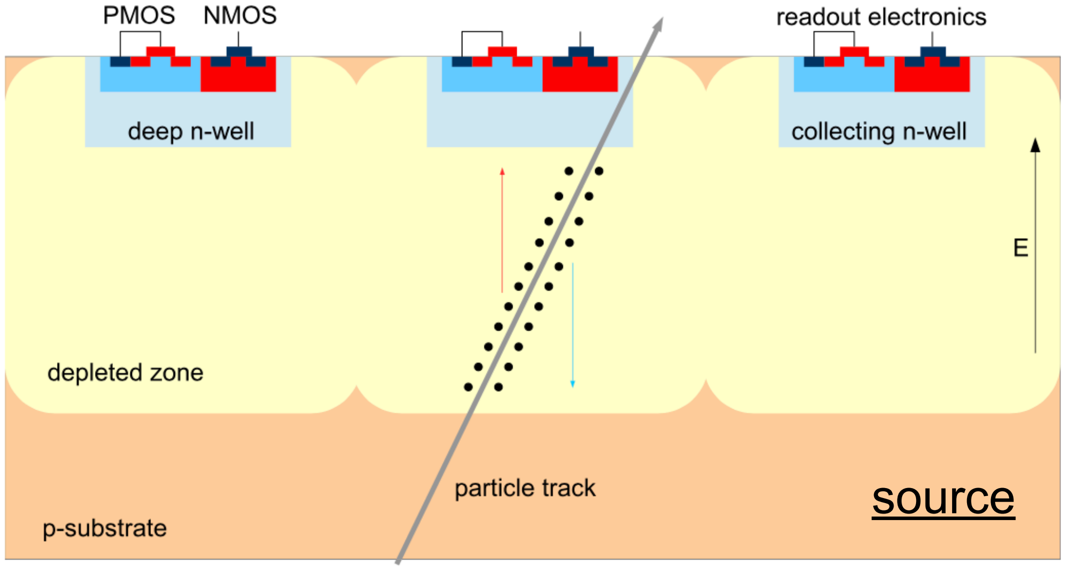
Choosing the right technology and design

Hybrid vs Monolithic

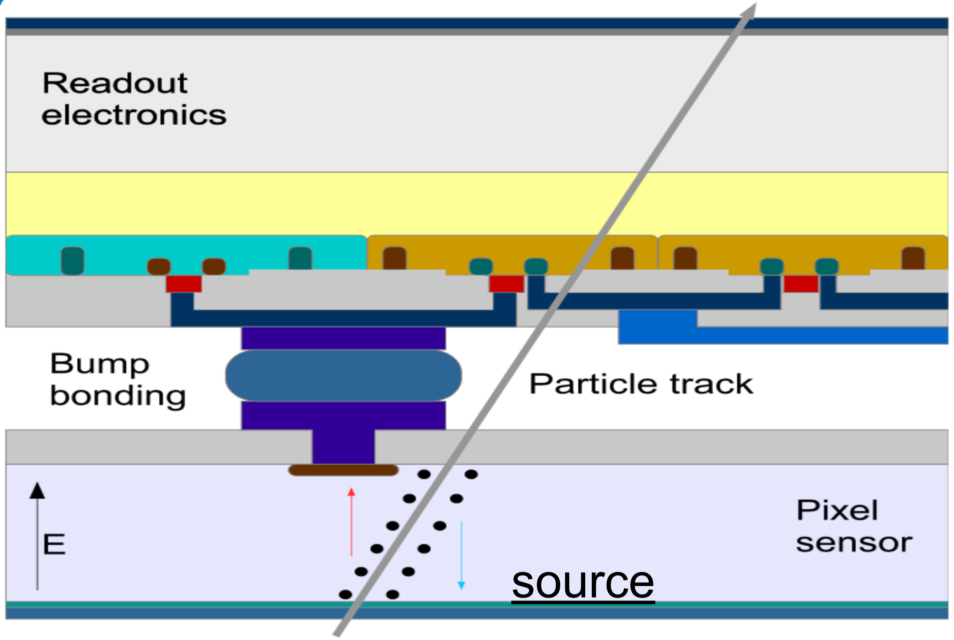


- Two silicon pieces: active sensor chip and readout
- 20 years+ in many vertex detectors
- Specialised process ➔ expensive and limited vendors
- Bump bonds limit pixel pitch and material

- Readout and sensitive structures in one
- Industry process, largely available
  ➔ Simpler, thinner and cheaper detectors
- Mostly 180 nm technologies in advanced sensors



Hybrid vs Monolithic



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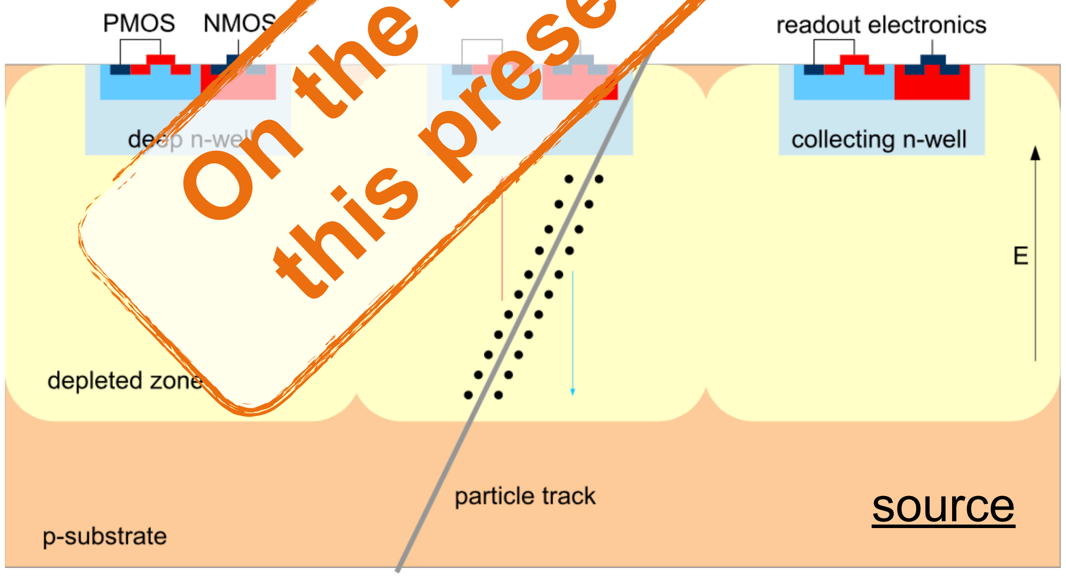
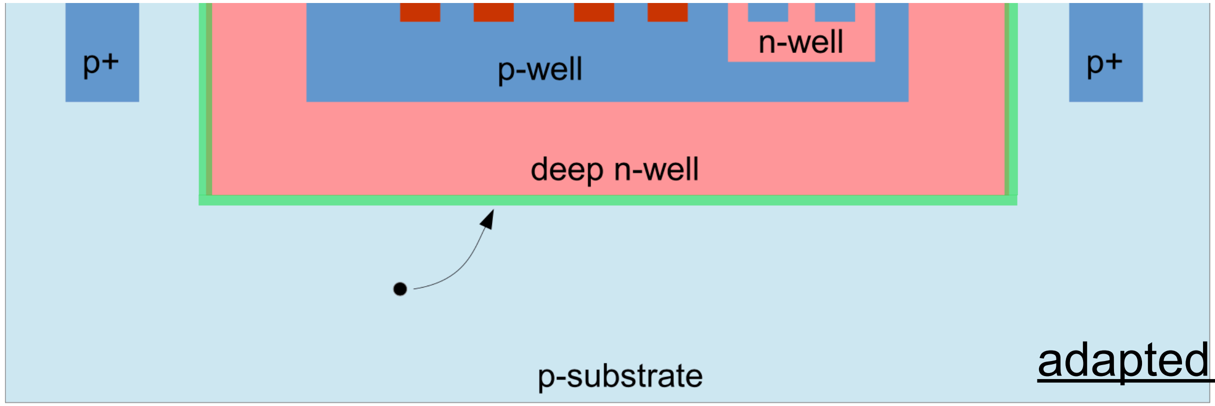


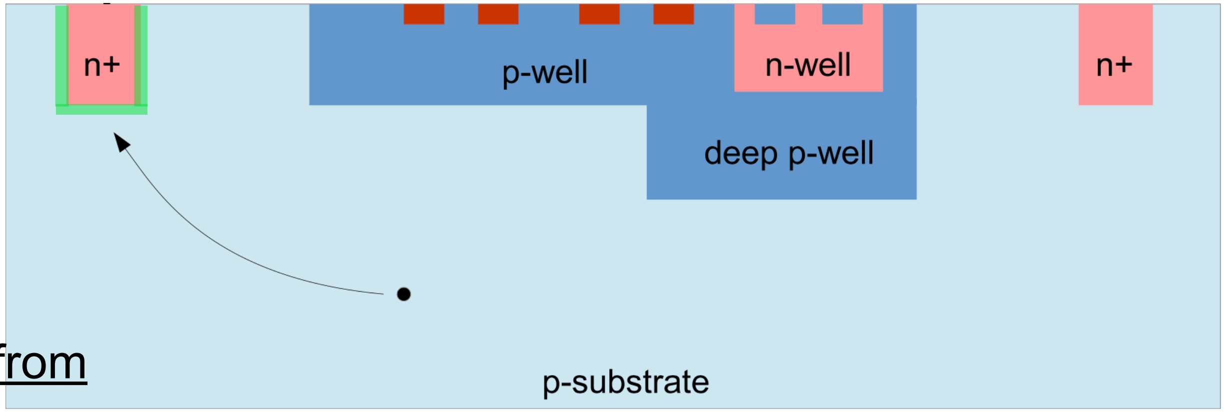
On the rise and in this presentation

Two approaches on MAPS

Large and small fill factor designs



adapted from



- Large fill factor
  - Large collection electrode
  - Higher noise
  - Fully depleted - high voltage
  - Short and constant drift paths
  - Example: HV-MAPS

- Small fill factor
  - Small collection electrode
  - Lower noise
  - < 20 µm depleted high resistivity
  - Variable propagation length
  - Example: ALPIDE

Technology choice at the end application driven

Data acquisition systems

Developing readout for testing and experiments

The MuPix Telescope - towards the Mu3e detector

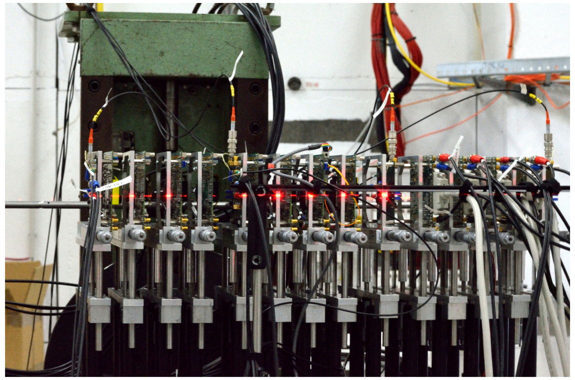
A test beam DAQ for HV-MAPS tests

Single Chip DAQ

- PCB carrying Chip
- Connection to FPGA/PC
- DAQ soft- and firmware

MuPix8 Telescope - A slice of a vertex detector

- Test of Mu3e DAQ concept: vertical slice including tiles
- Flexible workhorse deployed at DESY, CERN, PSI and MAMI from 2014 until today
- Up to 1.5 MHz particle rate

