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DPG SPRING CONFERENCE 2025

ADVANCES IN SILICON DETECTORS

Matthias Hamer, University of Bonn

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OUTLINE

- Introduction
- State of the Art
- Future Detectors
    - Low Mass Detectors
    - Silicon Timing Detectors
    - Calorimetry with Silicon Sensors
    - Further R&D and Other Applications

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- **Introduction**
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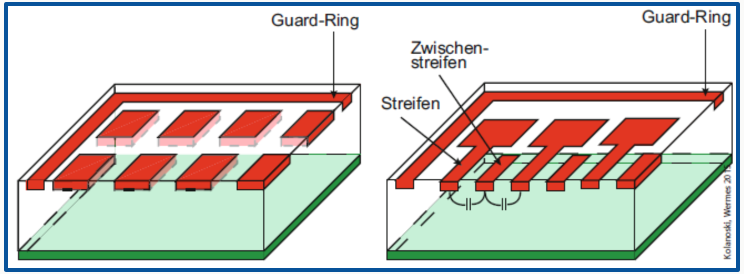
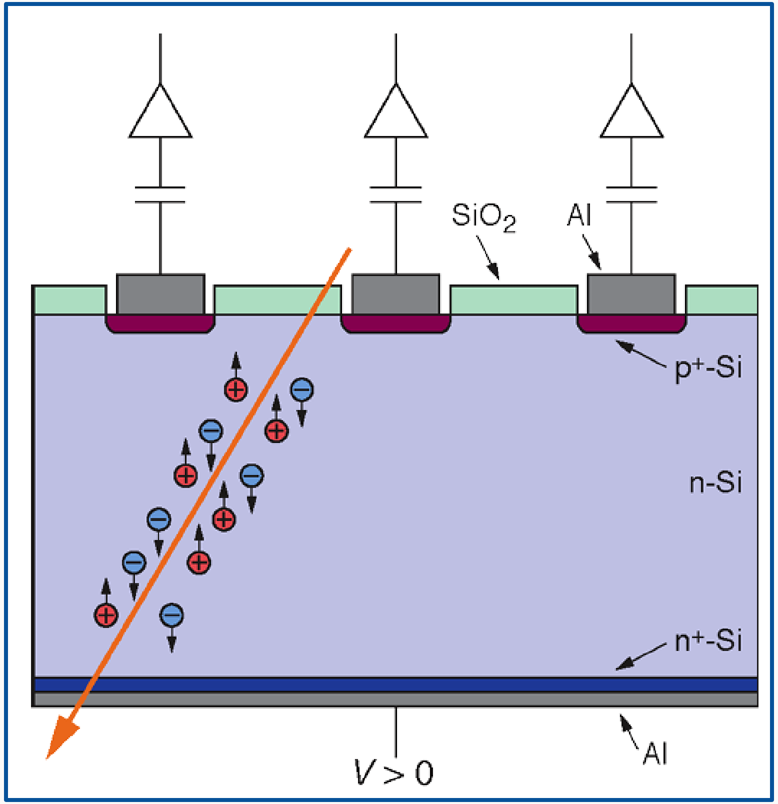
INTRODUCTION

- requirements for tracking detectors:
  - excellent spatial resolution
  - good signal to noise ratio
  - low X/X_0
  - …
- silicon detectors can meet all of the requirements
  - micro-structuring
  - no excessive cooling required
  - thin and radiation hard sensors and FE electronics

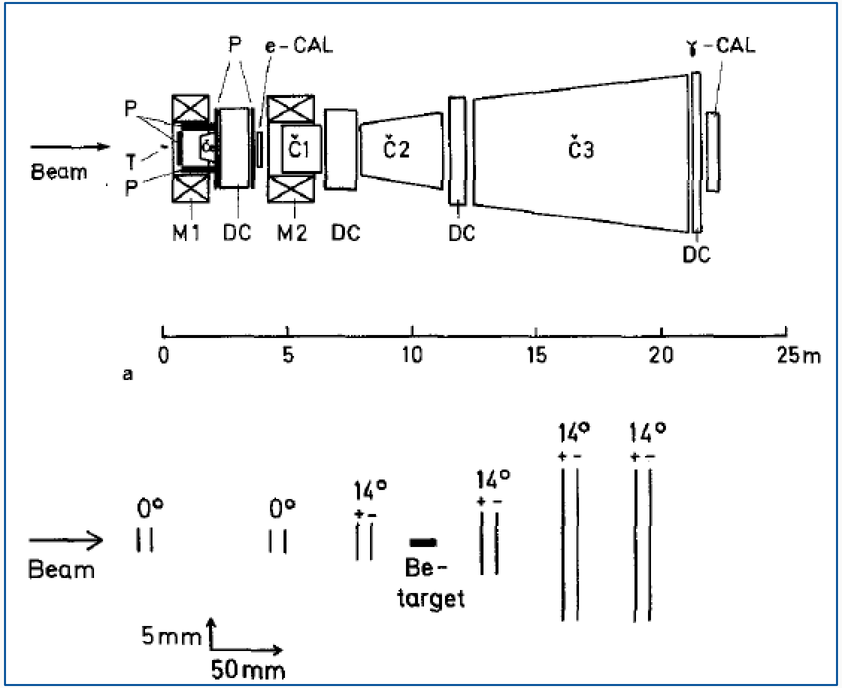




INTRODUCTION

- silicon detectors in HEP – 2 examples
  - NA11/NA32 – lifetime of D-mesons

Abstract. We have measured the lifetime of charged and neutral D mesons using high resolution silicon strip detectors in the NA11 spectrometer at the CERN SPS. The D mesons were produced in 200 GeV π^--Be interactions. We obtain a value of $\tau_{D^\pm} = \left(10.6^{+3.6}_{-2.4}\right) \cdot 10^{-13}$ s based on 28, and $\tau_{D^0} = \left(3.7^{+1.0}_{-0.7}\right) \cdot 10^{-13}$ s based on 26 fully reconstructed decays for the lifetime of the charged and the neutral D meson, respectively. For the ratio $\tau_{D^\pm}/\tau_{D^0}$ we find $2.8^{+1.1}_{-0.8}$.



