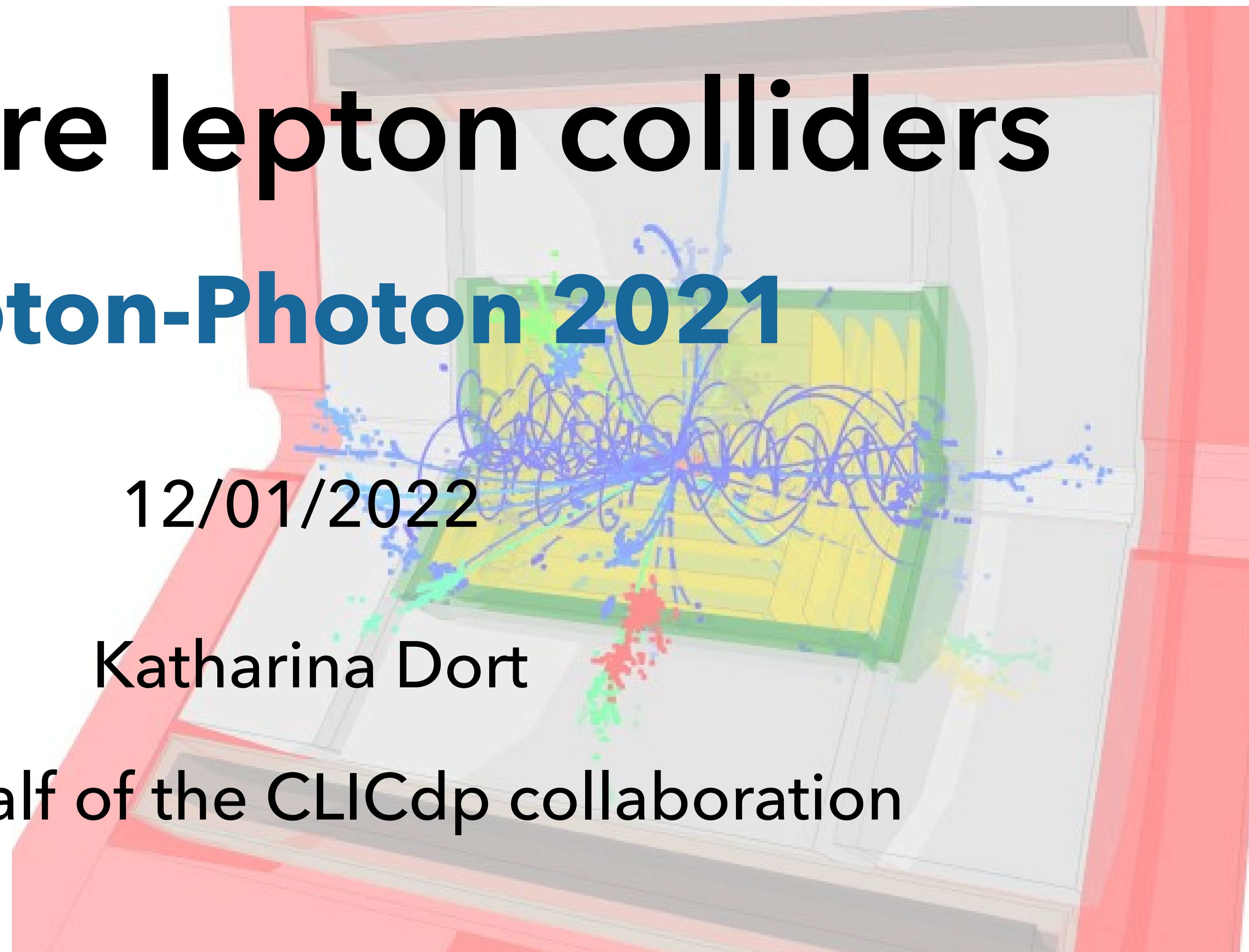
Silicon pixel-detector R&D for future lepton colliders

Lepton-Photon 2021



12/01/2022

Katharina Dort

On behalf of the CLICdp collaboration

Future lepton colliders

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CERN EP R&D

- Several proposals for future lepton colliders (linear/circular) with maximum CMS energies of 350 GeV to 3 TeV

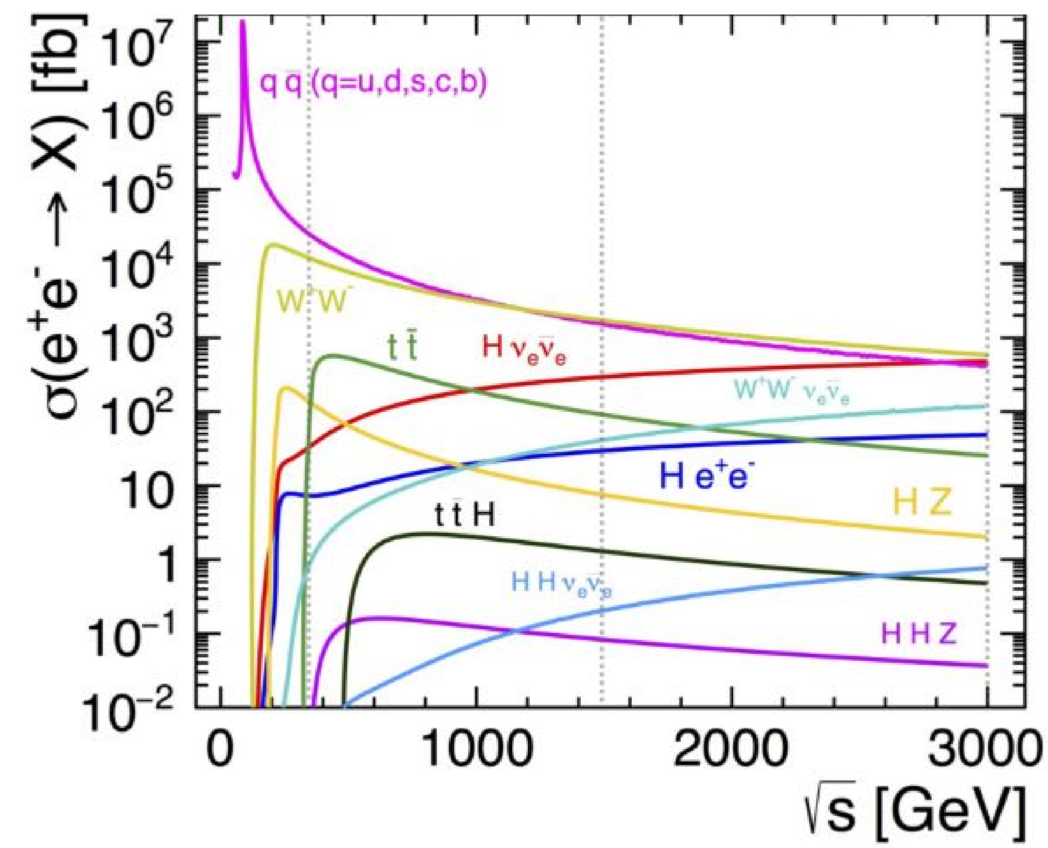
  ➡ Precision measurements of Higgs/Top properties
  (Only produced in hadron collisions so far)

  ➡ Measurement of electroweak precision observables

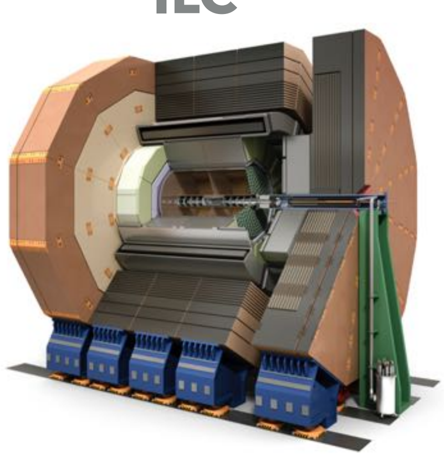
  ➡ Beyond the Standard Model searches
  (direct and indirect)

- Excellent vertex and tracking detectors needed for
  - Resolving secondary vertices
  - Excellent momentum resolution