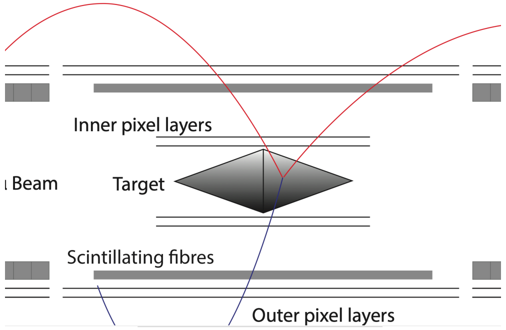


Mu3e Experiment

μ➔ eee in SM only with BR<<10^{-50}

➔ Observation == new physics

➔ Muon decays at rest, thin tracker

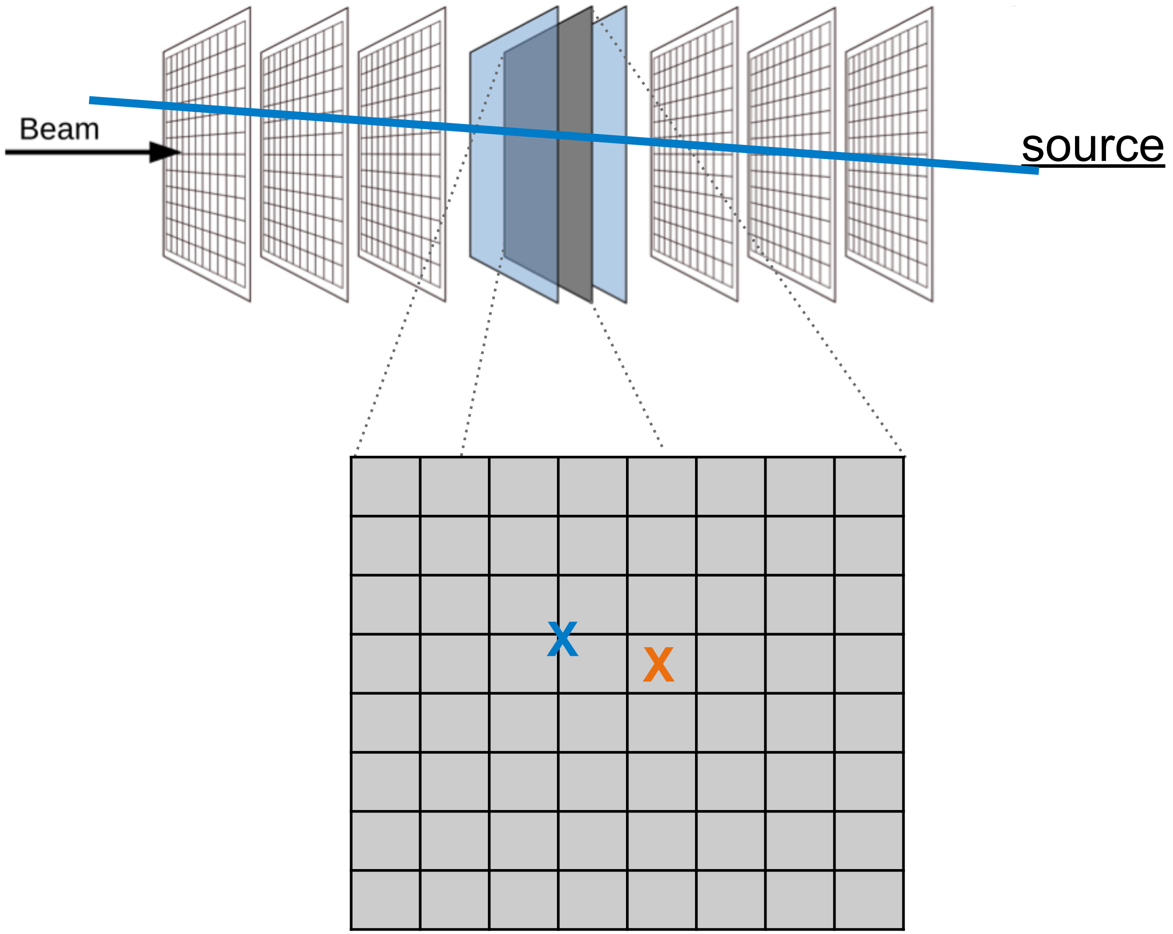


TDR

Particle tracking telescopes

From prototype to detector system

- Precise reference system for test beam studies
- Test bench for sensor integration tests
- At low momenta: As thin as possible to minimise trajectory disturbance
- 2 approaches presented
  - MuPix telescope: High rate capability/timing
  - EUDET telescope: Highest spatial resolution



DESY II Test Beam

Providing beam and the ultimate toolkit for sensor studies

DESY TEST BEAM.

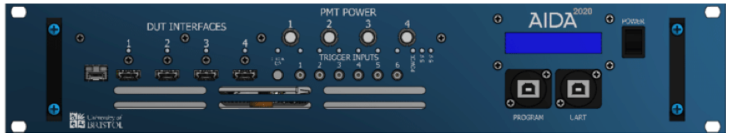
Reference Telescope

- 6 MIMOSA26 planes
- 3 µm resolution on DUT
- 115-230 µs integration time
- Installed at DESY, SPS, ELSA and SLAC/TRIUMF

Common DAQ

EUDAQ
EUDAQ2

EUDAQ

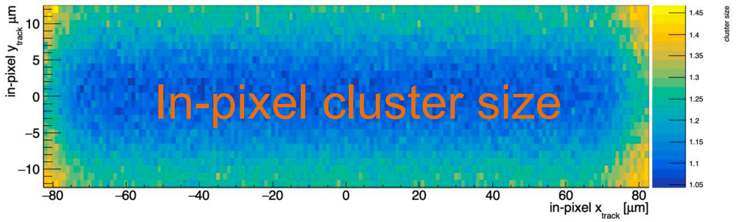


Identical setups at different beam lines

- EUDAQ: Distributed DAQ framework
- AIDA-TLU: Flexible DUT integration
- Active developments in AIDA: Task 3.4 - Next gen DAQ

AIDA innova

Analysis Framework



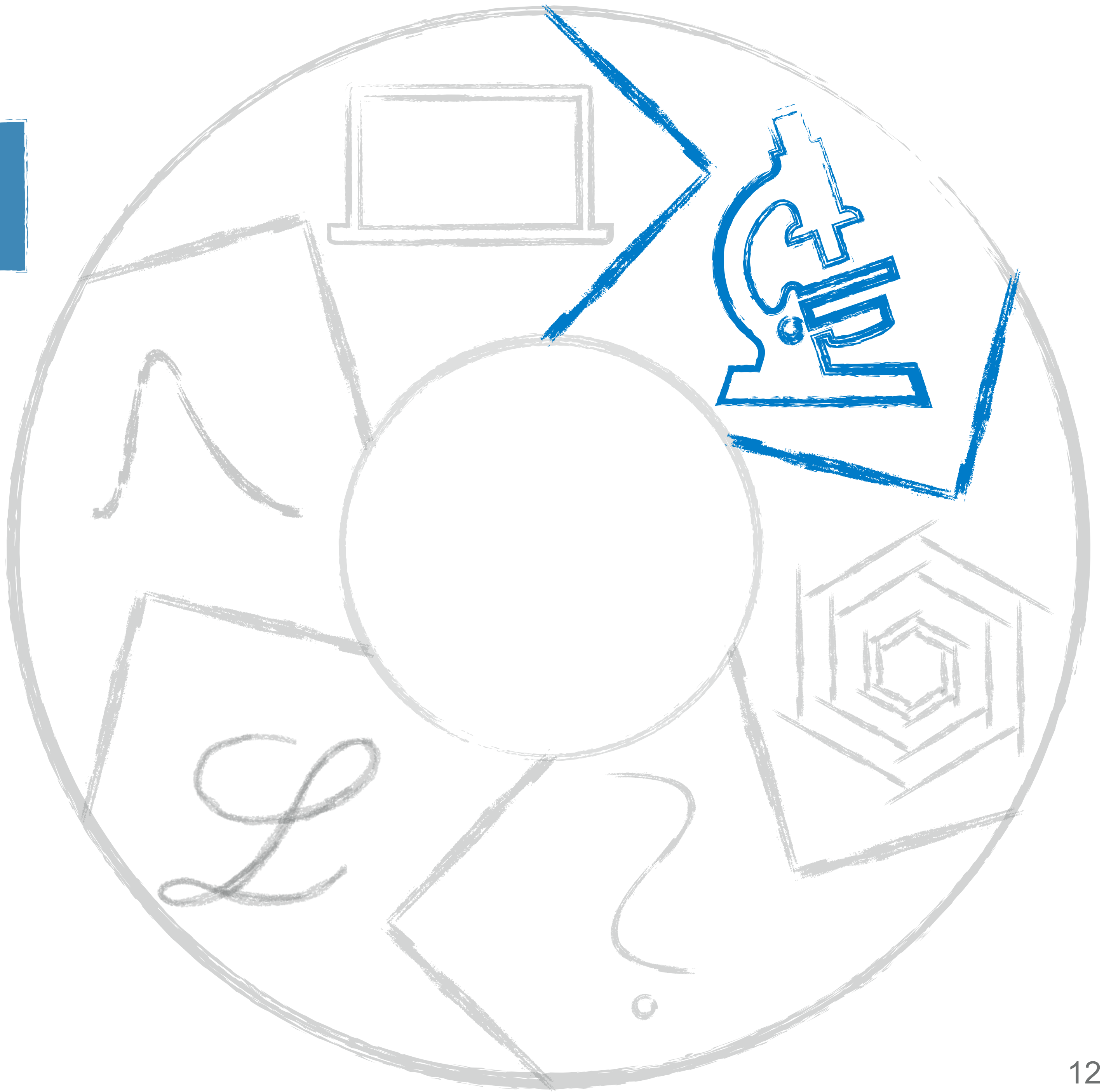
Modular framework

Corryvreckan

- Flexible event building
- Clustering, track reconstruction (Line or GBL), alignment and analysis modules provided
- Active community ➔ continuous improvements
- Well documented ➔ low starting threshold

Characterisation

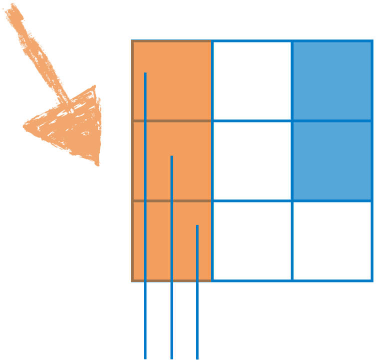
Understanding and optimising everything



Example: Clusters and crosstalk on readout lines

Assumption:

- Clusters at the test beam with perpendicular impact can be maximal 2x2
- Expect to see only few/none with 3 pixels along x/y