Bailey et al., *Z. Phys. C - Particles and Fields* 28, 357–363 (1985)

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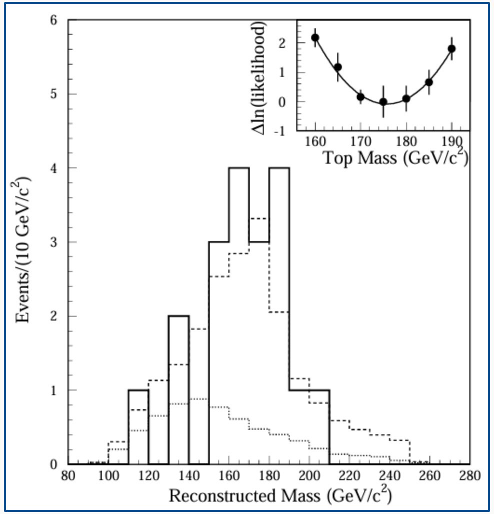
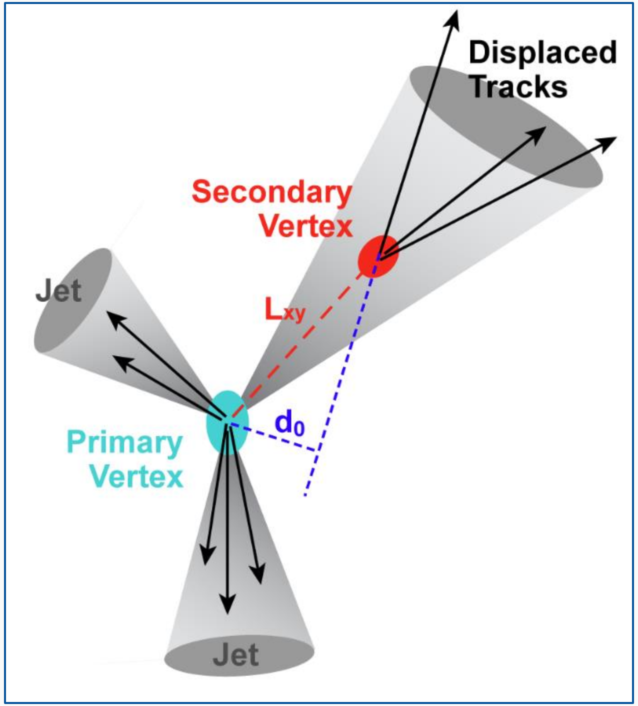
INTRODUCTION

- silicon detectors in HEP – 2 examples
    - NA11/NA32 – lifetime of D-mesons
    - Tevatron experiments – discovery of the top quark



CDF Collaboration., Phys.Rev.Lett.74:2632-2637,1995



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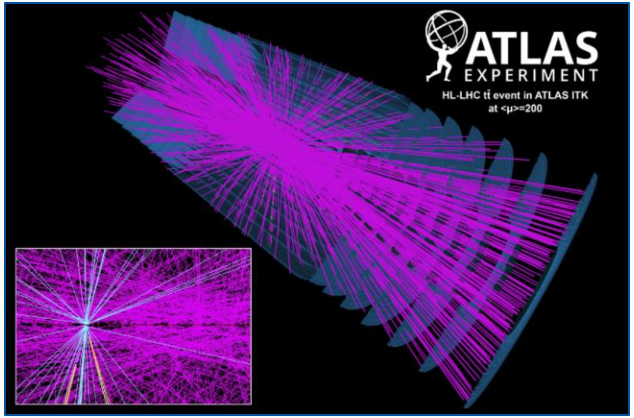
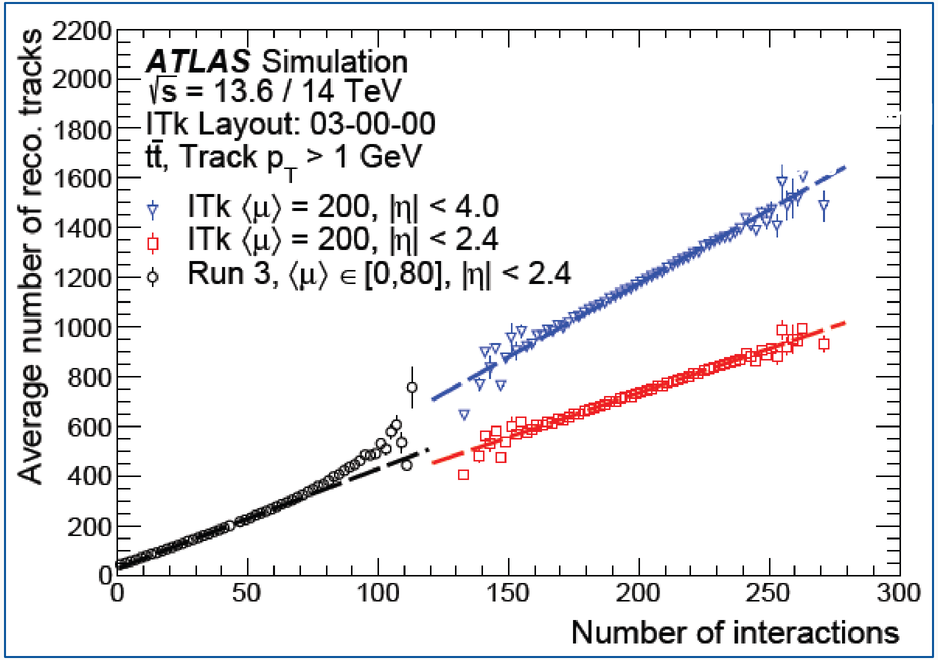
STATE OF THE ART