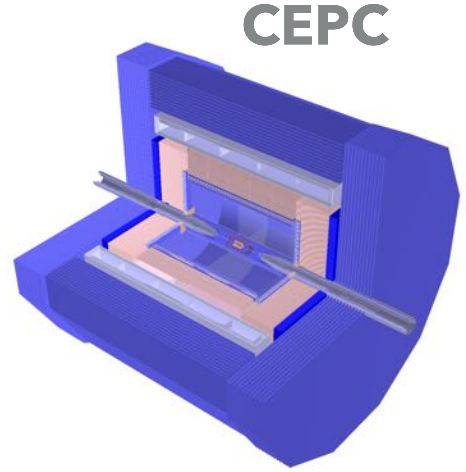
CERN-2018-009-M



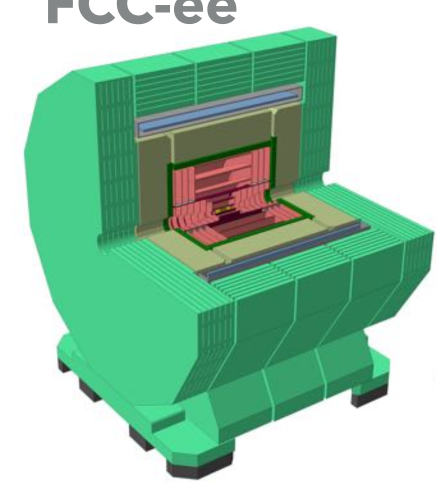
ILC



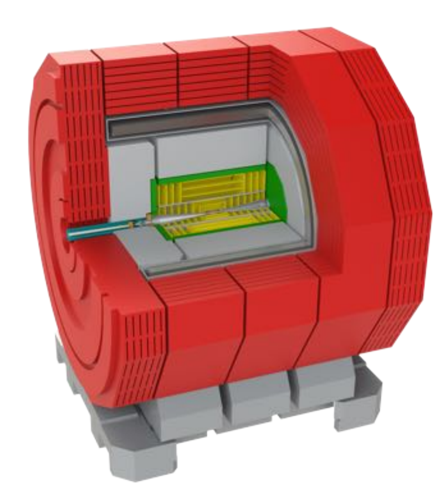
CEPC



FCC-ee

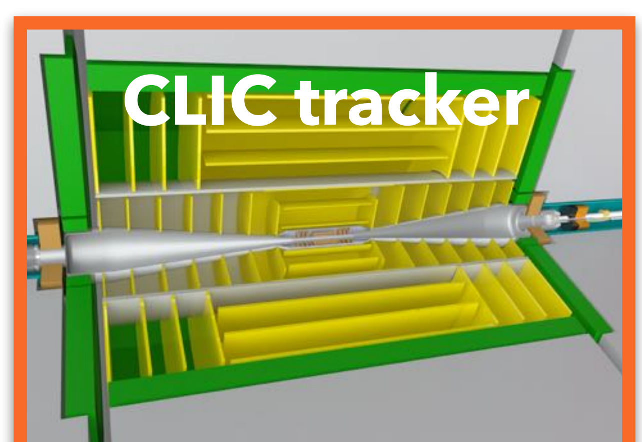


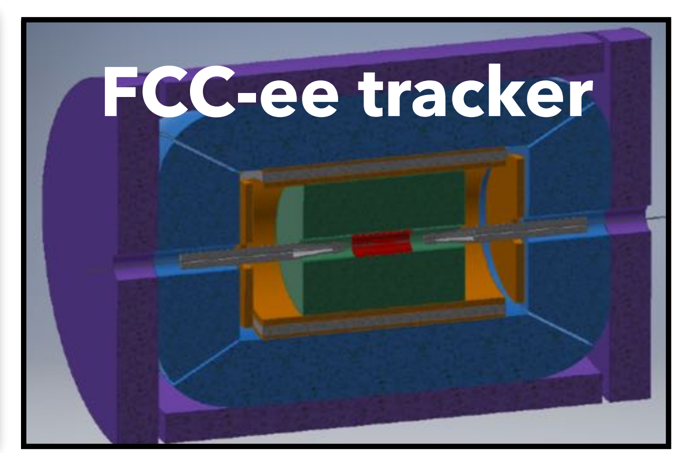
CLIC



Vertex and tracking detector requirements

- Vertex and tracking detectors for future lepton colliders require
  - Low material budget per layer : 0.2 - 0.3 %X0 (vertex) / 1 - 2 % X0 (tracker)
    - Low power consumption (to reduce material for cooling): 50 mW/cm² (vertex) / 150 mW/cm² (tracker)
  - High spatial resolution : 3 µm (vertex) / 7 µm (tracker)
  - Good time resolution for background rejection : down to 5 ns
- Benefits of precision timing (< 100 ps) for particle identification under study
- Less stringent requirements on radiation hardness compared to LHC experiments ($< 10^{10} - 10^{11} n_{eq}\, cm^{-2}\, y^{-1}$)
- Main differences linear/circular collider inner tracker requirements:
  - Much shorter duty cycle for linear collider
    - ➡ Power pulsing to reduce avg. power consumption
  - Higher background rates for linear collider
    - ➡ More stringent requirements on hit-time resolution





https://ep-dep.web.cern.ch/sites/default/files/Report%20final_0.pdf

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CLIC Silicon Detector R&D Overview

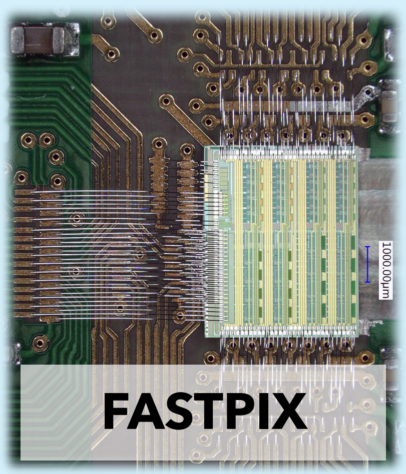
CERN EP R&D

Monolithic Sensors

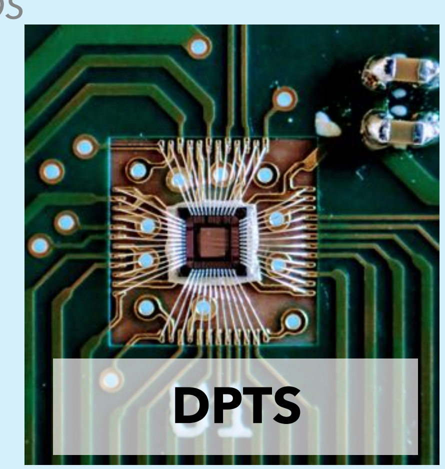
180 nm HV-CMOS

180 nm CMOS

200 nm SOI

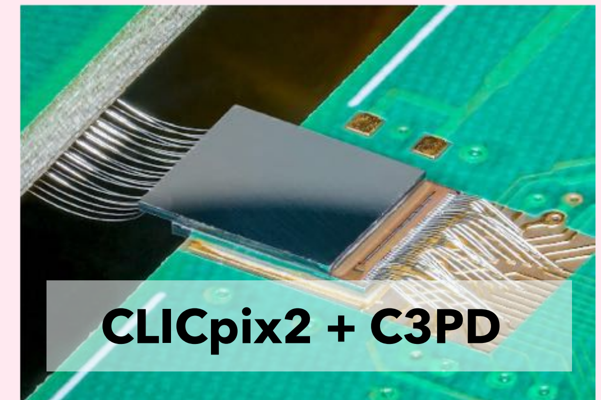


180 nm CMOS

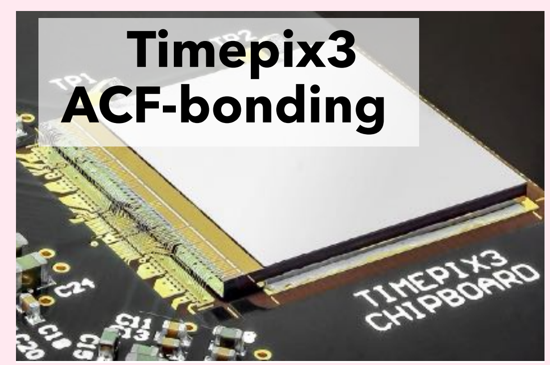


65 nm CMOS

Hybrid Assemblies



65 nm CMOS + 180 nm HV-CMOS



130 nm CMOS

65nm CMOS

Tools

Detector technologies for CLIC, CERN-2019-001

Caribou readout system

https://gitlab.cern.ch/Caribou

PoS 2020 (TWEPP2019), 100

MC Simulation framework: Allpix Squared

https://gitlab.cern.ch/allpix-squared/allpix-squared

NIM A 901 (2018) 164-172

Analysis & reconstruction framework: Corryvreckan

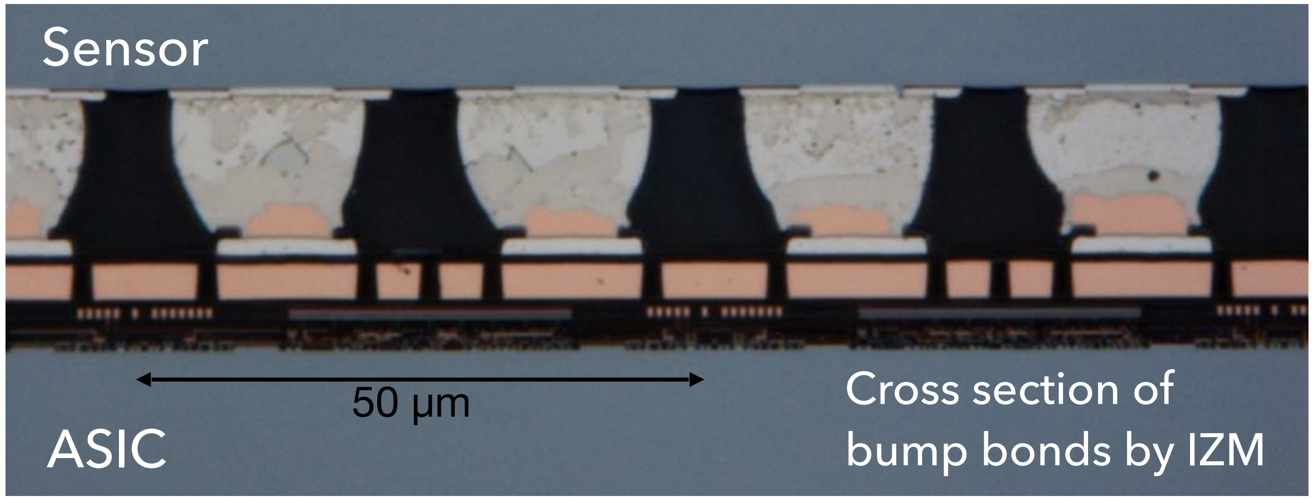
https://gitlab.cern.ch/corryvreckan/

2021 JINST 16 P03008

Hybrid fine-pitch pixel detector

CLICpix2 readout ASIC:

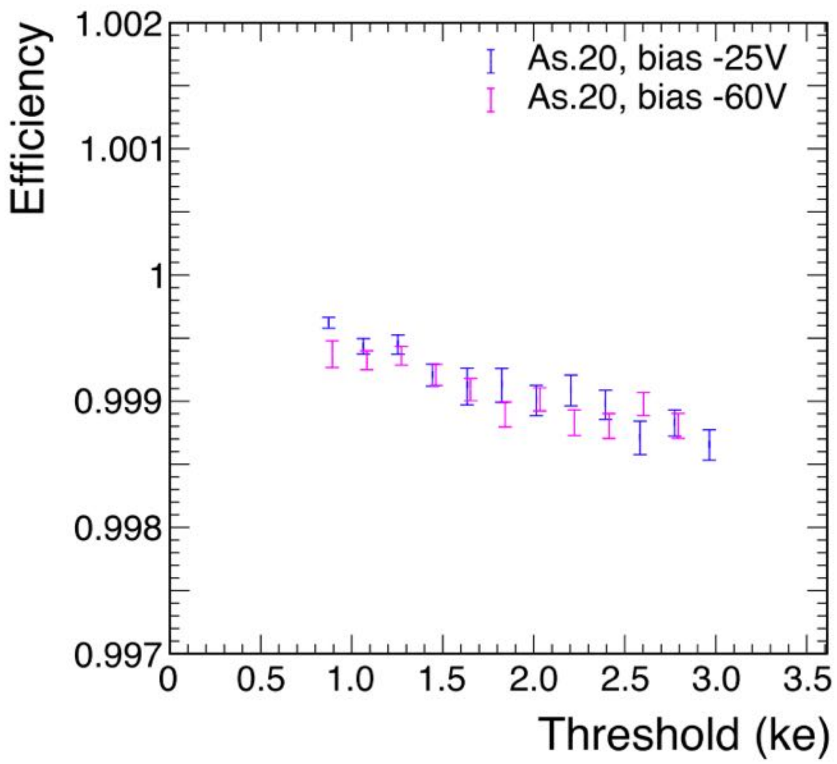
- 65 nm CMOS process
- Pixel pitch 25 μm x 25 μm (128 x 128 pixels)
- Bump-bonded to planar silicon sensors of thickness 50 μm - 200 μm
- Simultaneous 5-bit ToT + 8-bit ToA readout
- Part of Timepix/Medipix family



- Challenging single die bump-bonding process with pixel pitch of 25 μm developed by IZM
- Interconnect yield of up to 99.6%

JINST, 15(03), C03045

CERN-THESIS-2020-338



- Position resolution of ~3.2 μm for sensor thickness of 130 μm
- Timing resolution of ~4 ns
- Hit detection efficiency up to 99.97%
- Improved 50 μm thick samples (target thickness) are currently investigated

Anisotropic Conductive Film (ACF)