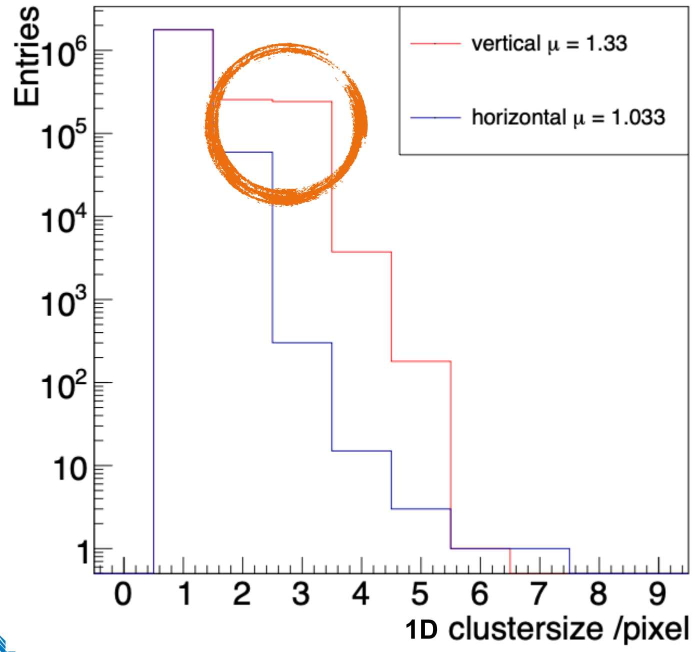
PhD thesis

MuPix8:

- First 2 cm high HV-MAPS

➔ long connection lines from pixel to digital cells

Observation

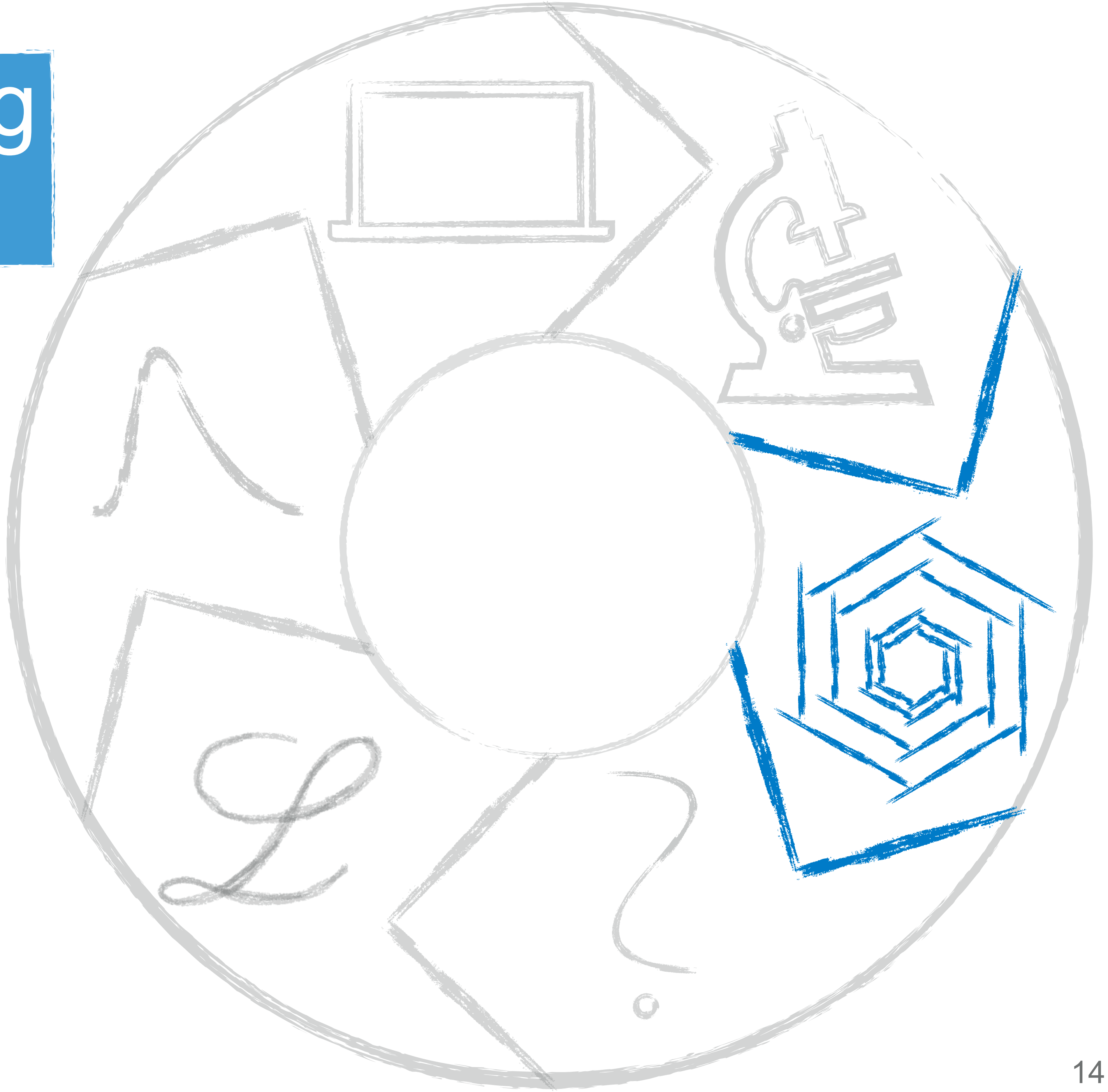


Conclusion

- Connection lines introduce crosstalk
- longer lines ➔ larger crosstalk
- Issue solved for final chip by improved routing scheme