- tracking at the HL-LHC – ever increasing requirements
  - dense environments in dense events
  - high hit rates and high data rates
  - high overall power consumption
  - low material budget



https://cds.cern.ch/record/2674770



G. Aad *et al* 2025 *JINST* 20 P02018

STATE OF THE ART

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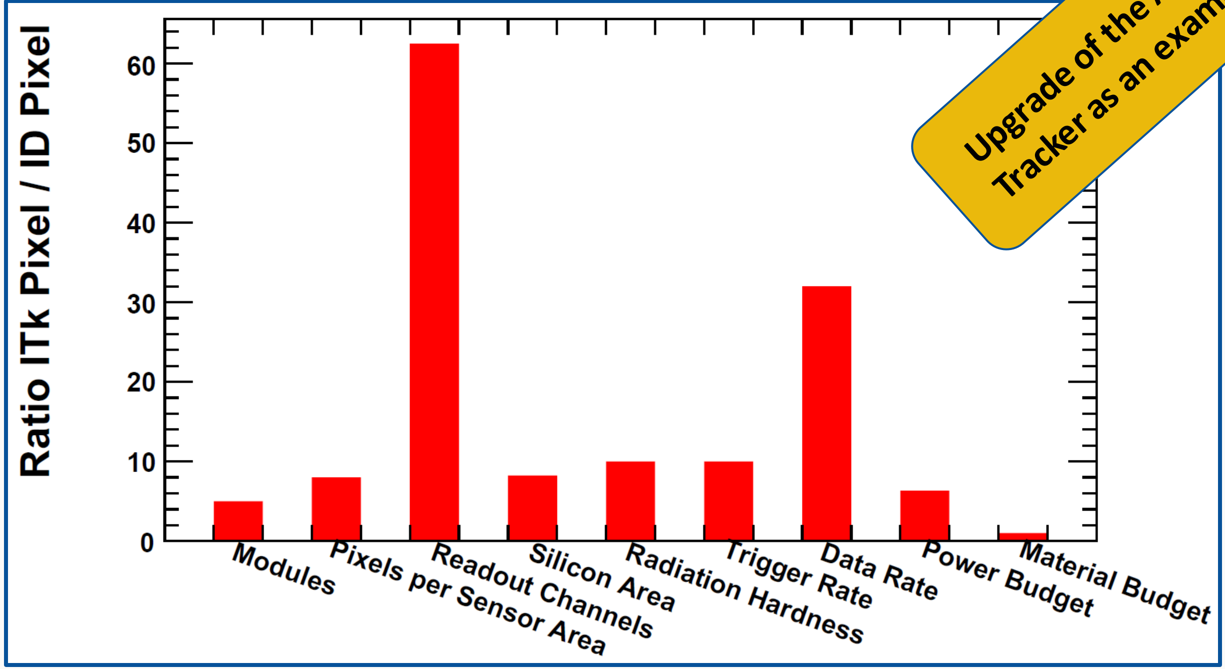
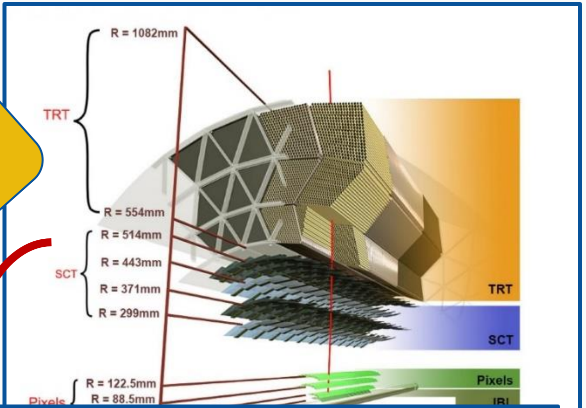
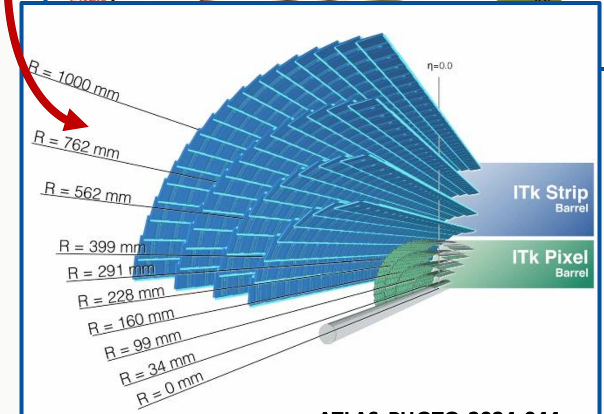
- HL-LHC era physics enabled by detector upgrades



Upgrade of the ATLAS Tracker as an example





ATLAS-PHOTO-2024-044

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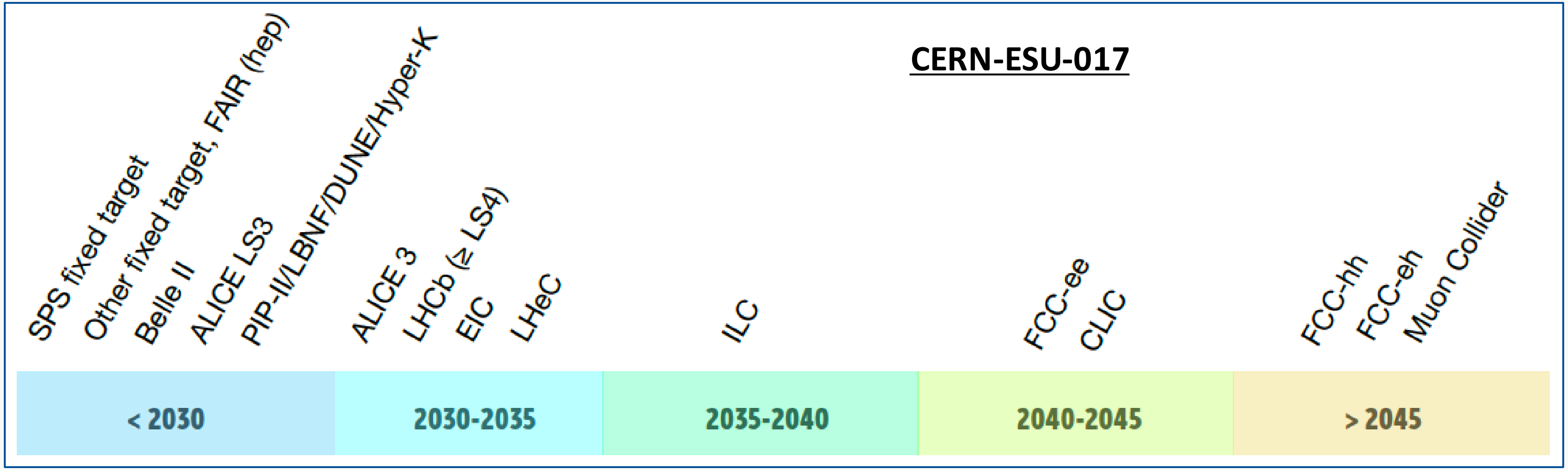
WHAT COMES NEXT?