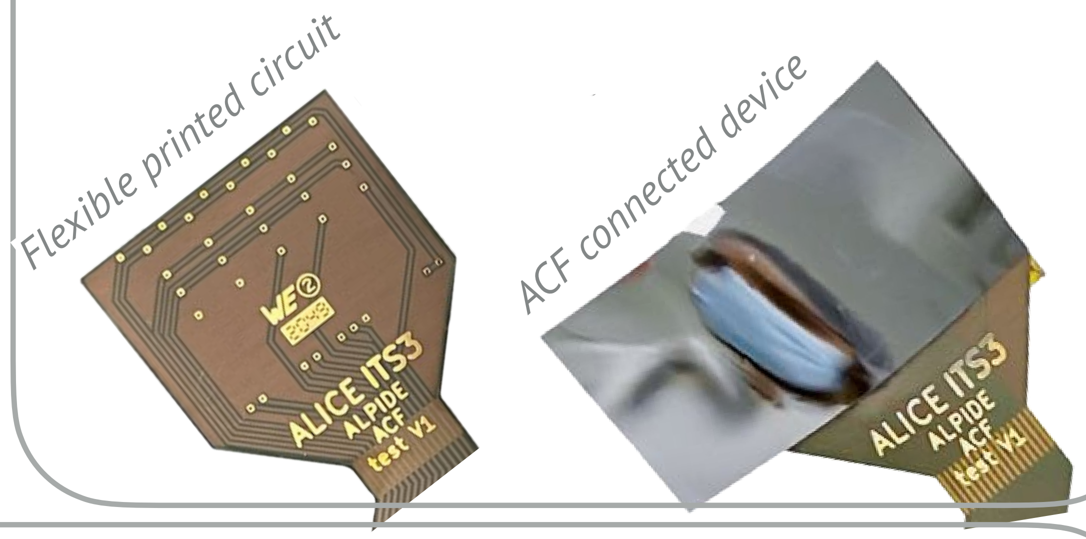
- Adhesive epoxy film with conductive micro particles
  - Compression of particles enables electrical connection between pads
- In HEP : new prospects for hybridisation and module integration

- In-house chemical ENIG (Electroless Nickel Immersion Gold) deposition for Under Bump Metallization (UBM)
- In-house semi-automatic flip-chip bonder used to connect the chips

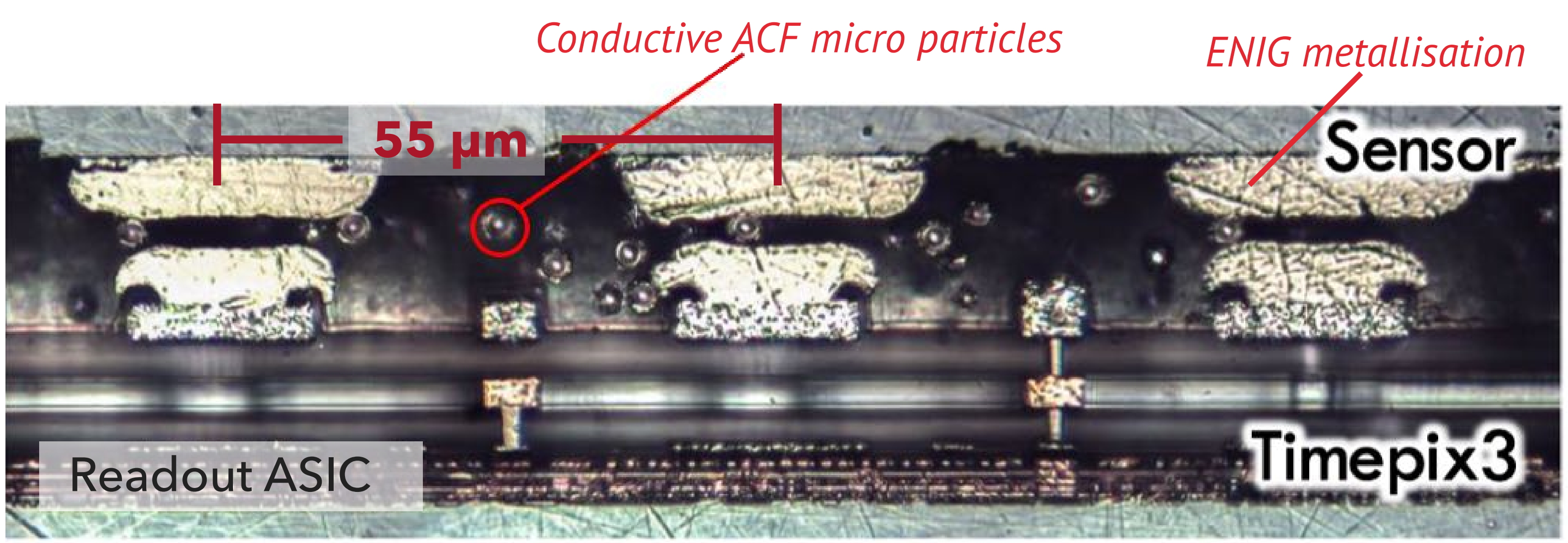
CERN-OPEN-2018-006

Module integration

- 50 μm ALPIDE sensor to flexible printed circuit
- Excellent electrical contact and nominal power consumption

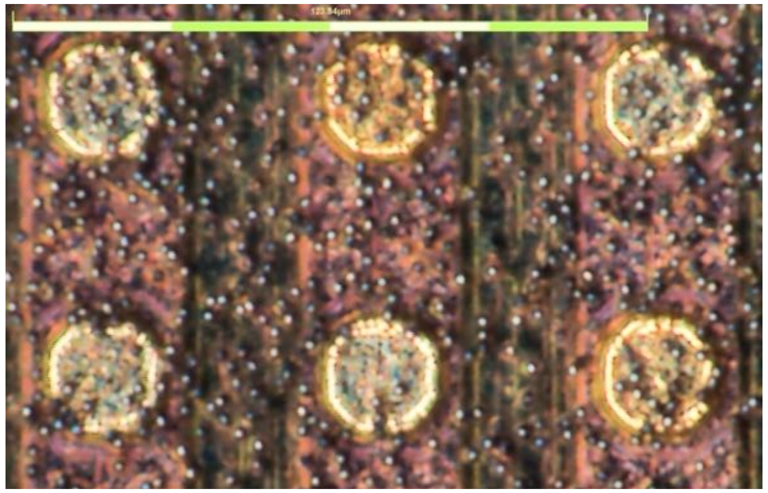


ACF-hybdridisation



https://agenda.linearcollider.org/event/9211/contributions/49469/attachments/37464/58685/ILCX_MVicente_ACF.pdf

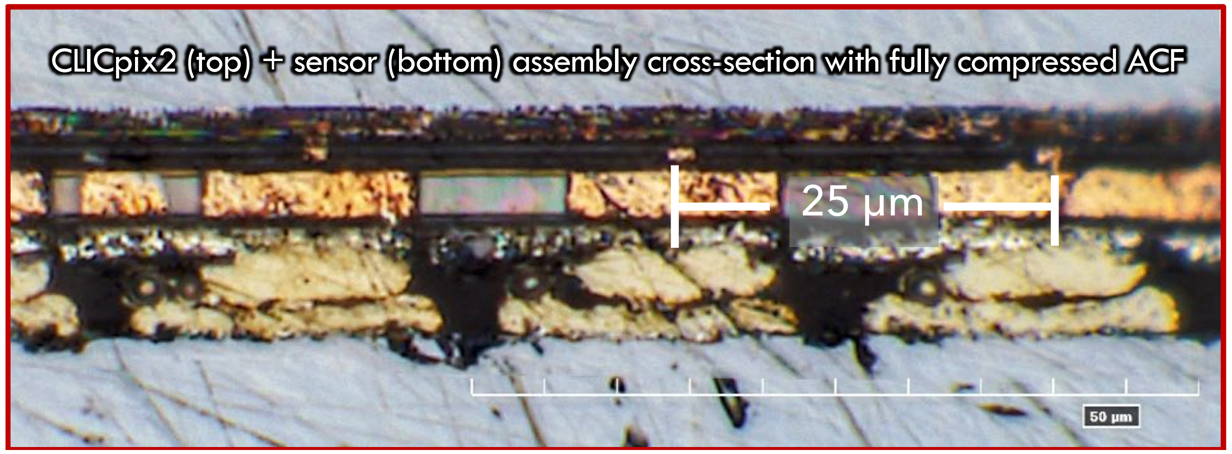
Timepix3 pixel matrix with ACF



ACF - Hybridisation Tests

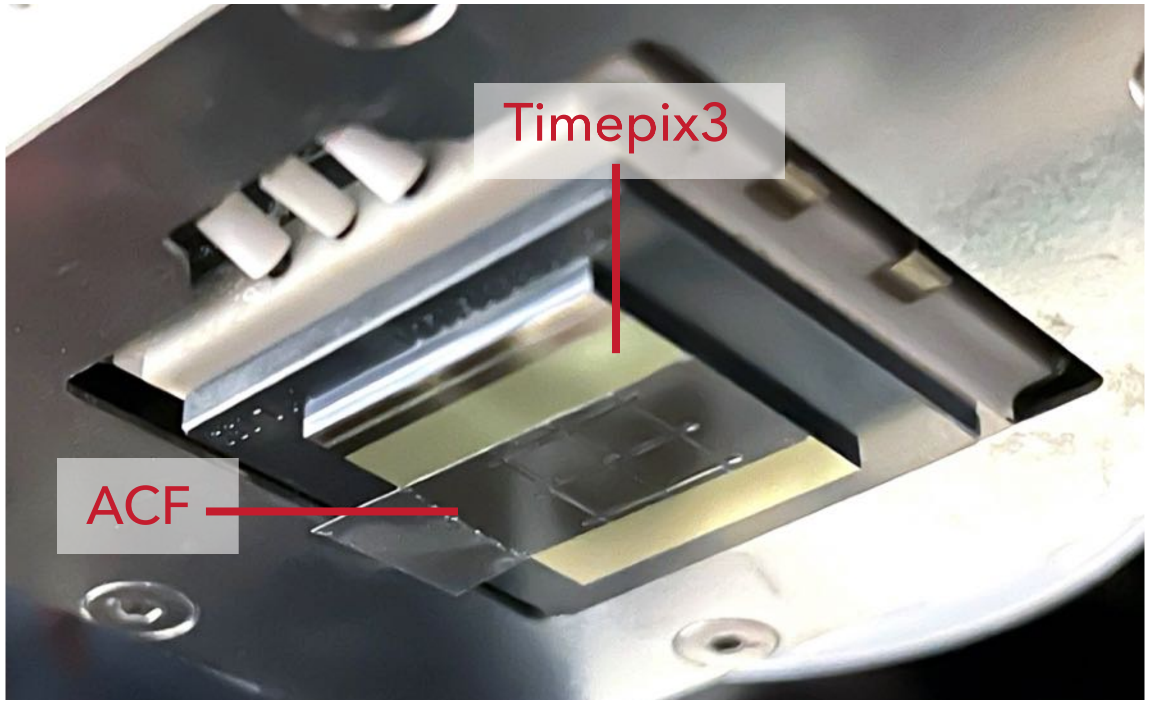
- Bonding tests performed with Timepix3 and CLICpix2 ASICs
- 18 µm film with 3 µm micro particles, 100 kg bonding force
- Proof-of-concept for bonding areas up to 1 cm² and 55 µm pitch
- Interconnection for larger areas / smaller pitch more challenging due to the required larger bonding force