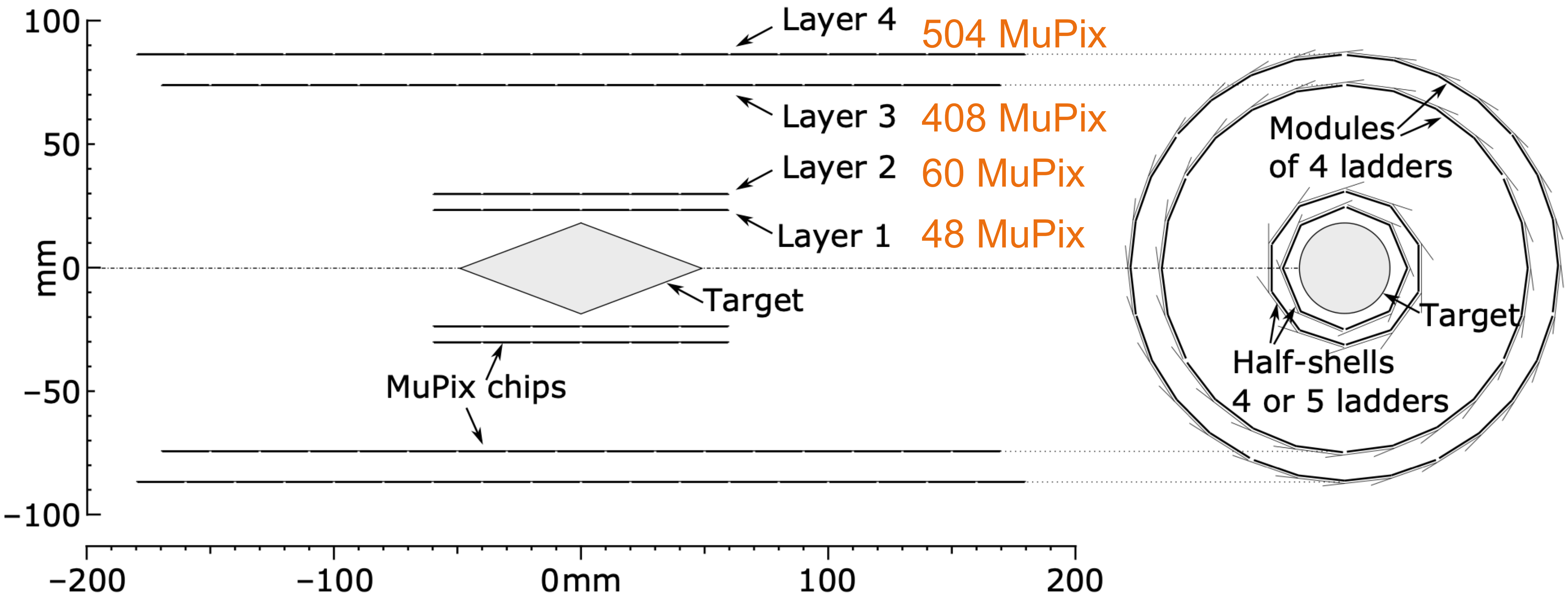
Designing/building a detector

The transition from a sensor to an experiment



The Mu3e tracker

An extremely low material tracking system

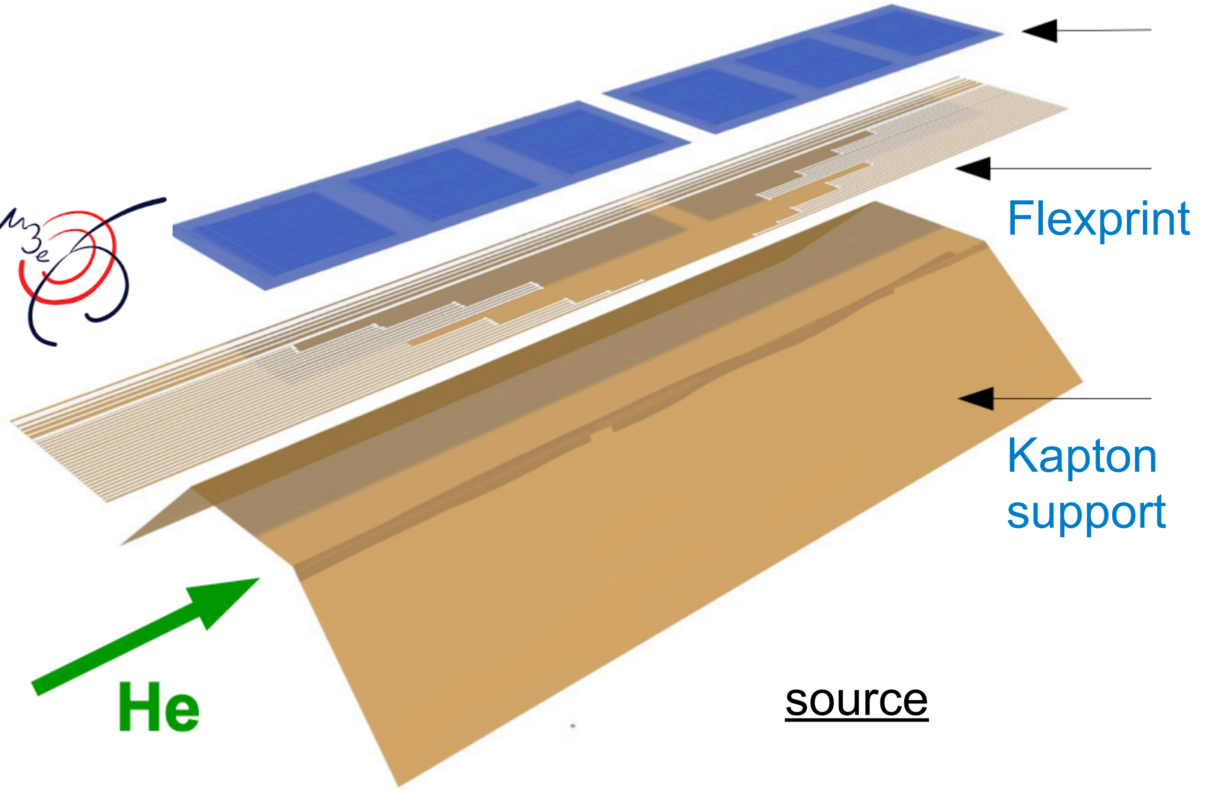


1128 fully functional MuPix chips on 70 modules

@ < 0.1% x/X_0 per module layer

The beauty of simplicity

Simplified detector construction with highly integrated sensors



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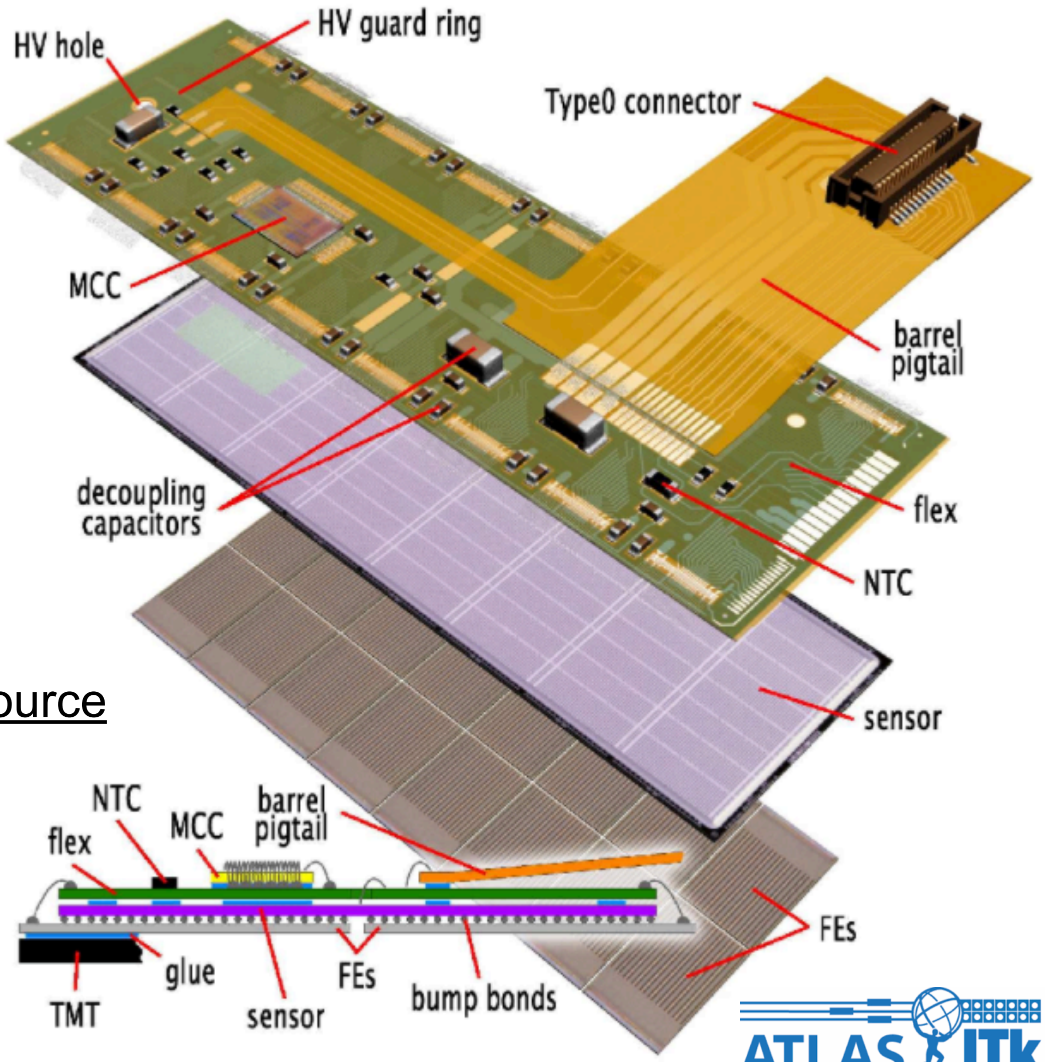

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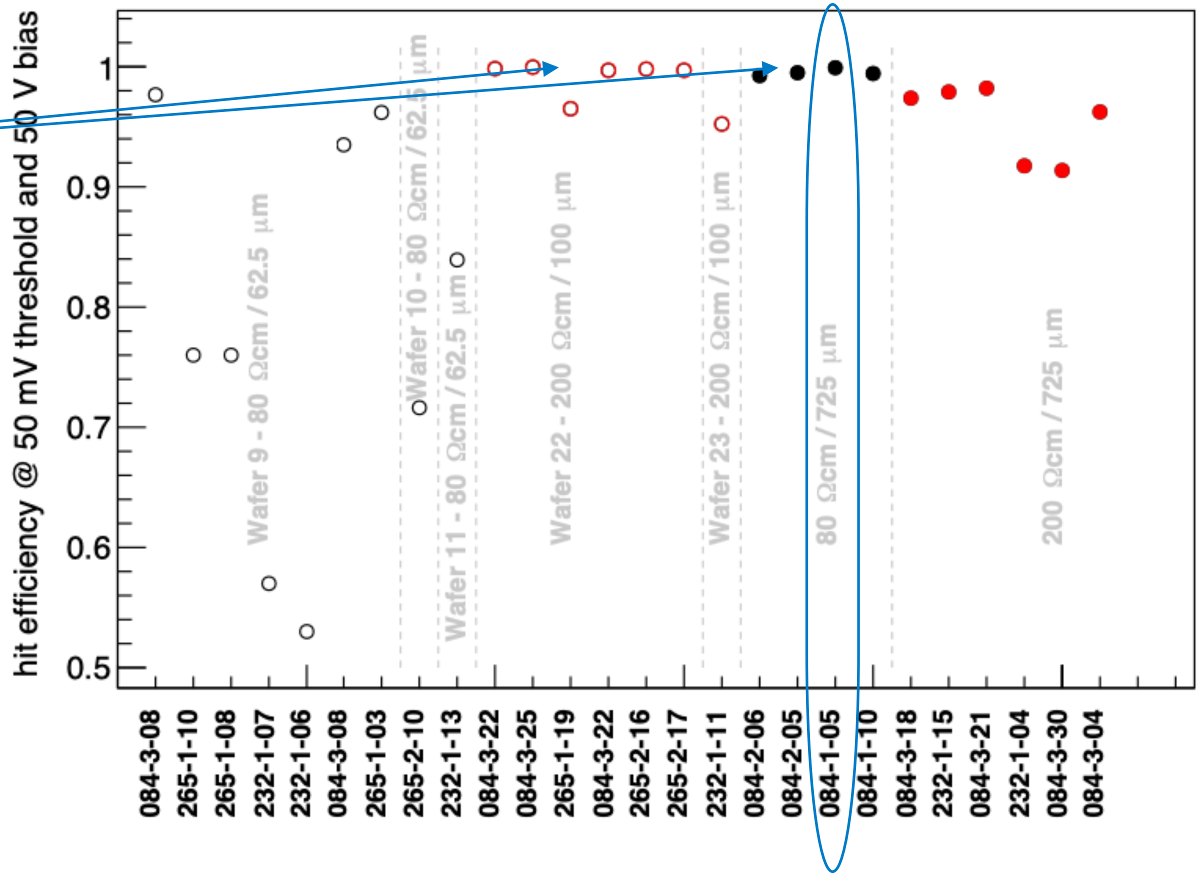
Moving from single sensors to a production

PhD thesis

Understanding perfomance fluctuations

Tested sensors from 7 wafers

- Only 2 with good yield
- Others show varying sensor performance
- Traced down to dicing/thinning process
- Company fixed issue
- Wafer probing for final production



Back to the future - Generic R&D at DESY and its future

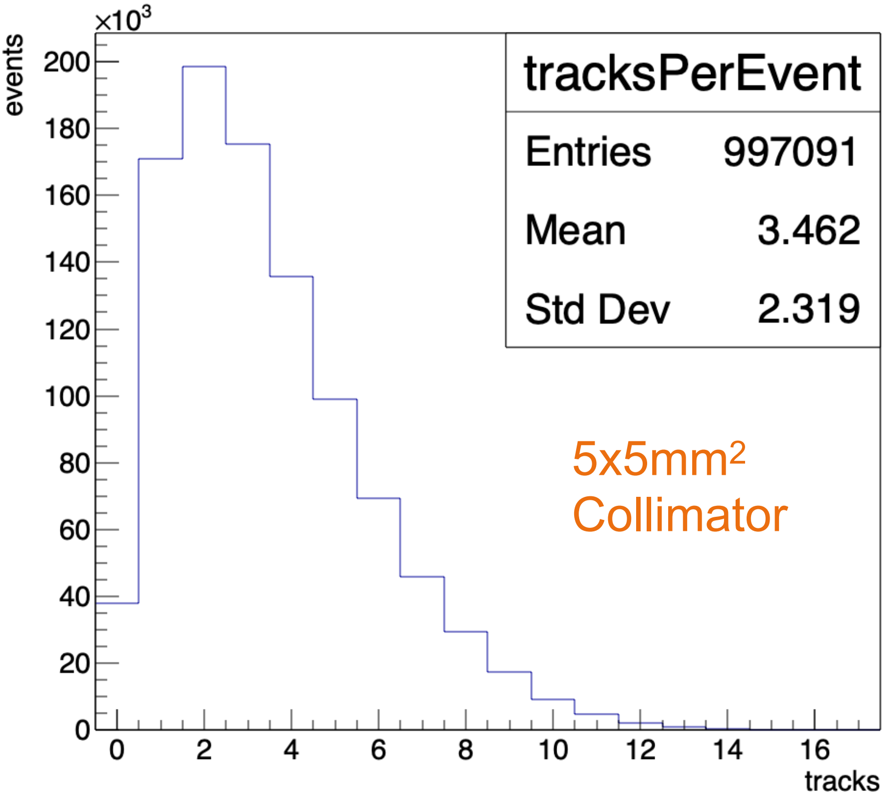
Many ideas but **no** experiment proposal at DESY