- Particle Physics: Collider Roadmap

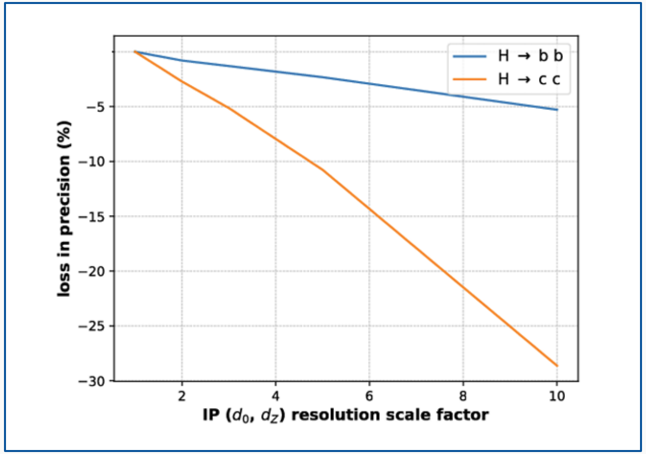


- e^+e^- collider for precision physics (Z, H)
- hadron-hadron collider at a later point
- many interesting "smaller accelerator" and "non-accelerator based" experiments along the way

TRACKING & VERTEXING AT FUTURE COLLIDERS

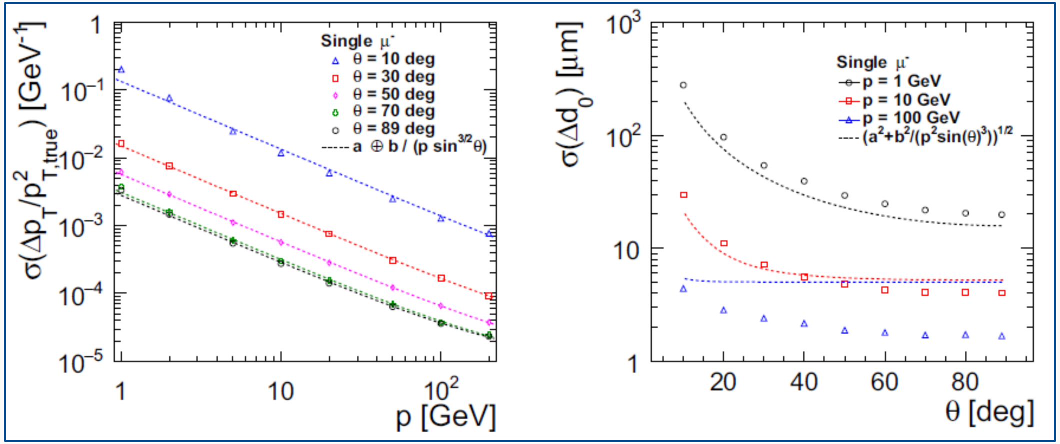
- impact parameter resolution

$$\boxed{\sigma_{d_0} = a \oplus b/(p \cdot \sin^{\frac{3}{2}} \theta)}$$



L. Gouskos, FCC Week 2024

Eur. Phys. J. Special Topics 228, 261-623 (2019)



CLIC Like Detector at the FCC-ee

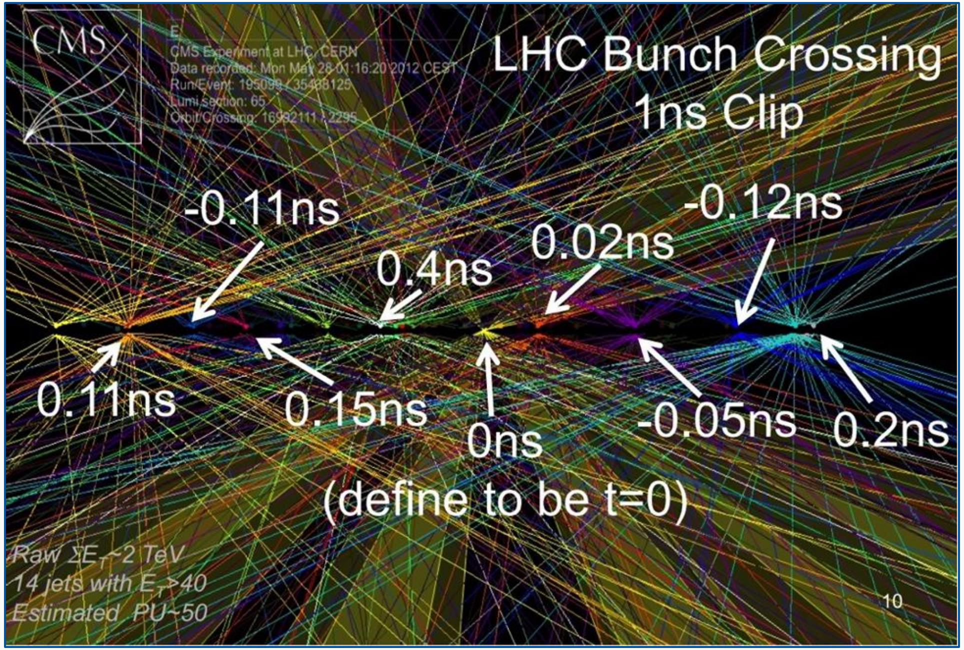
- key:
  - good single point resolution (a)
  - low material budget (b)