Fine-pitch UBM plating with CLICpix2 ASICs



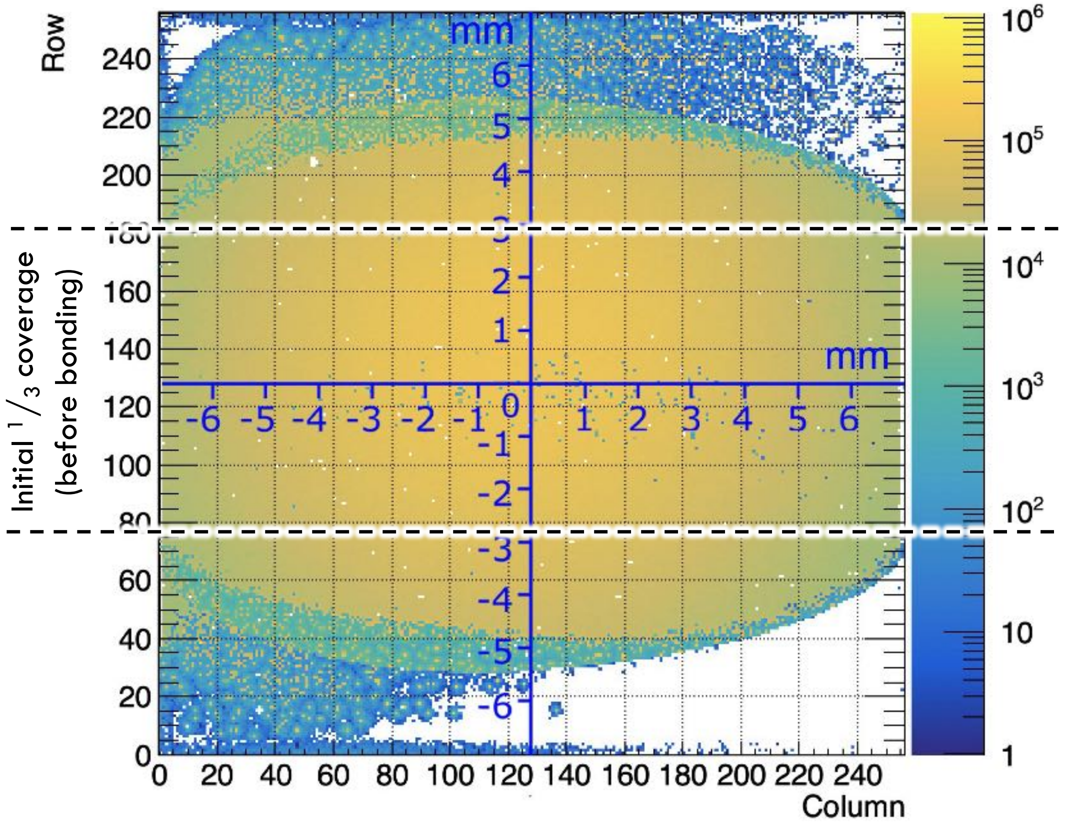
Bonding to Timepix3 sensor

Approx. 50% ACF coverage



Timepix3 hit map from Sr90 illumination

Approx. 30 % ACF coverage

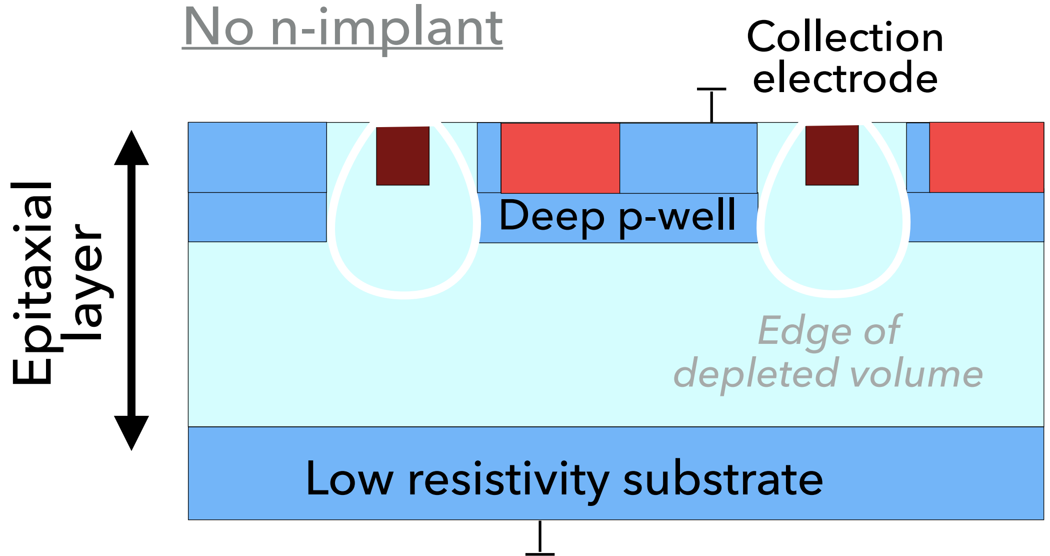


Small collection electrode monolithic CMOS

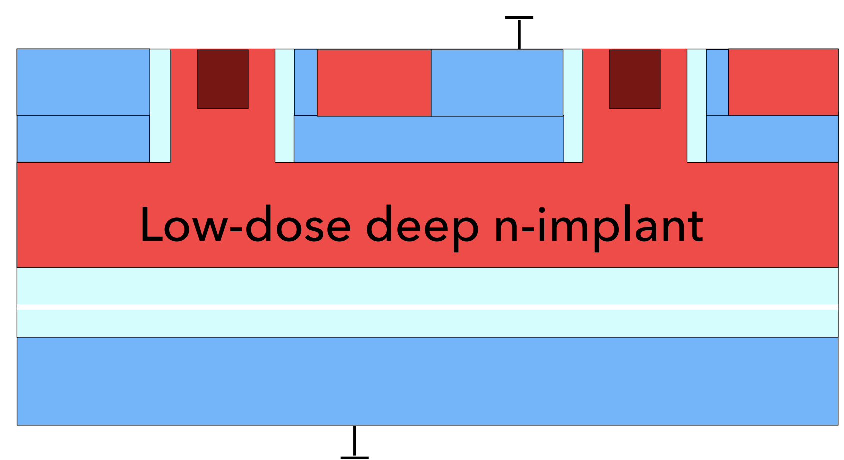
- Modified 180 nm CMOS imaging process with small collection electrode (O(fF) capacitance) (e.g. ALPIDE, (Mini-)MALTA, CLICTD, FASTPIX …)
- Deep low-dose n-implant for full lateral depletion
- Introduction of lateral doping gradient leads to accelerated charge collection
  - Comparison of various design modification in terms of detector performance