Generic Sensor R&D / Infrastructure Improvements

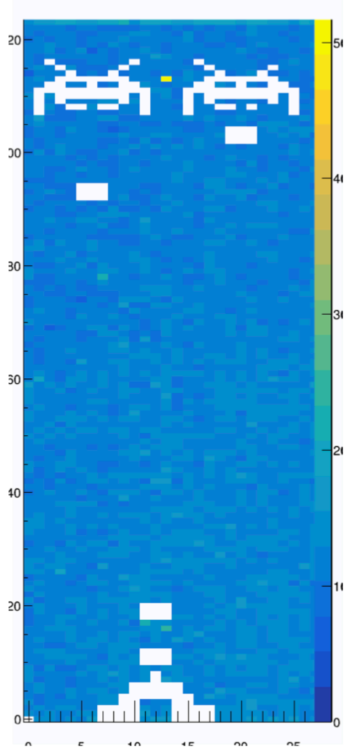
Potential Applications

Improving the time resolution of the beam telescopes

TelePix: An HV-MAPS as a trigger and timing plane



- HV-MAPS as trigger and timing layer
- PI of QU-funded project (ca 80k EUR invest)
- Trigger on OR of all unmasked pixels
- Full EUDAQ2 + AIDA TLU support



Pixel masking

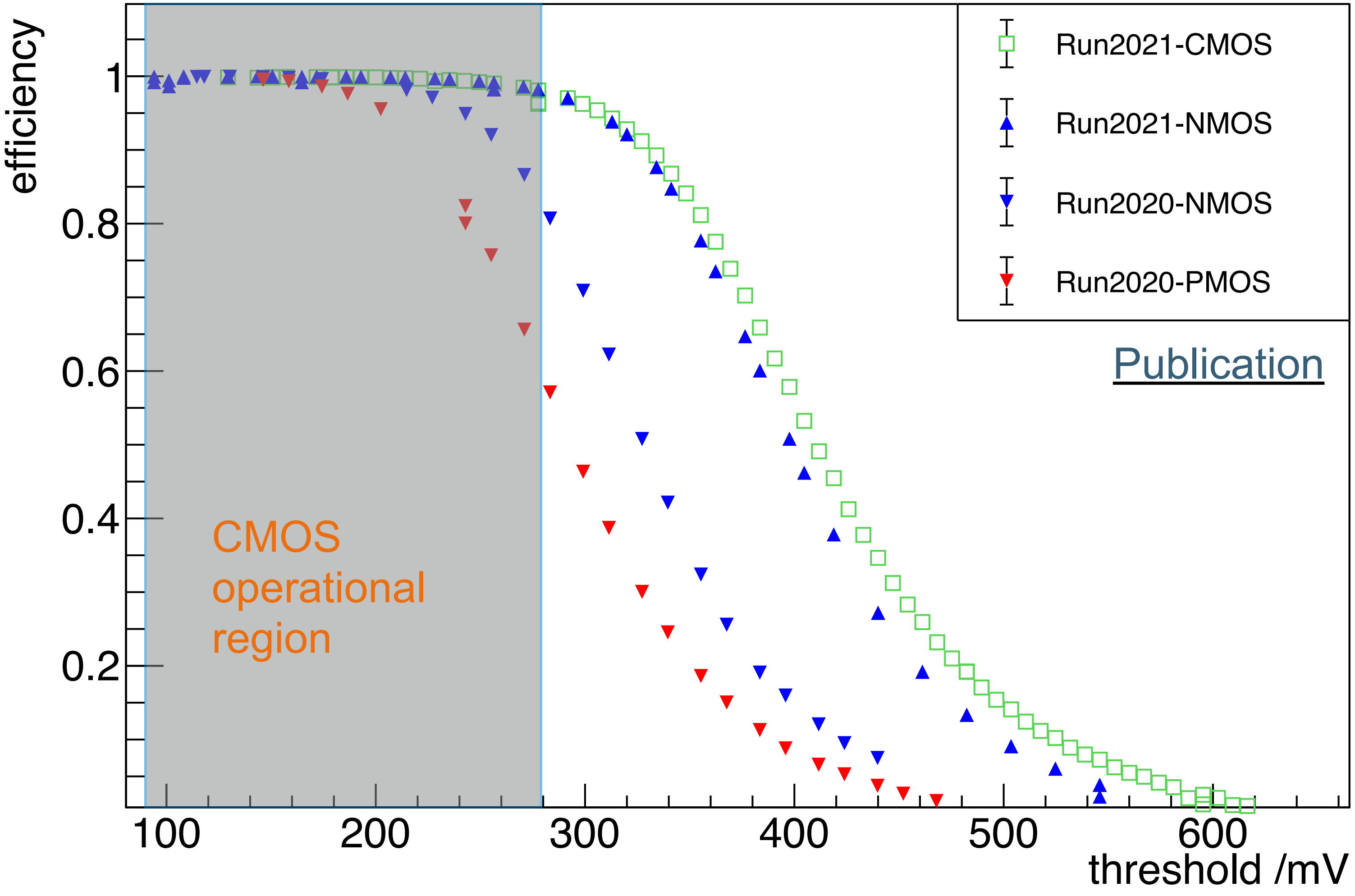
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

KIT Karlsruher Institut für Technologie

Improving the time resolution of the beam telescopes

Performance results: Efficiency

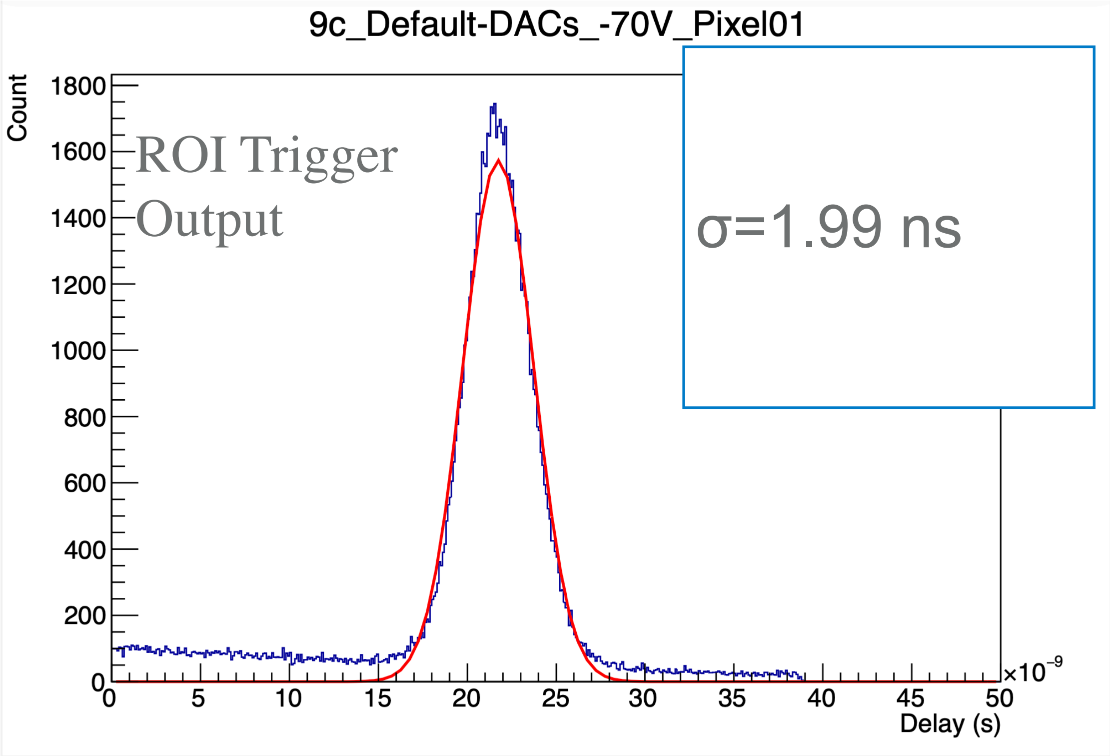


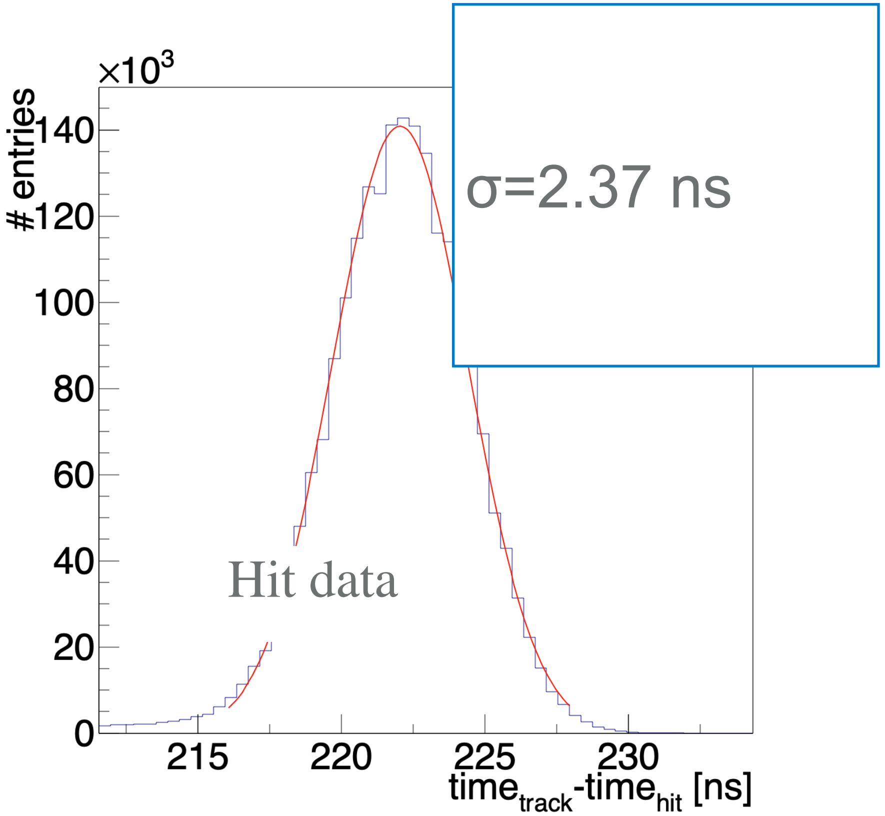
- Studied 4 amplifier flavours
- Run2021 outperforms Run2020
  - ➔ Improved biasing
- CMOS version optimal: ~200 mV operational region
- Noise 0.01 Hz/pixel ($2.5e^{-10}$/BC)

Improving the time resolution of the beam telescopes

Performance results: ROI trigger and timing

Preprint submitted to NIM-A





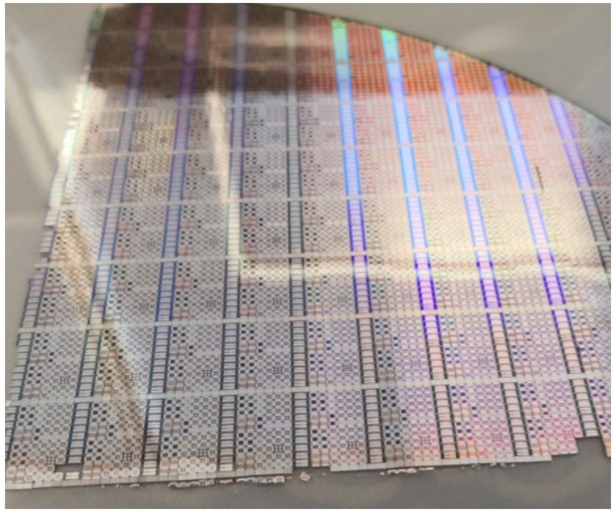
ROI trigger and data stream show excellent time resolutions