TIMING

- adding timing to track reconstruction - 4D tracking

σ_t = 10 ps → σ_x = 3 mm

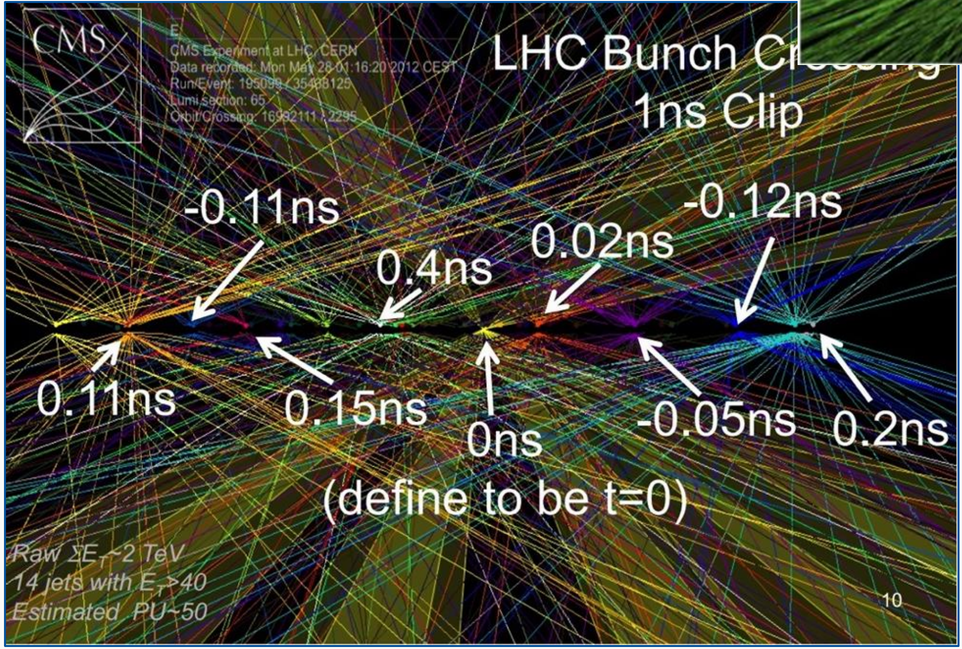
vertices are distributed in time and space!



10.1088/1361-6633/aa94d3

TIMING

- adding timing to track reconstruction - 4D tracking



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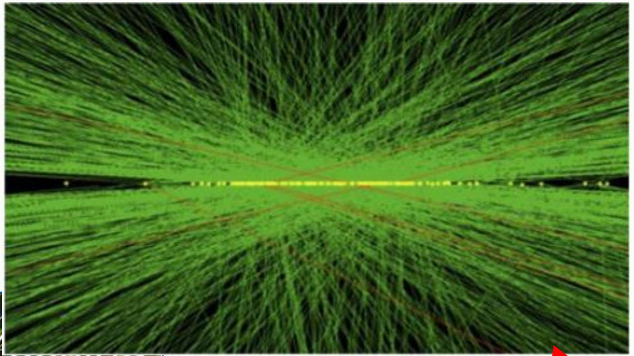


at HL-LHC:

200 vertices
over Δz = 20 cm

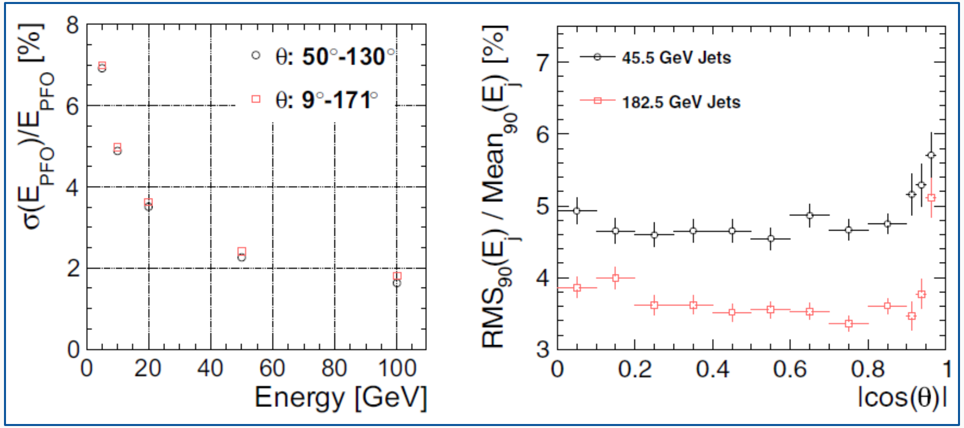
σ_t = 10 ps → σ_x = 3 mm

vertices are distributed in time and space!