JINST 14 (2019) C05013

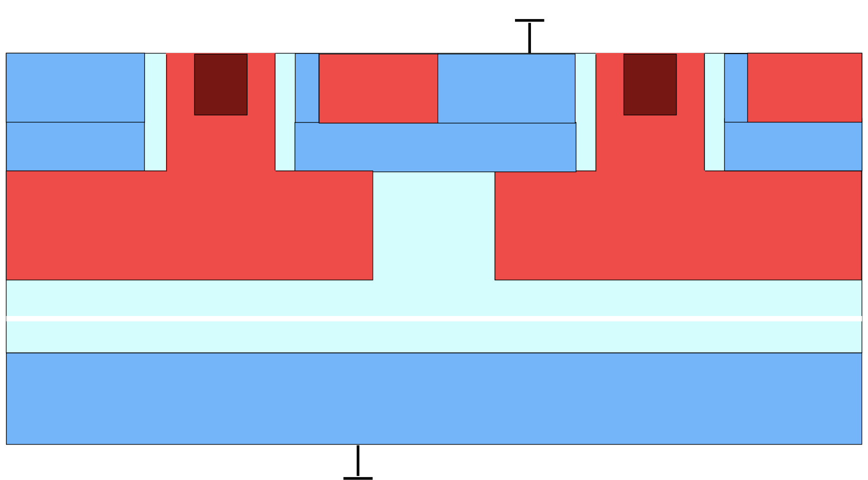
No n-implant



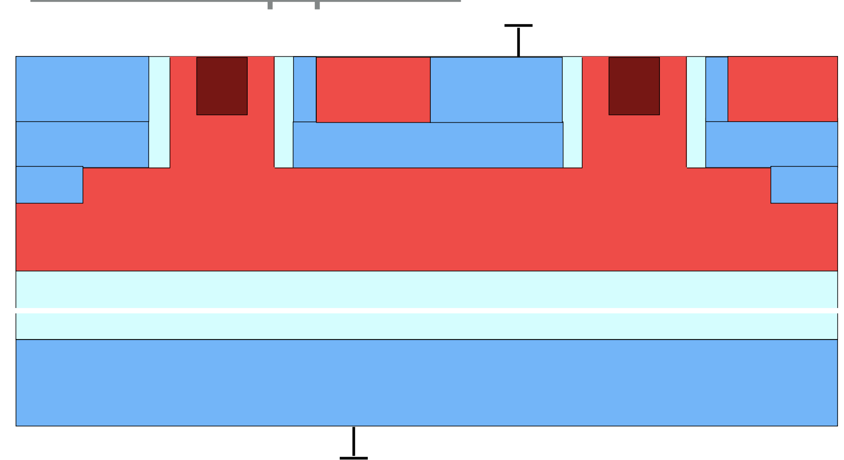
Continuous n-implant



Segmented n-implant



Extra deep p-well



Not to scale

Simulations

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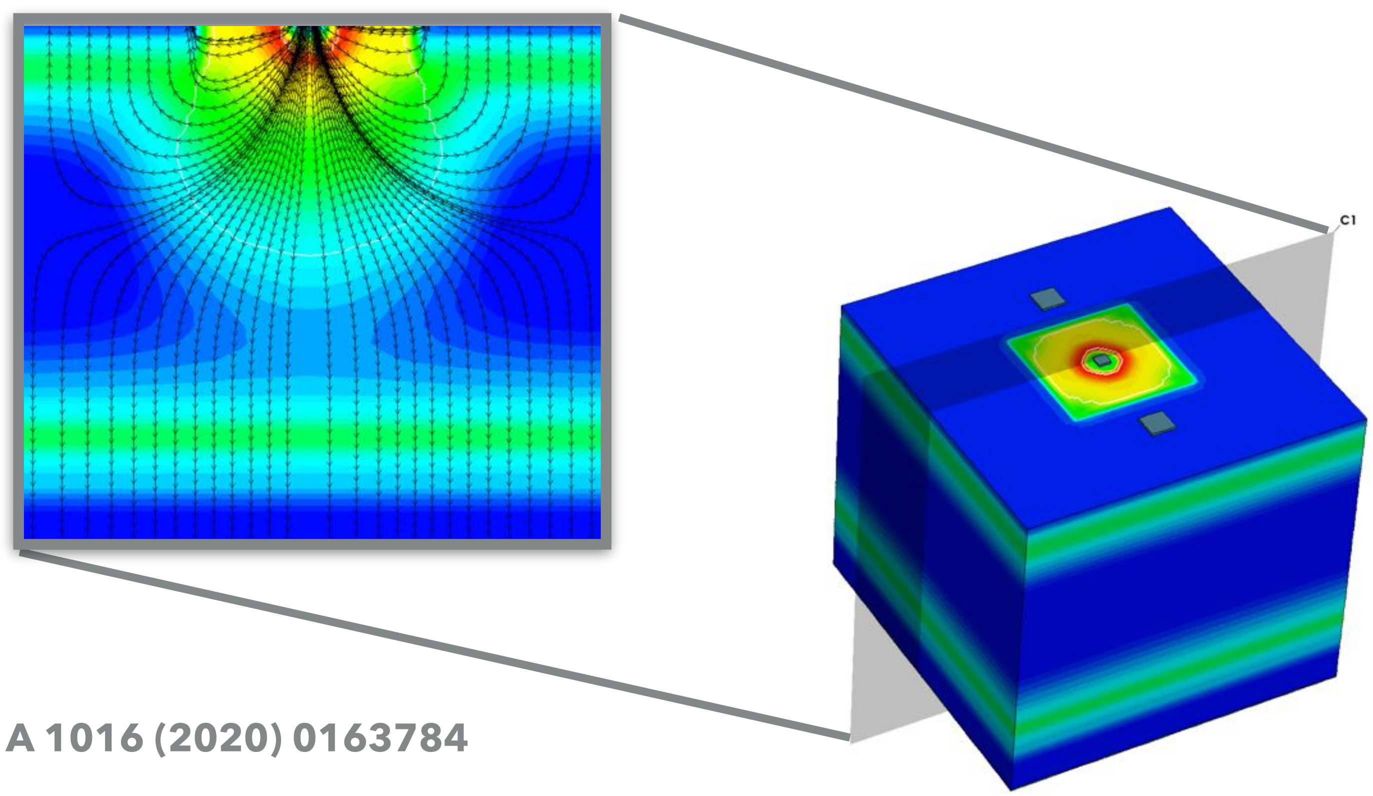
- Complex non-uniform field configurations in the small collection-electrode layout require design optimisations
- Finite-element (3D TCAD) and Monte Carlo (Allpix Squared) simulation to combine accurate sensor modelling with high simulation rates
- Validated against transient 3D TCAD and data

https://gitlab.cern.ch/allpix-squared/allpix-squared

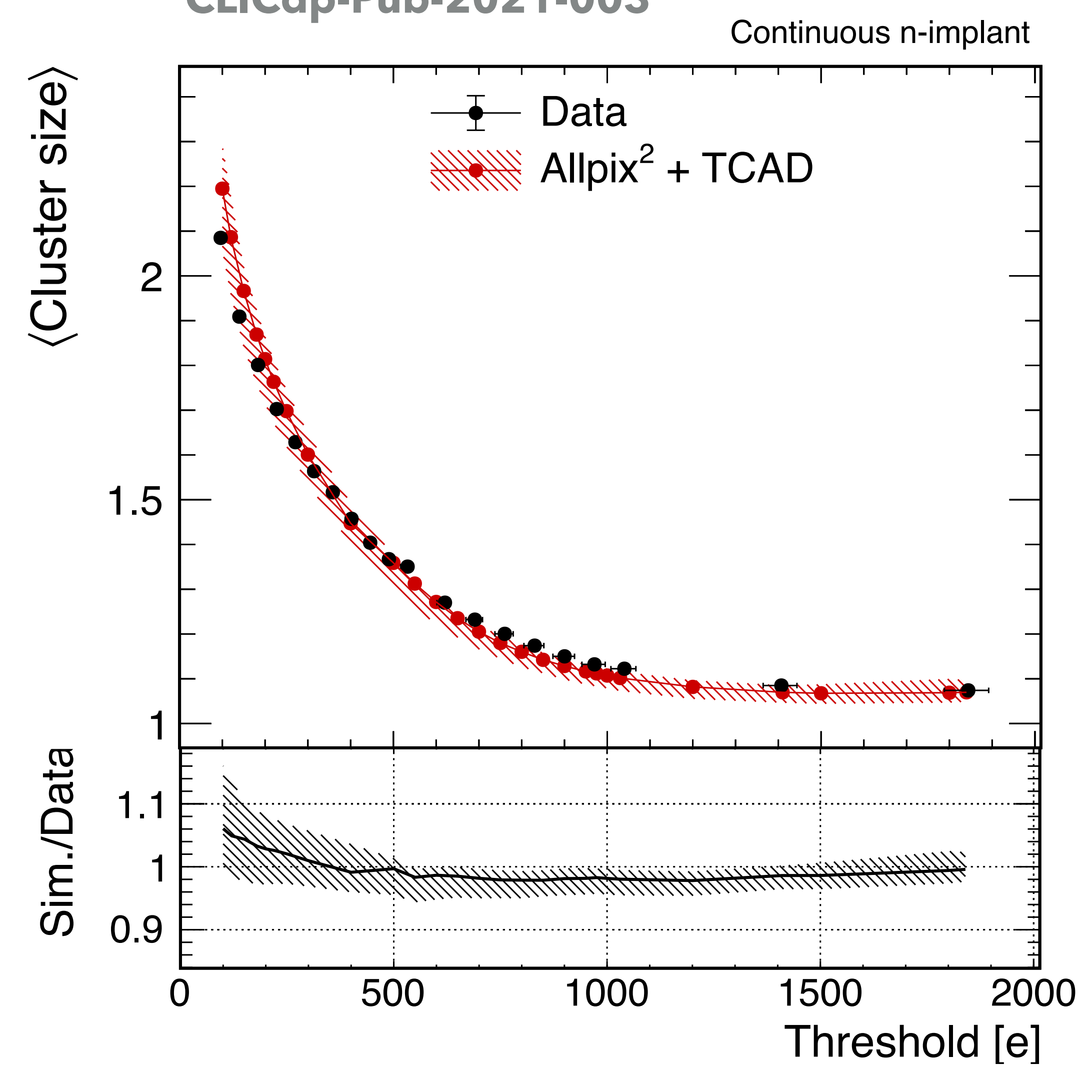
NIM A 901 (2018) 164172

Electrostatic potential + streamlines



NIM A 1016 (2020) 0163784

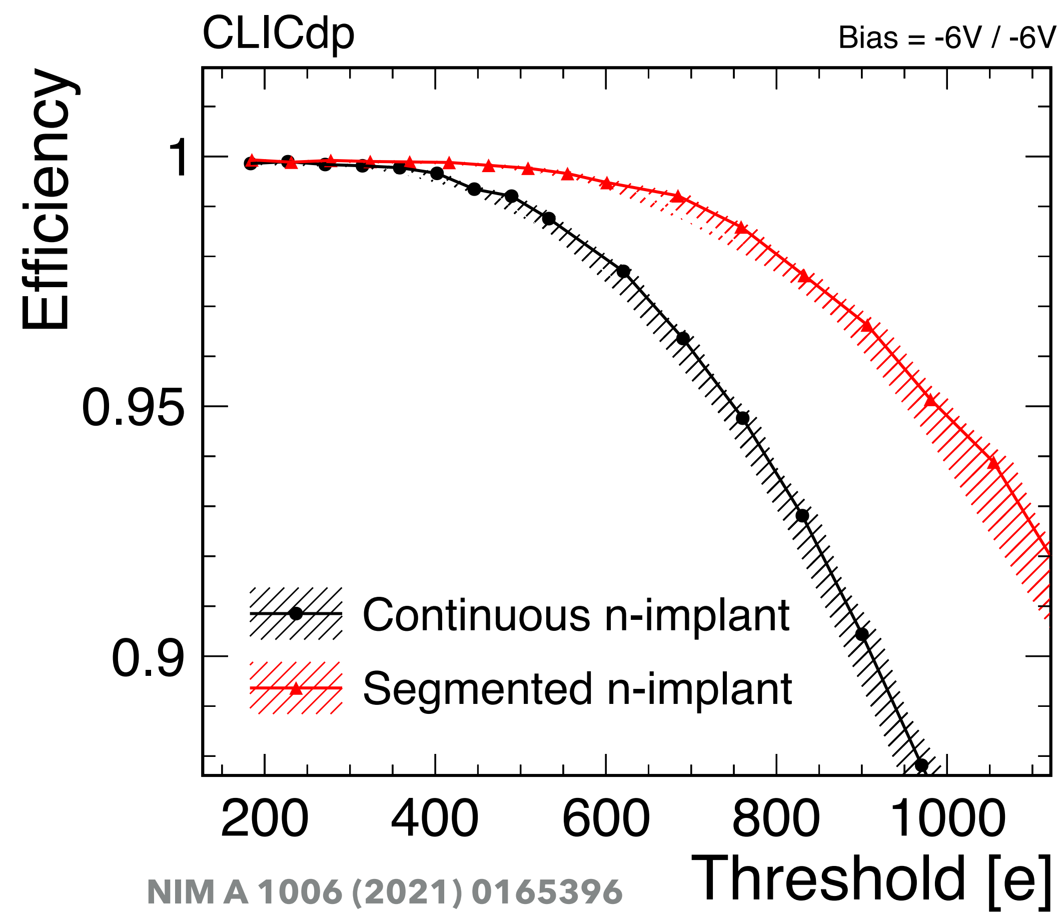
CLICdp-Pub-2021-003



CLICTD Technology Demonstrator

- Channel pitch: 300 μm x 30 μm (16x128 channels)
- Sub-pixel pitch: 37.5 μm x 30.0 μm
- Analogue front-end of 8 sub-pixels are grouped in one digital front-end (= readout channel)
- 8-bit ToA (10 ns ToA bins) + 5-bit ToT (combined ToA/ToT for every 8 sub-pixels in 300μm dimension)

IEEE Trans Nucl. Science 67.10 (2020): 2263-2272.