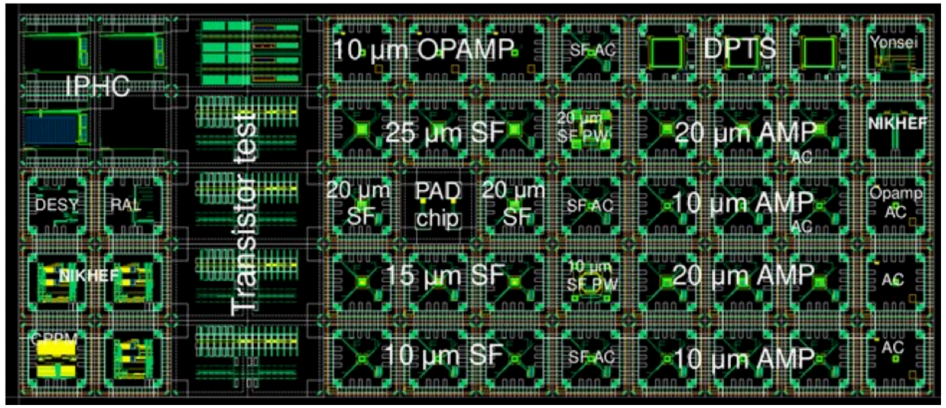
➔ Full scale sensor expected back December, to be put in operation in **2023**

Tangerine - Towards Next Generation Silicon Detectors

MAPS in a new 65 nm imaging process

- Helmholtz Innovation Pool project (2021 - 2023)
- Investigating new technologies for future (lepton) collider experiments
- Two structures tested:
  - **DESY CSA Test Chip**
  - Analog pixel test structures (**APTS**)
- Test beam studies at MAMI, SPS and DESY
- Readout integrated into EUDAQ2 via Caribou





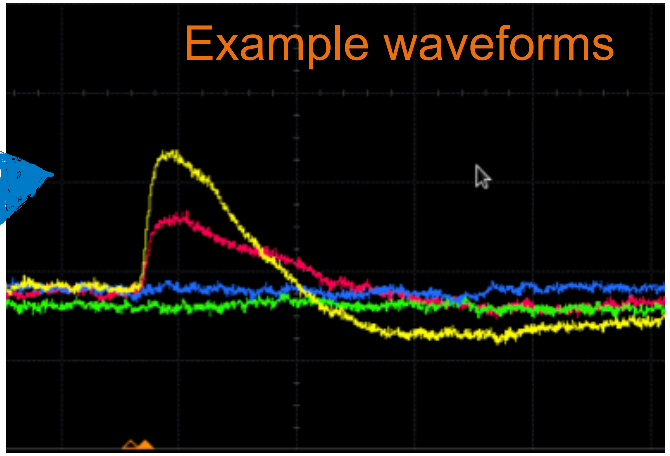
CERN DESY. IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG CPPM Nikhef Science & Technology Facilities Council Rutherford Appleton Laboratory Yonsei University

DESY CSA chip

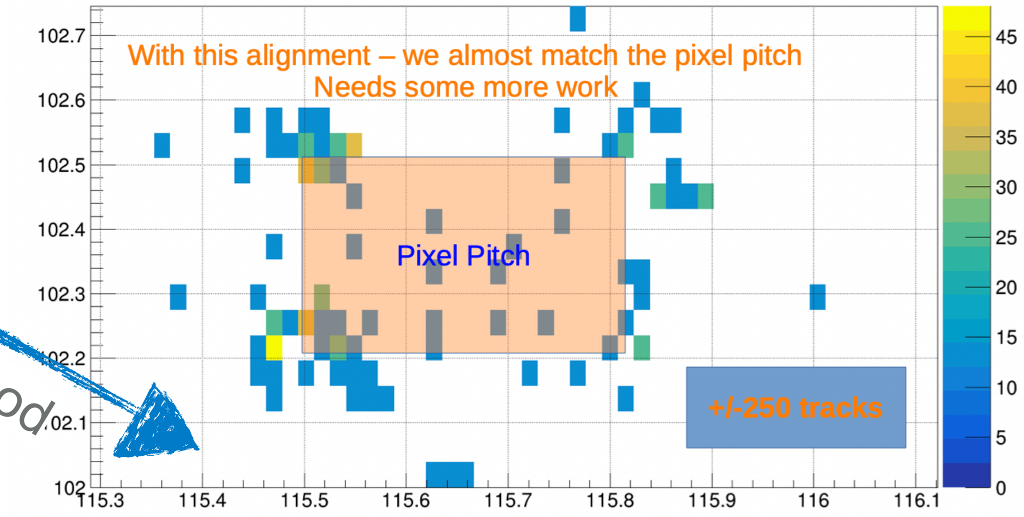
- 4 analog channels with charge sensitive amplifier & Krummenacher Feedback
- 16.3 µm pitch low event rates
- Efficient only underneath electrode

➔ Miscommunication during design phase

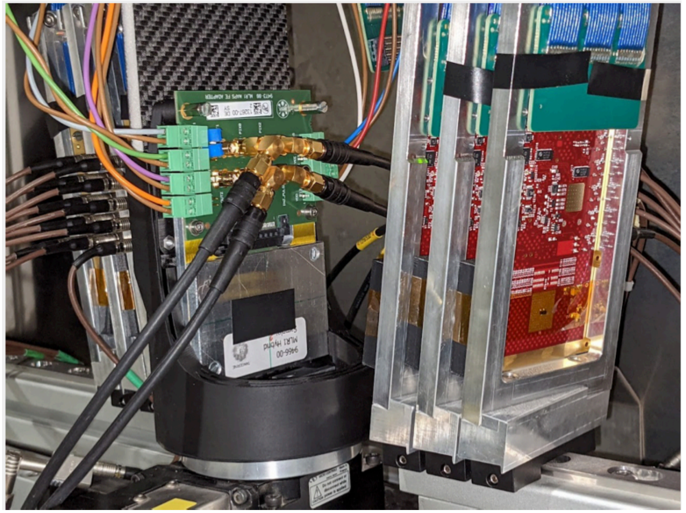
Circuit functional



Understood



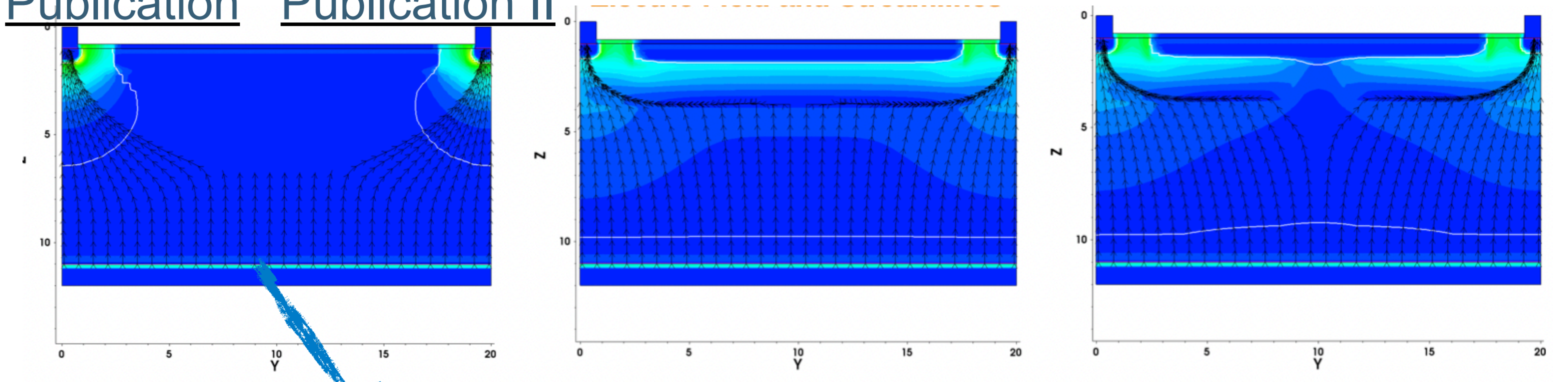
Track positions with signal on MLR1



Analog pixel test structures (APTS)

TCAD - Finite Elements simulation

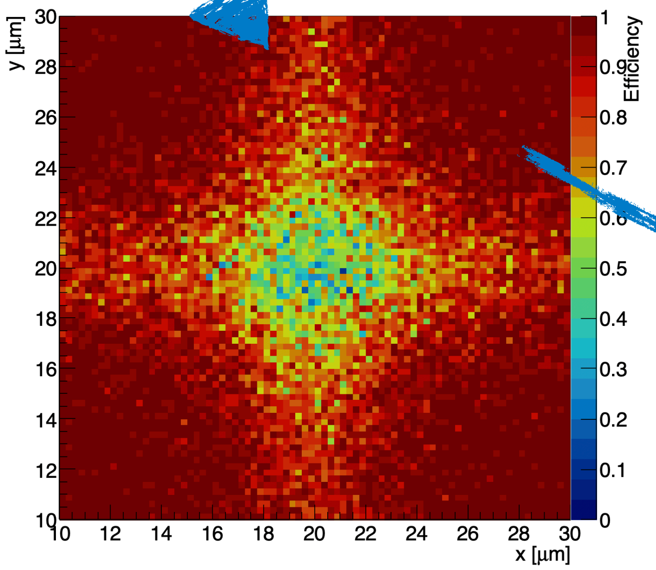
[Publication](#) [Publication II](#)



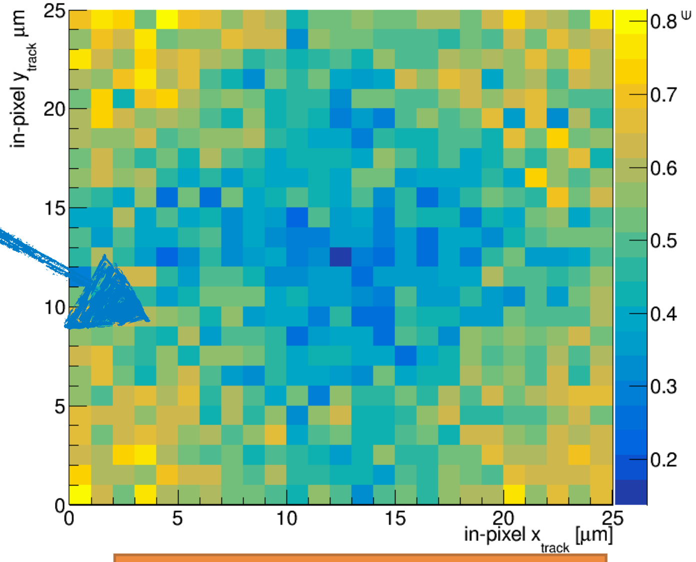
- Three design flavours with different field configurations
- Studied in TCAD, Monte Carlo, laboratory and test beam
- Consistent results for all three

➔ **Verified simulations can be used to engineer sensor layout and performance**

➔ **Continue the Tangerine efforts beyond 2023**



Allpix² - Monte Carlo



DESY II Test Beam
TelePix as ROI trigger

Potential 65 nm applications

Medical applications:

- Monitoring of ion beams (HIT,…) for cancer therapy ➔ in-situ treatment monitoring

Particle physics:

- LHCb is seeking for a monolithic upgrade of the outer tracker
- Belle II is looking for an upgrade
- Local experiments - e.g. LUXE
- New telescope
- **Higgs factory**

Technology transfer:

- 65 nm for **Petra IV/FLASH**
  - Stitching ➔ large surfaces
  - On-chip intelligence

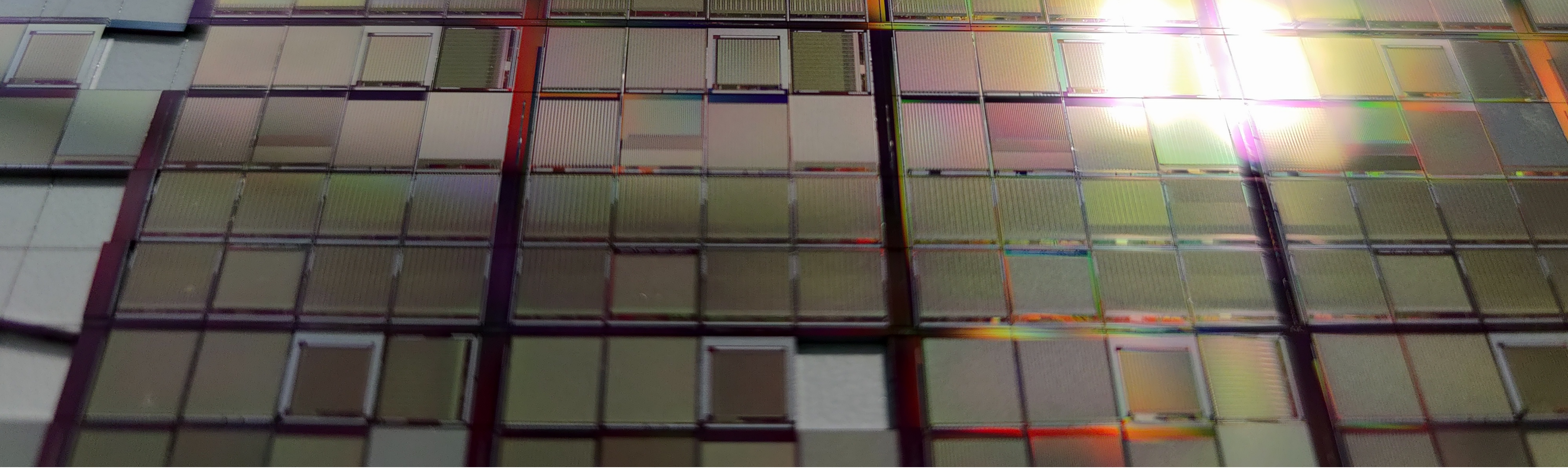
    ➔ reduce data
  - Modern process

    ➔ sustainable
  - Beam diagnostics (bunch population,…)
- Radiation detection
- Geology ➔ cosmic tracking in deep underground caverns
- Particle detectors for schools/education

Summary

- DESY provides essential common infrastructure/software
- MAPS have shown their potential, that now has to be fully explored
- 65nm MAPS are future-proof ➔ DESY could become leading institute for future vertex detector developments

Exciting times are ahead for silicon detector R&D



Contact

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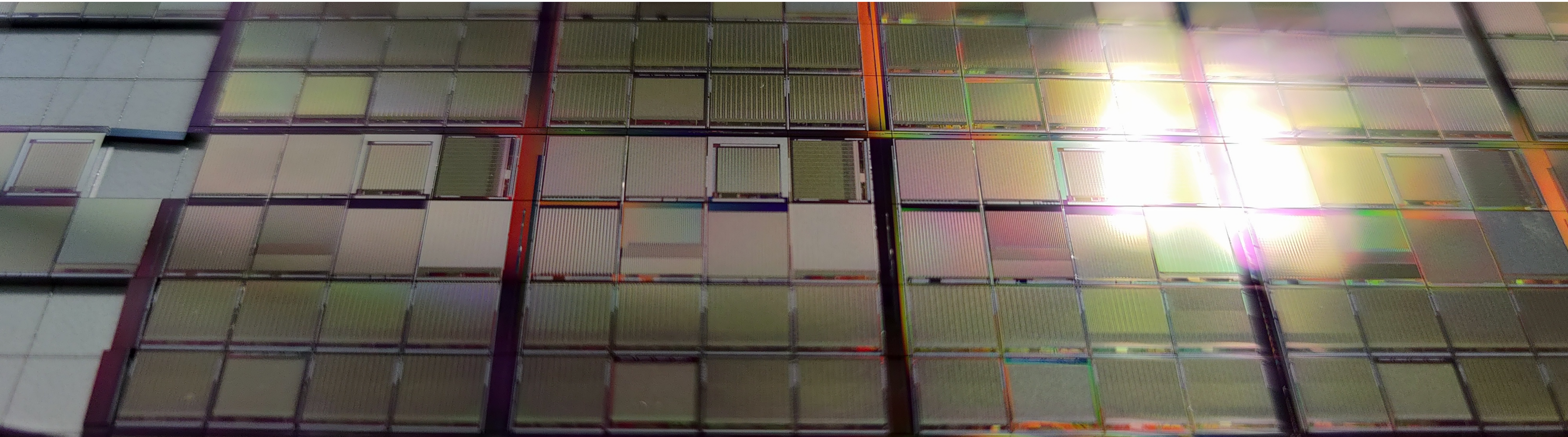
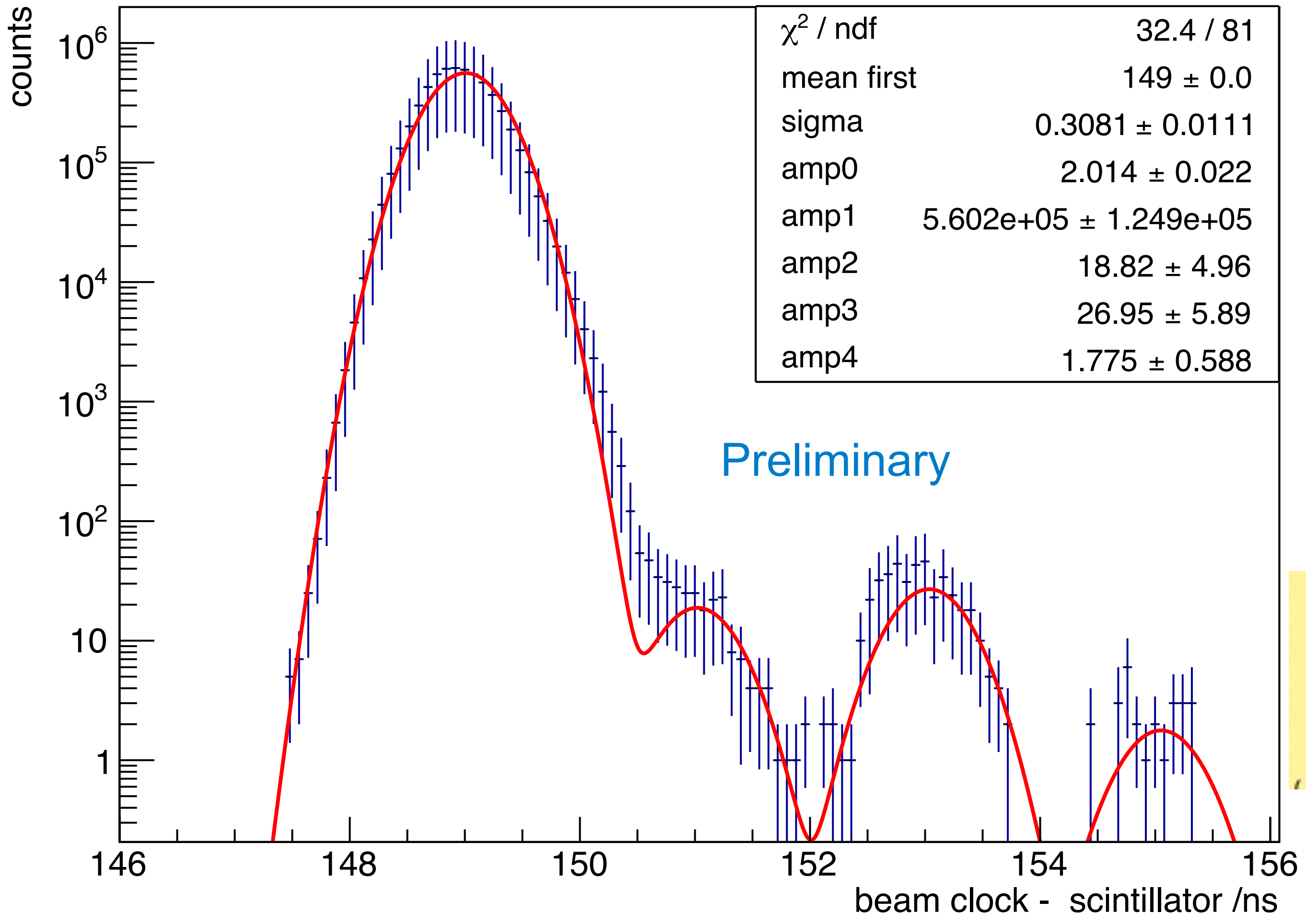
Backup



Measuring bunch structure with a fast timing layer

LYSO crystal to trigger the LGAD readout used to study the bunch clock - beam timing