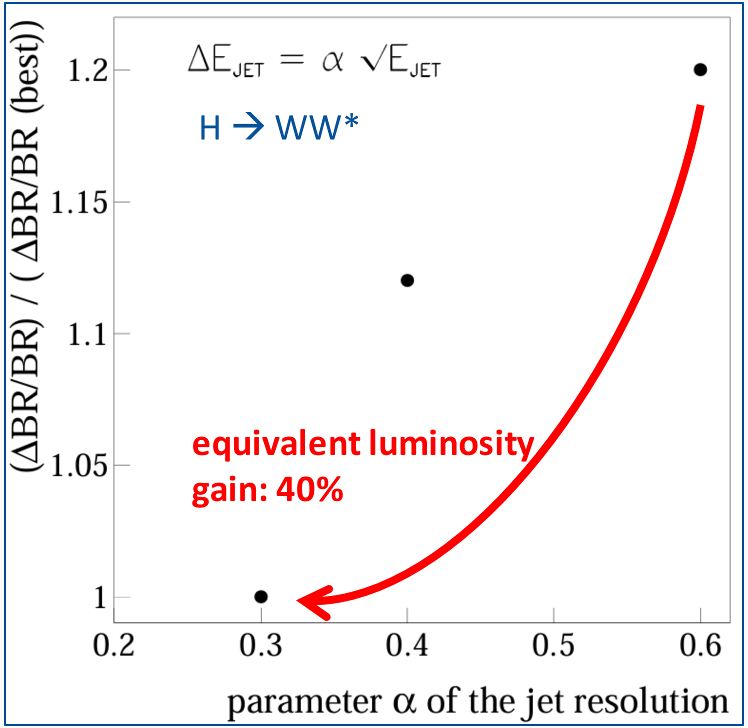
CALORIMETRY FOR FCC-EE

- Si based calorimetry systems for e^+e^- colliders:
  - highly granular sampling calorimeters
    - 5x5 mm^2 ECAL cells
    - 30x30 mm^2 HCAL cells

targeted JER: 3%-4%



Abada et al., Eur. Phys. J. Special Topics 228, 261-623 (2019)



ILC Reference Design Report Volume 4 - Detectors

ECFA DETECTOR ROADMAP

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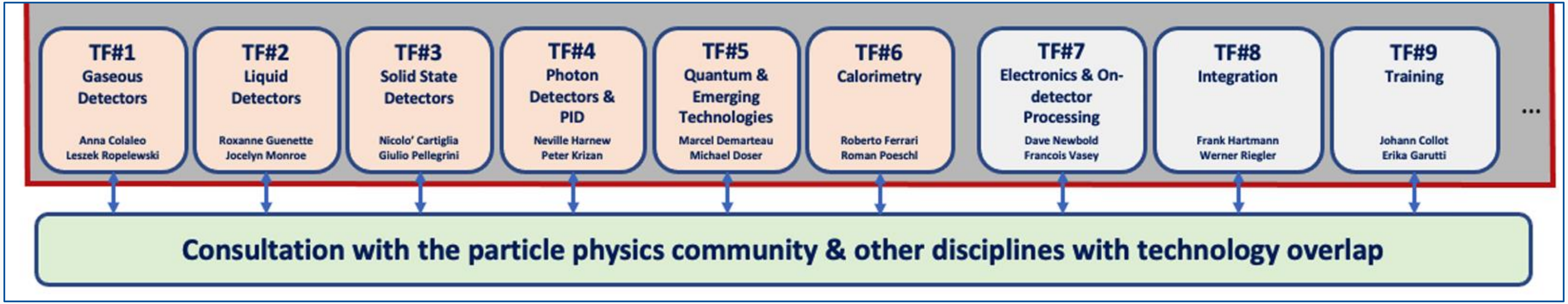
- development of detectors for future accelerators
  - roadmap presented for 9 task forces
  - development aligned with collider timeline

Key Contributions from German Institutes Expected



CERN-ESU-017

ECFA DETECTOR ROADMAP

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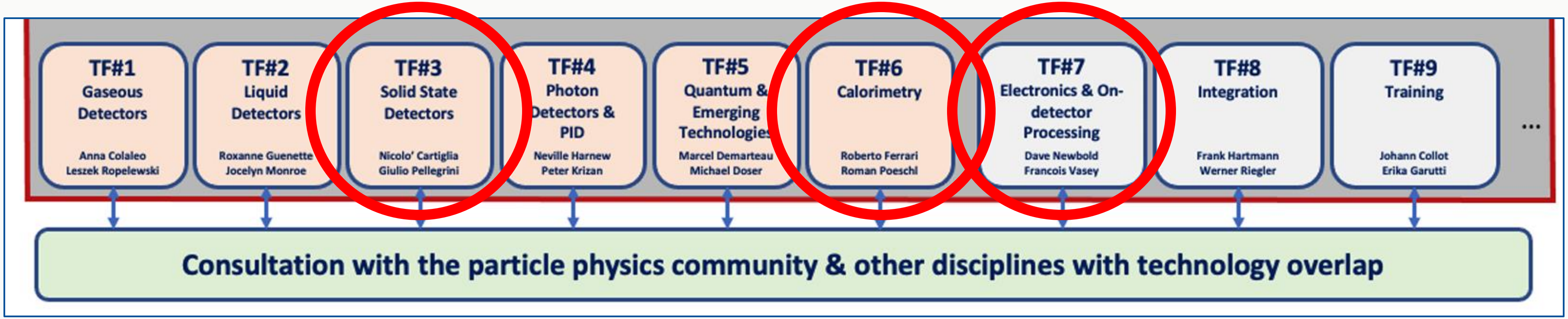

CERN-ESU-017

SILICON DETECTOR R&D IN GERMANY

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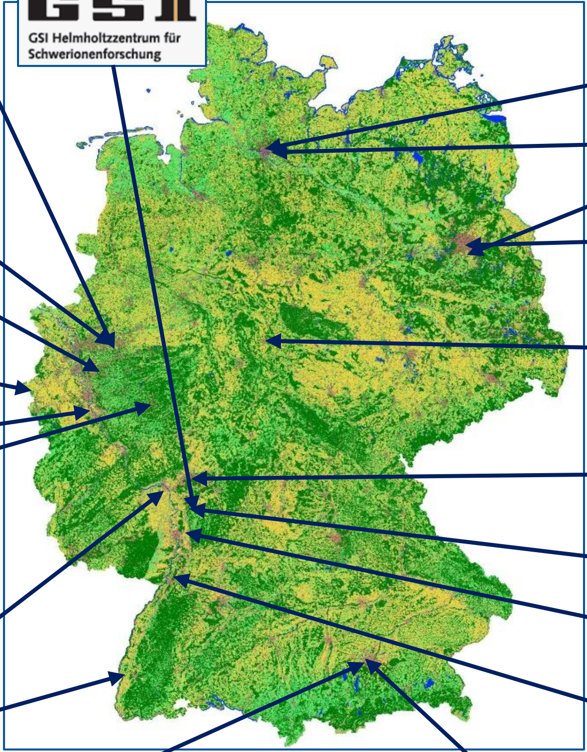