NIM A 1006 (2021) 0165396

- Threshold: ~100 - 180 e (occupancy < 10^{-3} hits/sec)
- Single pixel noise : < 15 e
- Spatial resolution : 4.6 μm
- Time resolution : 5.2 ns (Limited by front-end time resolution)
- Hit detection efficiency : > 99.7 %
- Sensor thickness : 40 - 300 μm

- Reduced charge sharing for pixel flavour with segmented n-implant leads to a higher concentration of charge in one pixel cell

➡ Improved efficiency at high thresholds

Advanced sensor materials

- Recent production using high-resistivity Czochralski (> 800 Ωcm) wafers allowing for larger depleted volume
  ➡ Larger active sensor volume

NIM A 986 (2021) 164381

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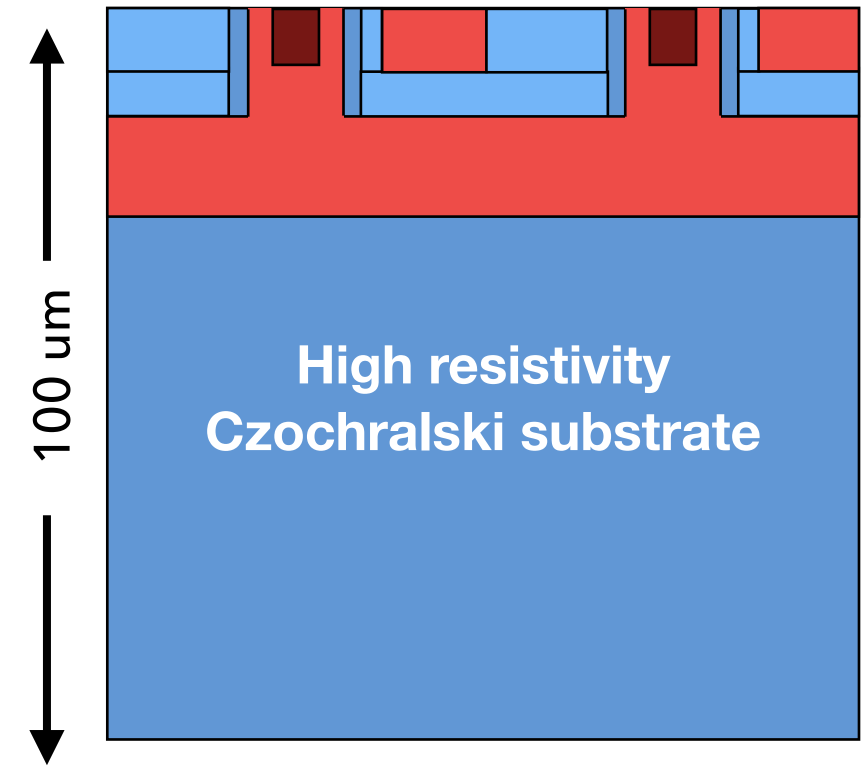
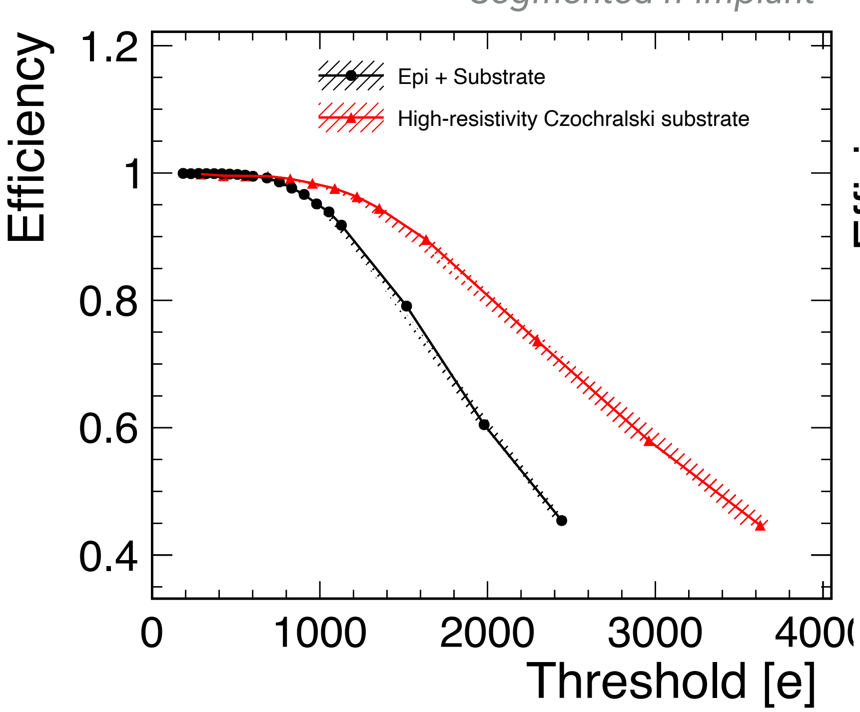
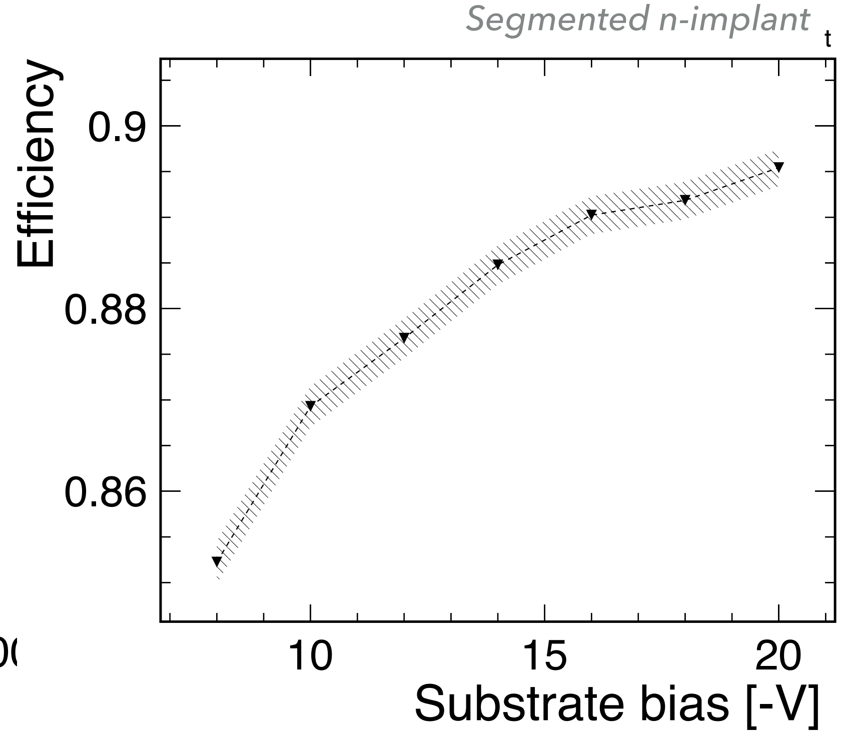


- Improved efficiency at high thresholds due to higher signal
- High-resistivity Czochralski sample enables combination of small collection electrode with large depleted volume
  ➡ Improvement for all performance parameters (though limited by front-end)

Segmented n-implant



Segmented n-implant



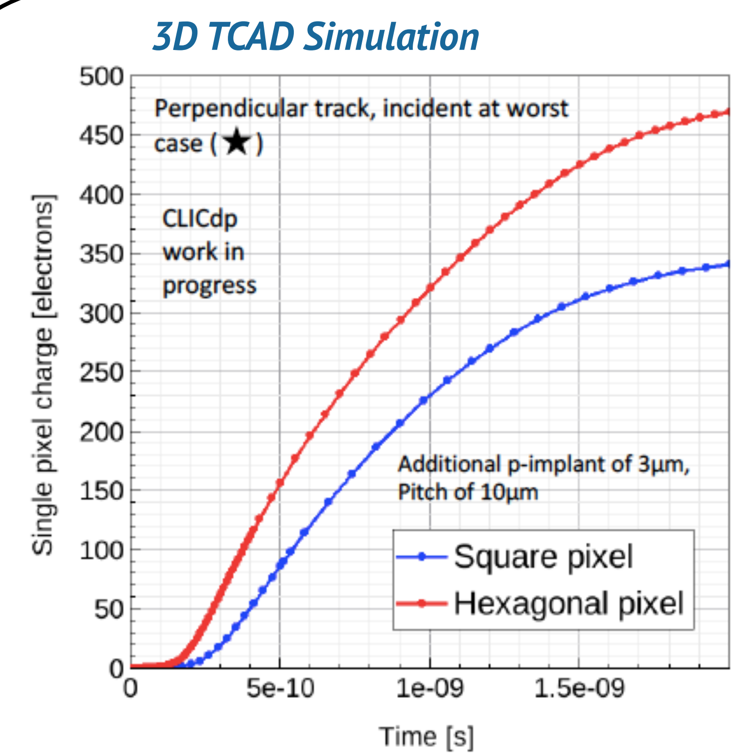
	Required (CLIC tracker)	Epi	Cz*
Spatial resolution	< 7 µm	4.6 µm	4.3 µm
Time resolution*	~ 5 ns	5.2 ns*	4.4 ns
Efficiency	> 99.7 %	> 99.7 %	> 99.7 %
Material content	< 200 µm	40 - 100 µm	100 µm

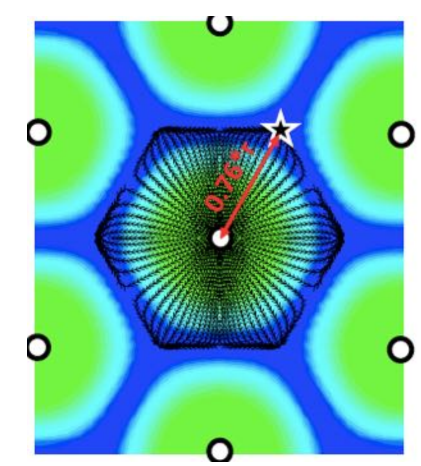
*limited by front-end

FASTPIX: Sensor design

Technology demonstrator for monolithic pixel detector with
sub-nanosecond timing

- Modified 180 nm CMOS imaging process
- 32 mini-matrices of hexagonal pixels (8.66 to 20 μm pitch)
- Each matrix has 4 analogue outputs + 4x16 pixels with position-encoded ToT/ToA
- Various sensor designs and process options
- Position and ToT encoding via delay lines (asynchronous readout)





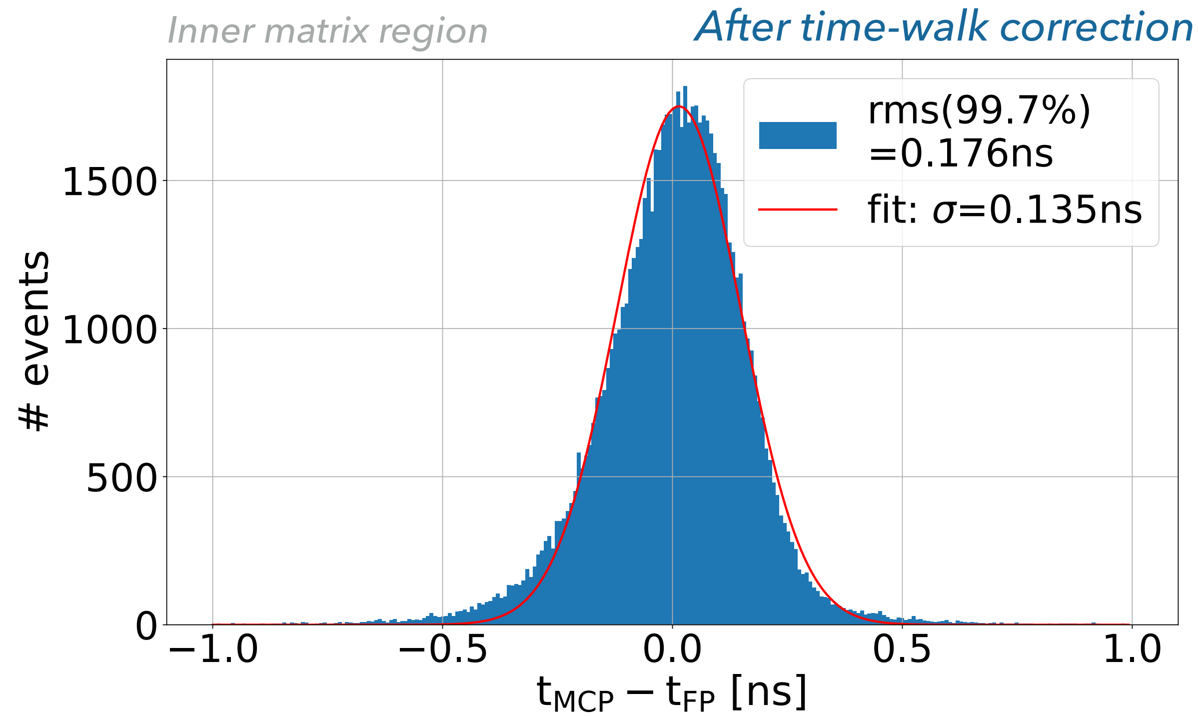
T. Kugathasan et al: Monolithic CMOS sensors for sub-nanosecond timing, Hiroshima 2019