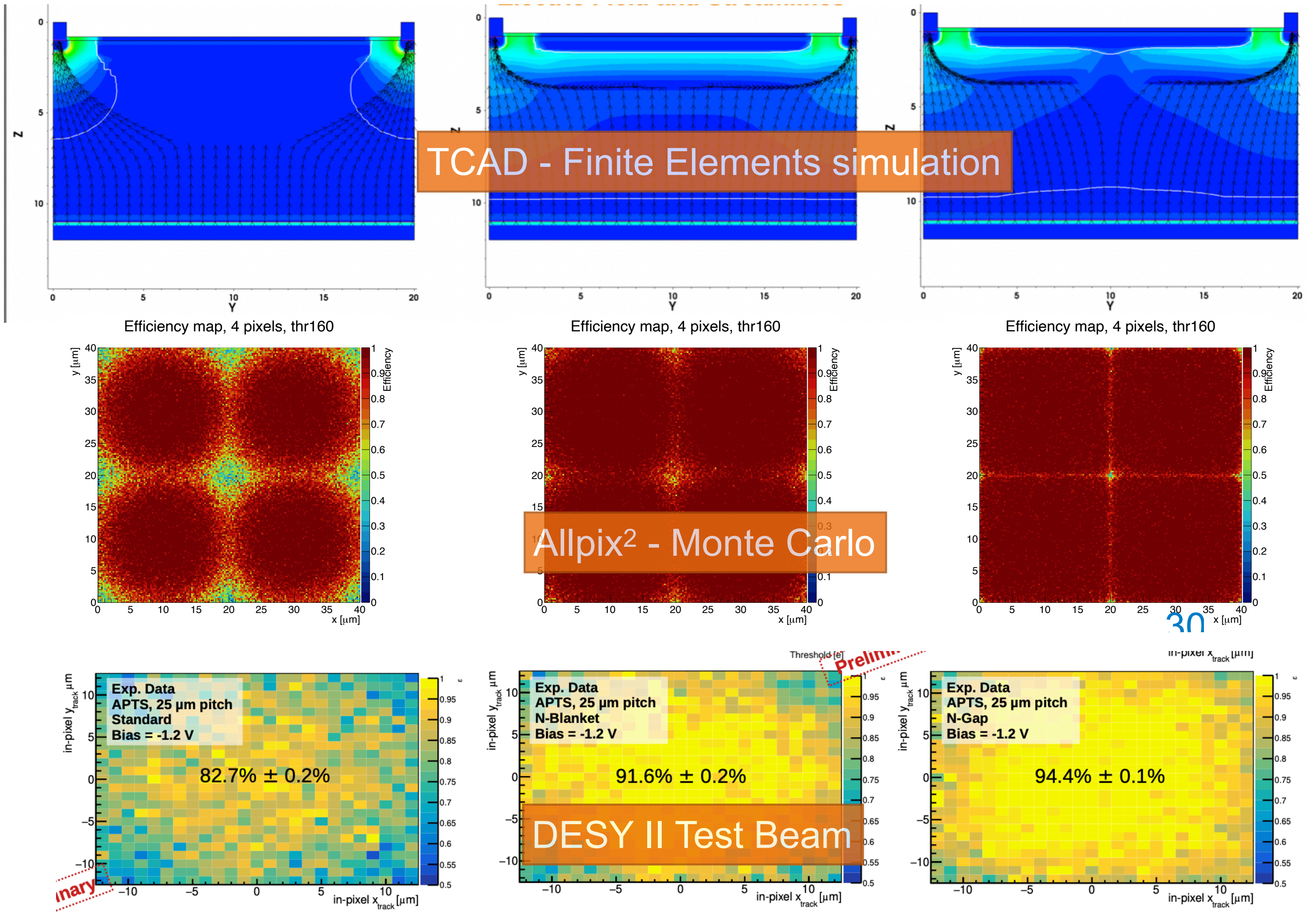


Probabilities
Hauptbunch: 99.9915%
1. Nebenbunch: 3.35e-5
2. Nebenbunch: 4.81e-5
3. Nebenbunch: 3.17e-6

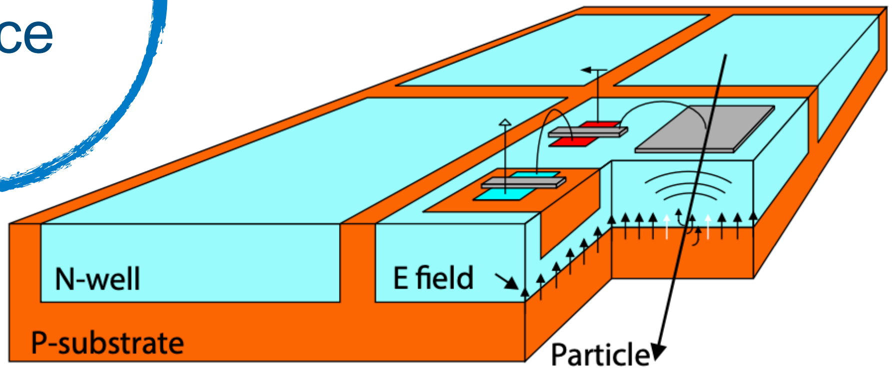
All *Nebenbunche* equidistant and equal width in fit. Bunchspacing **2.01ns**

1	mean first	1.49007e+02	3.14367e-02	-3.45151e-06	-1.47339e-03
2	sigma	3.08078e-01	1.10621e-02	1.73421e-06	-1.38808e-02
3	amp0	2.01443e+00	2.15818e-02	8.79099e-06	-2.20820e-03
4	amp1	5.60245e+05	1.24854e+05	-3.85852e+01	-1.29486e-09
5	amp2	1.88201e+01	4.95867e+00	-2.08059e-04	2.84947e-06
6	amp3	2.69452e+01	5.89412e+00	-1.55420e-03	-7.95977e-06
7	amp4	1.77495e+00	5.87509e-01	2.96536e-04	-5.02792e-05

Analog pixel test structures (APTS)

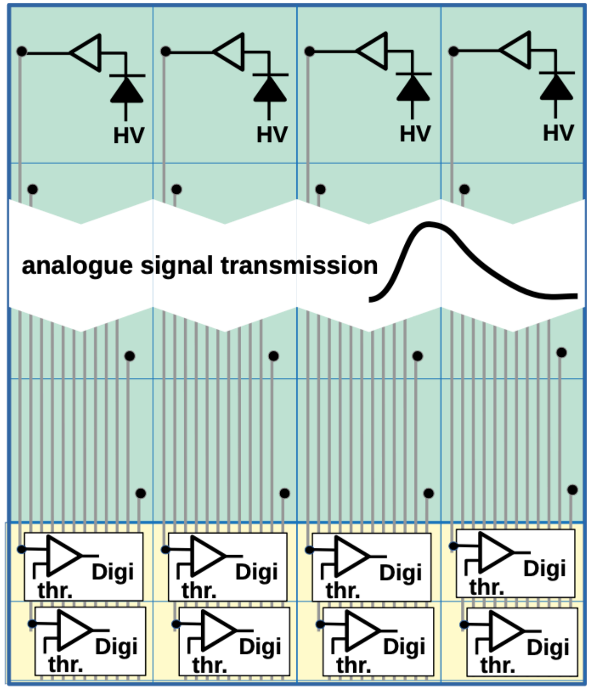


Technology choice



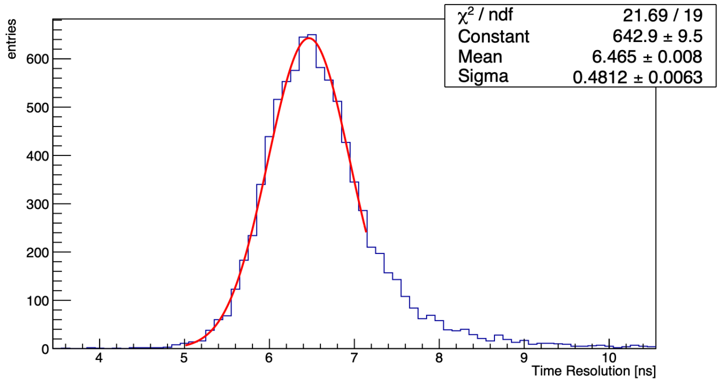
High Voltage Monolithic Active Pixel Sensors (HV-MAPS)

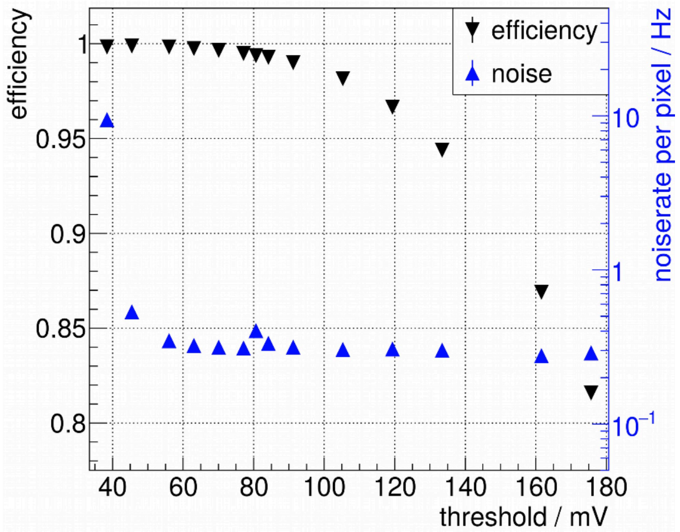
- 255x255 pixels, 80 μm pitch
- In pixel amplifier and line driver
- Point-to-point connection to periphery
- Digitisation, threshold trimming, time stamping
- Zero suppressed data driven readout @ 1.25Gbit/s LVDS



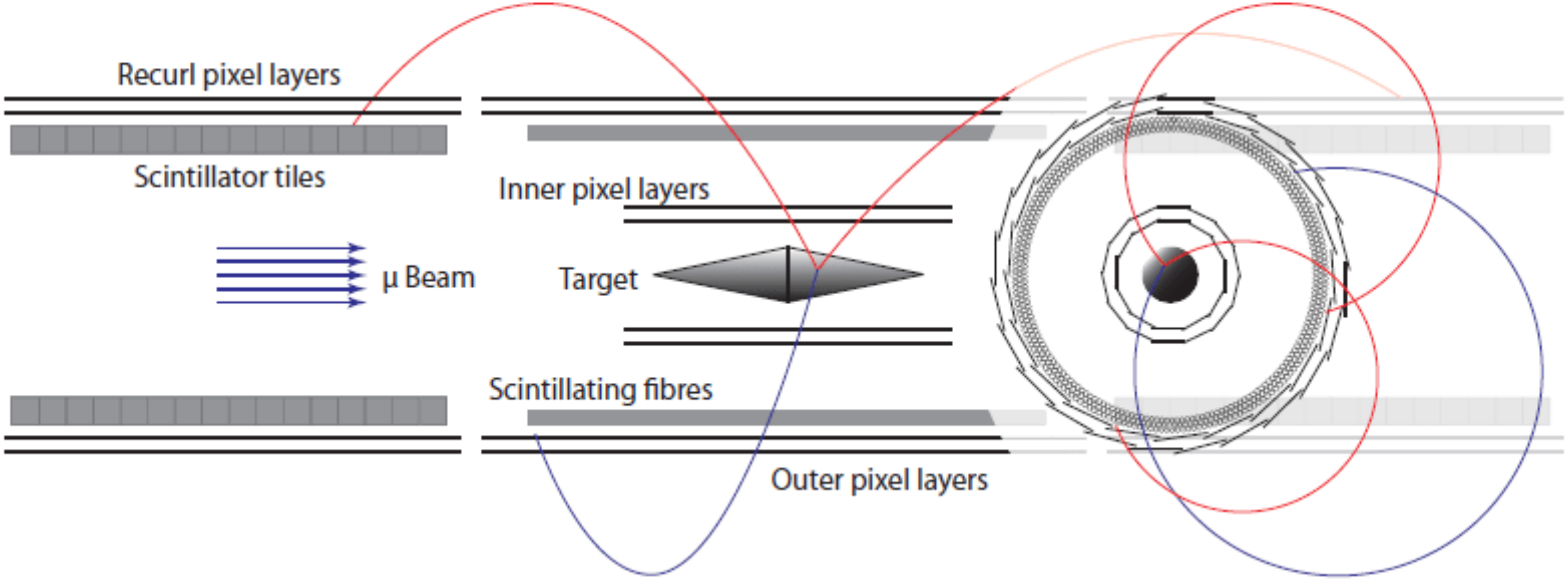
Sensor R&D

Large Scale HV-MAPS MuPix8 fulfilled all specifications:





The Mu3e detector



Mu3e physics