Fachhochschule Dortmund
University of Applied Sciences and Arts

GSI Helmholtzzentrum für Schwerionenforschung

technische universität dortmund

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KIT
Karlsruher Institut für Technologie

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

SILICON DETECTOR R&D IN GERMANY

Si-D Consortium

WP1: Position-Sensitive Monolithic Detectors
Dingfelder, Weber

WP 1.1
CMOS tracking detectors
Bonn, DESY, TU Dortmund, FH Dortmund, Frankfurt, Freiburg, Heidelberg, KIT, Siegen, Göttingen, GSI, HLL-MPG

WP 1.2
CMOS detectors for particle identification and energy measurement
HU Berlin, Heidelberg, KIT, DESY

WP2: Fast Timing
Garutti, Galatyuk

WP 2.1
LGAD sensors
Darmstadt, DESY, Frankfurt, Göttingen, Hamburg, KIT, Mainz, GSI, HLL-MPG, MPP-MPG

WP 2.2
3D sensors
Bonn, DESY, Freiburg, MPP-MPG

WP 2.3
CMOS sensors with gain layers
Freiburg, Heidelberg

WP3: System Integration and Simulation
Dierlamm, Karagounis, Masciocchi, Stroth

WP 3.1
Power management
Aachen, FH Dortmund

WP3.2
Optical data transmission
Wuppertal, FH Dortmund, KIT

WP3.3
2.5D/3D integration
FH Dortmund, KIT, HLL-MPG

WP3.4
Al strips on pCVD diamond carrier
Frankfurt, GSI, Mainz

WP3.5
Reusability by on-detector intelligence
FH Dortmund

WP3.6
Radiation hardness and simulation
Frankurt, GSI, Hamburg, Heidelberg, KIT

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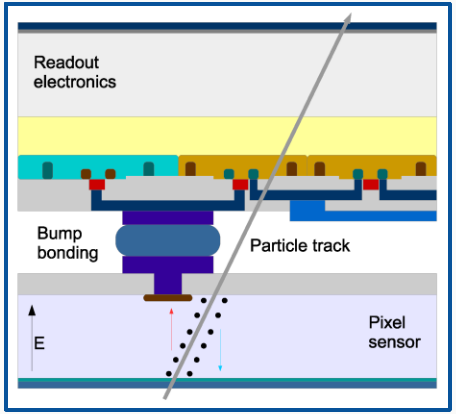
CMOS SENSORS

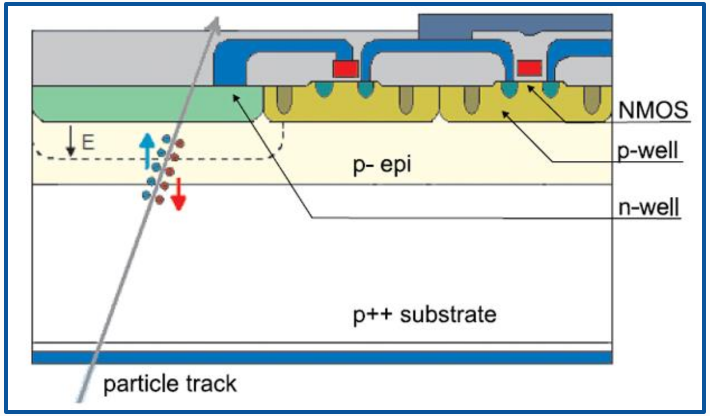
- CMOS detectors
  - integrate active sensors and readout on a single die
  - cost efficient, fast turnaround
  - lower material budget



~~UBM~~

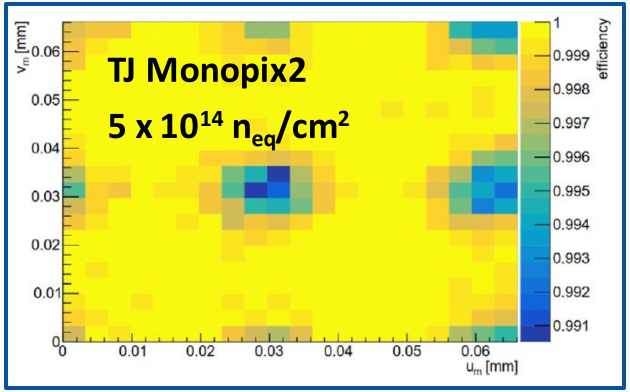
~~Bump Deposition~~

~~Flip Chip Process~~

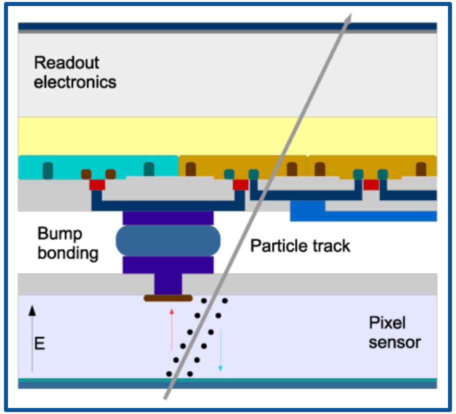


CMOS SENSORS

10.1016/j.nima.2024.169428



- CMOS detectors
  - integrate active sensors and readout on a single die
  - cost efficient, fast turnaround
  - lower material budget
  - many designs with good performance already exist