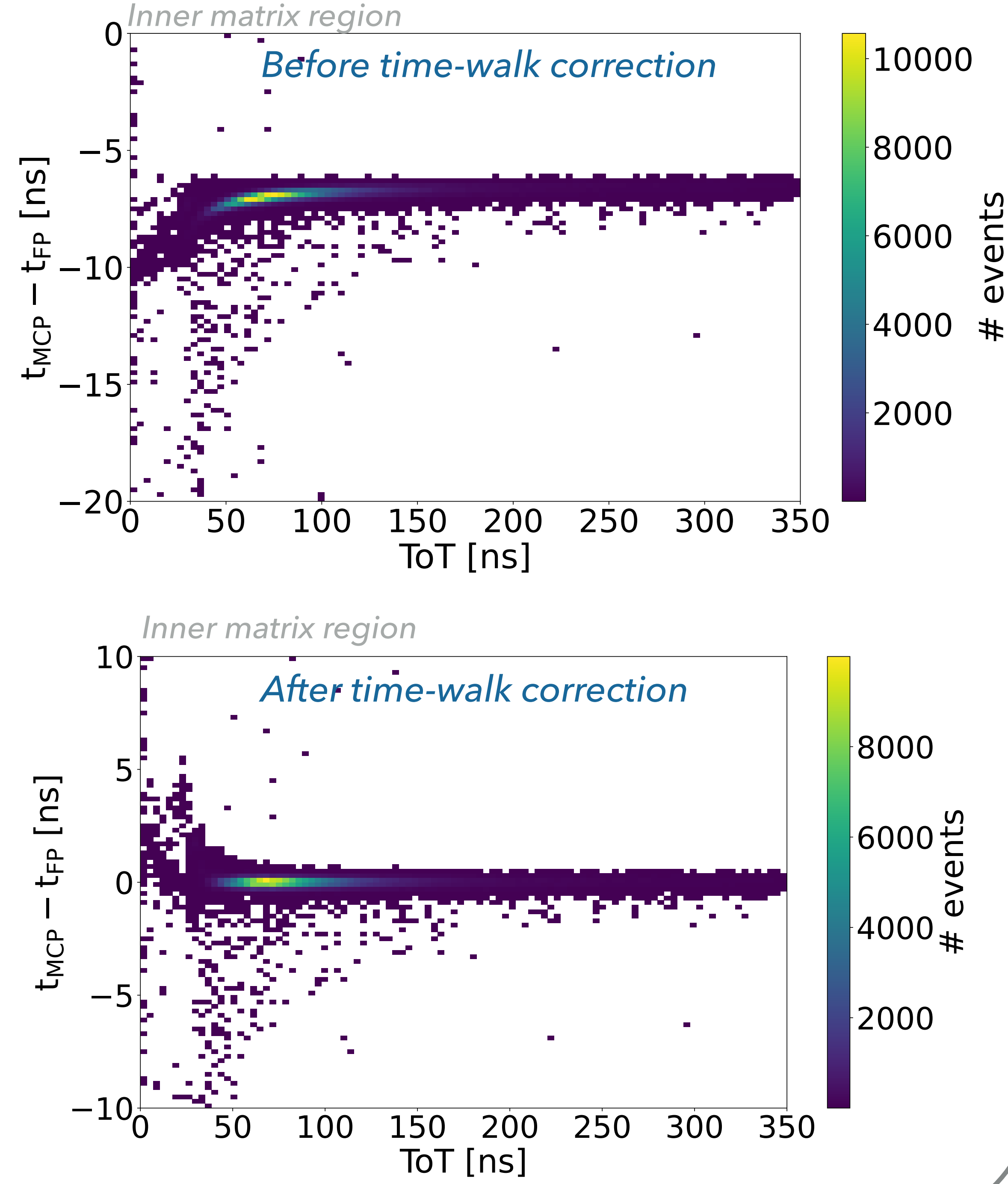
- Optimised for precise sensor timing in 3D TCAD studies
- Hexagonal pixel layout
  - Improved charge collection at pixel edges
  - Reduced number of neighbouring pixels
    ➡ less charge sharing

- Fast readout to investigate sensor time resolution (in sensor periphery)

FASTPIX: Measurements

- First calibration results (~ 20% uncertainty) : 43 e threshold and 5 e noise
- Strong time-walk effects in particular at matrix edge due to charge sharing
- Time resolution without time-walk correction: 500 ps
- Time resolution on the order of 120 -180 ps achieved after time-walk correction





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Summary

CERN EP R&D

- Diverse R&D programme to meet challenging requirements of future vertex and tracking detectors for lepton colliders

- Fine-pitch bump-bonding and alternative interconnection techniques for thin hybrid detector assemblies and advanced module concepts
  - ➡Individual vertex requirements are achieved with CLICpix2 hybrid assemblies
  - ➡Combination of required performance + low material budget still challenging

- Monolithic small-collection electrode sensors with optimised sensor design, wafer materials and pixel geometries
  - ➡Tracker sensor requirements are fulfilled in CLICTD demonstrator

- Sub-nanosecond time resolution achieved with FASTPIX demonstrator

Thank you for your attention

DESY.

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

Back - up

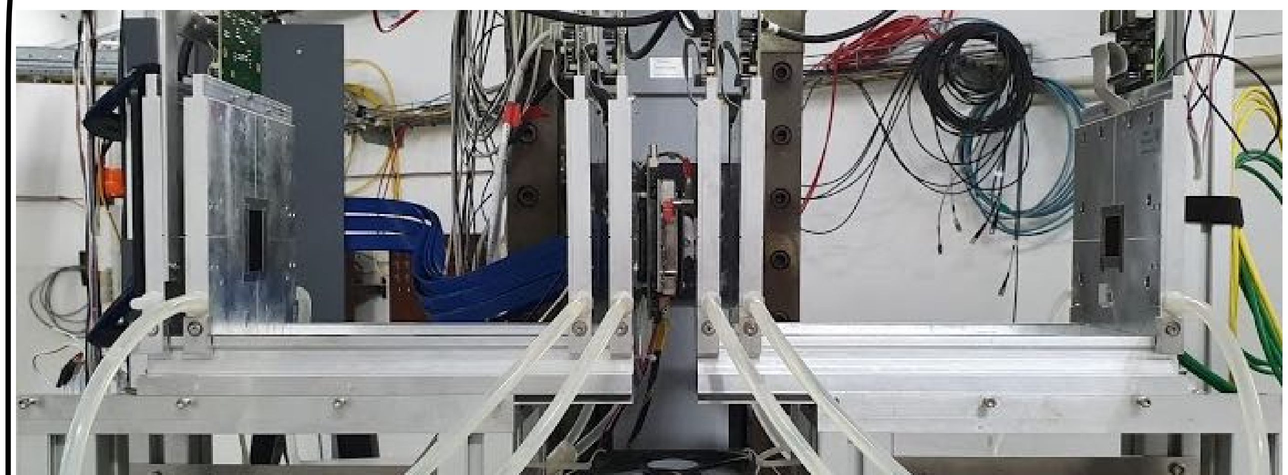
Test-Beam Set-Up

CERN Super Proton Synchrotron (SPS)

- 120 GeV pion beam
- Telescope with high-rate capabilities for small prototypes
- 6 Timepix3 planes + Micro-channel plate as fast time reference

(2 LGADs for additional time reference)

DESY II Test Beam Facility



- 5.4 GeV electron beam
- MIMOSA-26 reference telescope equipped with Timepix3 plane for improved time reference

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

Corryvreckan reconstruction framework

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

2021 JINST 16 P03008

Simulations

- Simulations were compared to data from various sensor designs with different charge collection properties

- Realistic simulation scenario by including stochastic effects, fluctuations and generation of secondary particles

- Good agreement with data is achieved if 3D TCAD sensor model is used

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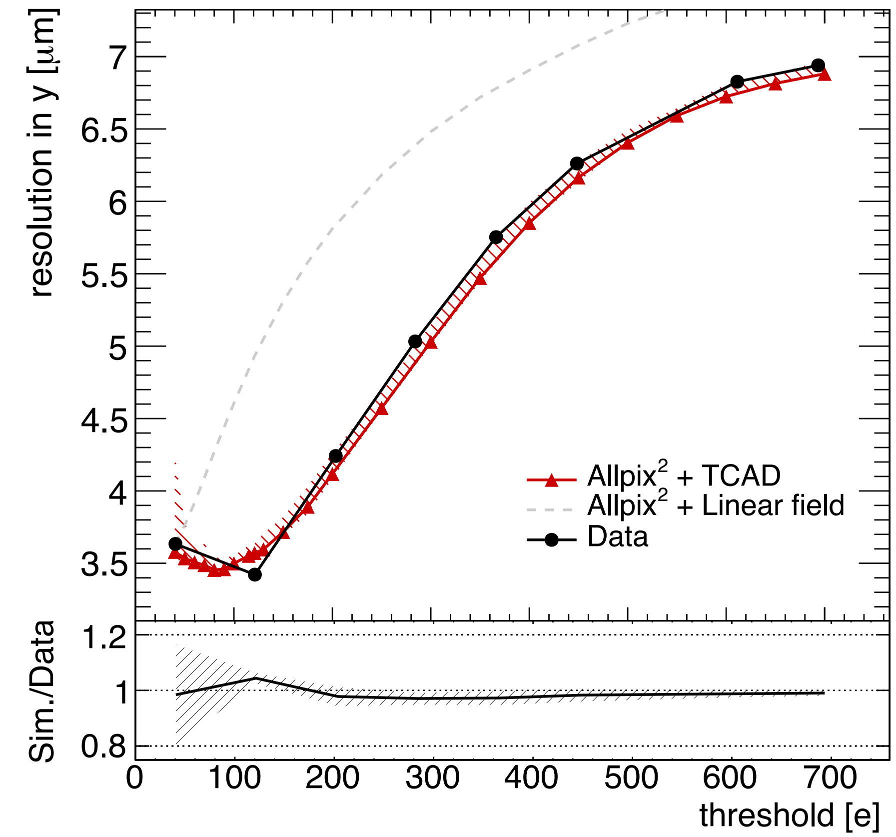
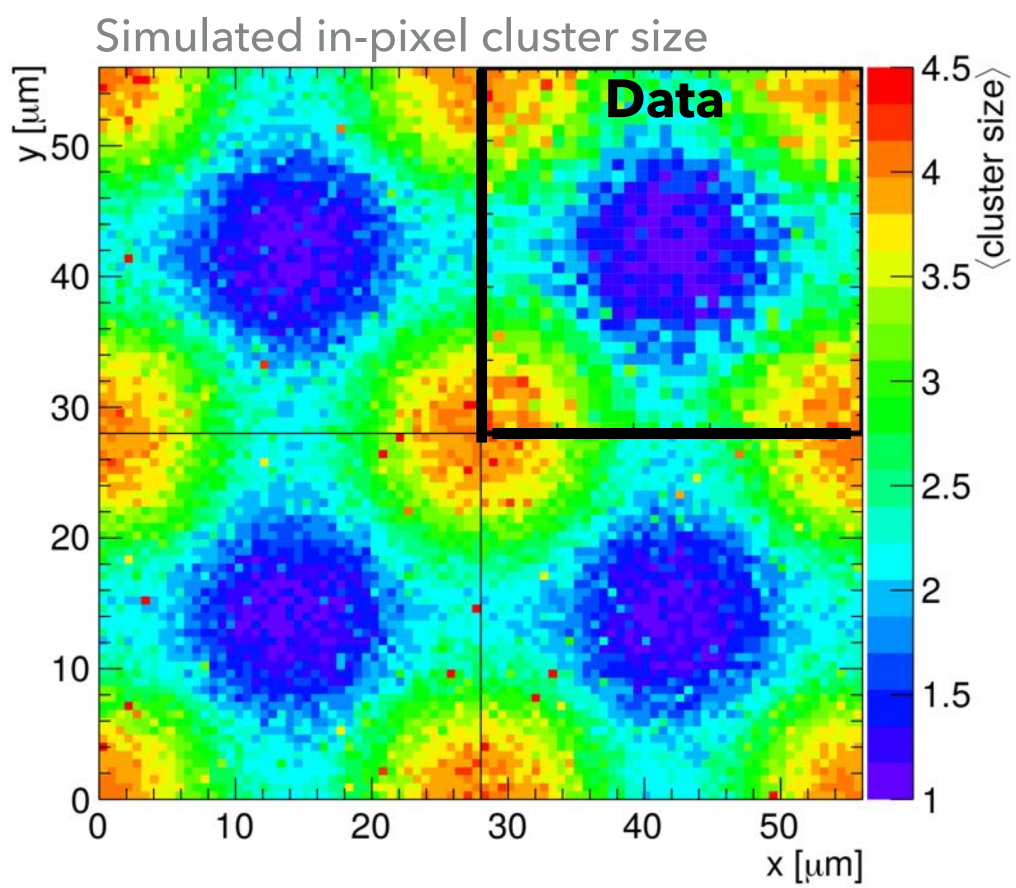
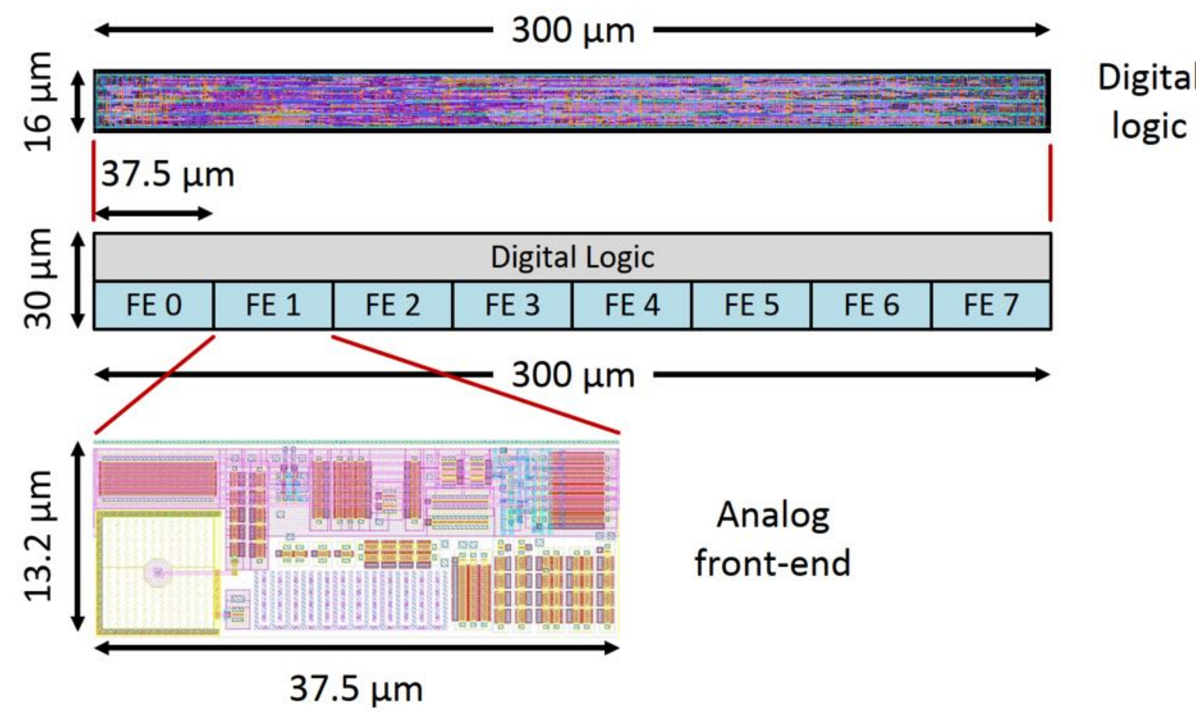
- Crucial ingredient in the sensor optimisation for the next-generation of small collection electrode monolithic sensors in 65 nm CMOS design





CLICTD - front-end design

- Detector channel consists of 8 sub-pixels (diode + analogue front-end)
- Channel pitch: 300 µm x 30 µm (16x128 channels) (Higher granularity in B-field bending plane for momentum measurements)
- Collection electrode pitch: 37.5 µm x 30.0 µm



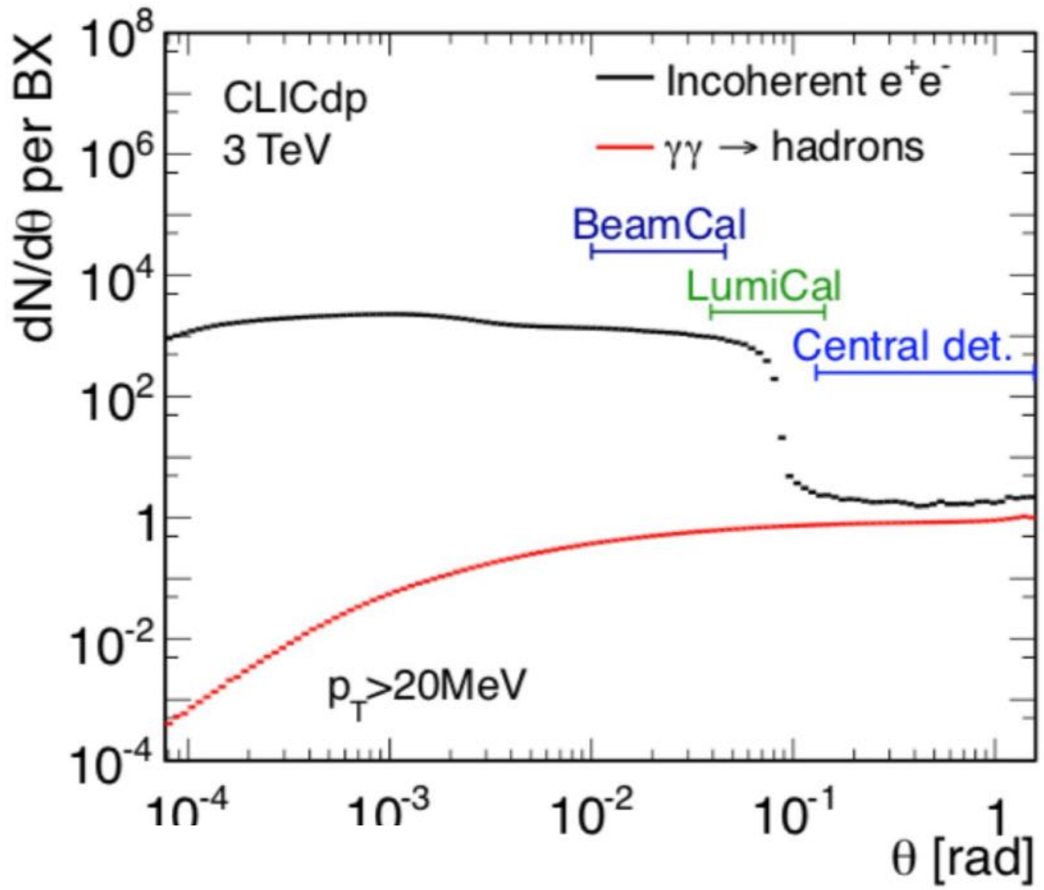
IEEE Trans Nucl. Science 67.10 (2020): 2263-2272.

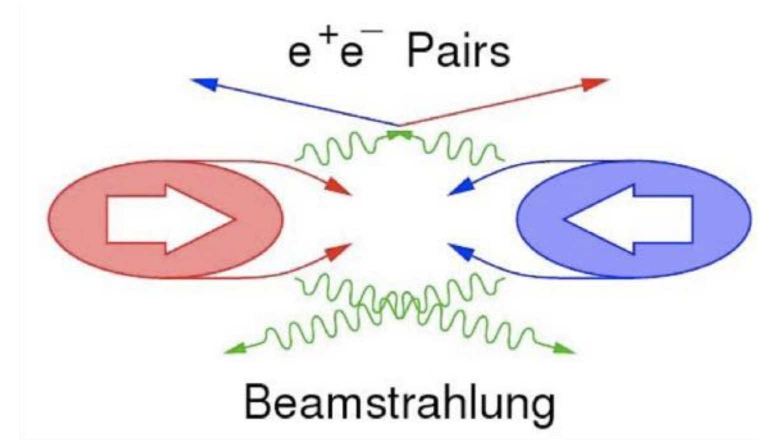
- Discriminator output of sub-pixels is combined in logic OR for ToT (charge) and ToA (time) measurements (one ToT and ToA per channel)

  ➡ Save space for digital circuitry while maintaining small capacitance and fast charge collection

- Binary hit-map in detection channel available
- 8-bit ToA (10 ns ToA bins) + 5-bit ToT (programmable from 0.6 - 4.8 µs) (combined ToA/ToT for every 8 sub-pixels in 300µm dimension)

CLIC/FCC-ee Background





- Incoherent e+e- pairs (19k particles/ bunch train)

Table 7.1. Total numbers of $e^{\pm}$ created per BX by incoherent pair production, their total energy, and the rates of these particles that would reach the CLD vertex detector within a magnetic field of 2 T. Numbers are obtained from GuineaPig, prior to any detector simulation.

$\sqrt{s}$ (GeV)	91.2	365
Total particles	800	6200
Total E (GeV)	500	9250
Particles with $p_T \geq 5$ MeV and $\theta \geq 8°$	6	290

https://link.springer.com/content/pdf/10.1140/epjst/e2019-900045-4.pdf

FASTPIX Front-end