~~UBM~~

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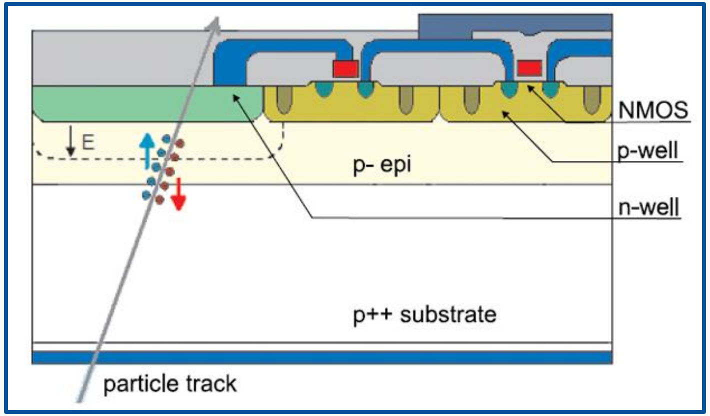
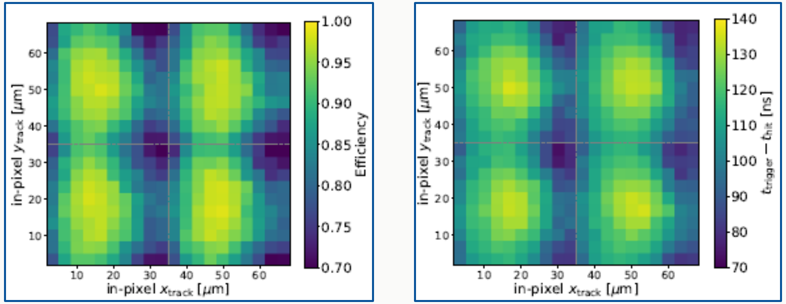
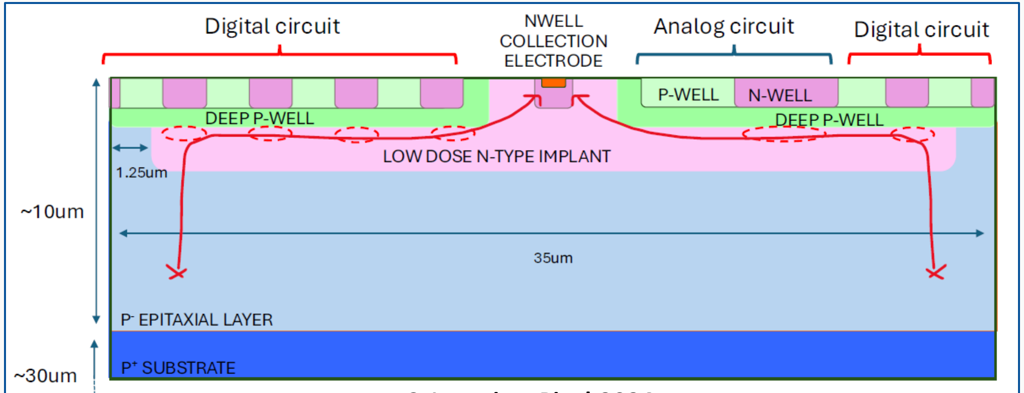


CMOS SENSORS

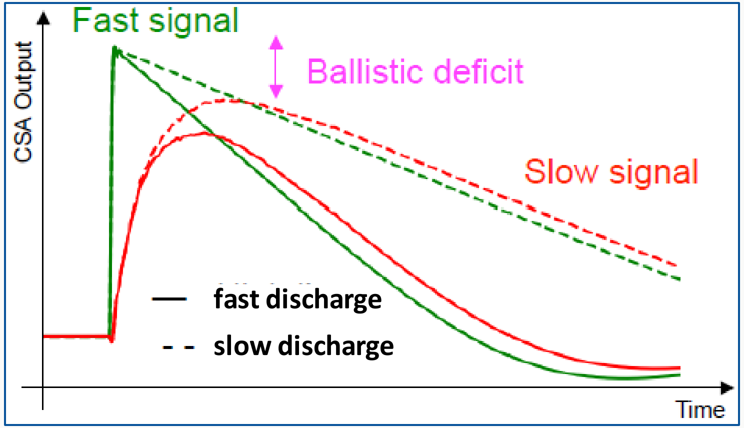
- Example for monolithic active pixel sensors
  - H2M: transfer from hybrid to monolithic
  - small feature size – 65 nm process
  - ultrathin devices possible: 20 μm under study



S. Ruiz Daza, https://doi.org/10.48550/arXiv.2502.06573 and Pixel 2024

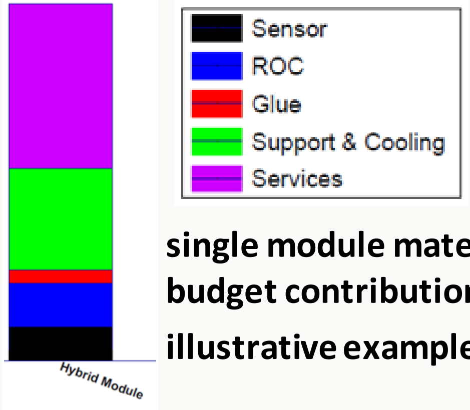


C. Lemoine, Pixel 2024



ALL SILICON MODULES

- all-silicon modules



single module material budget contributions

illustrative example!

ALL SILICON MODULES

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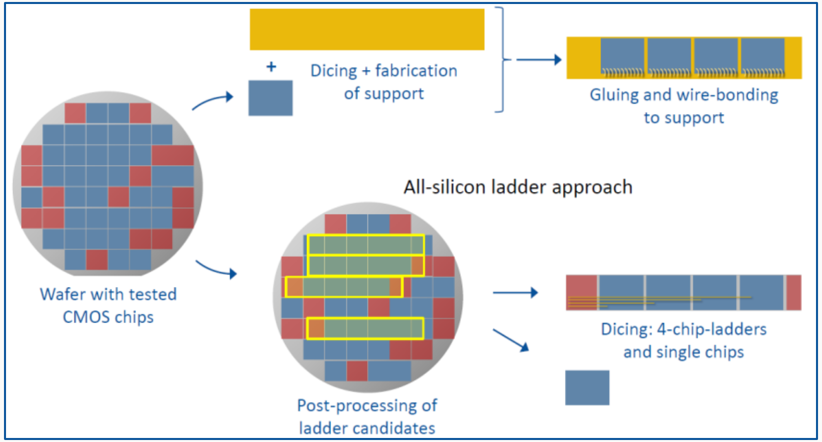
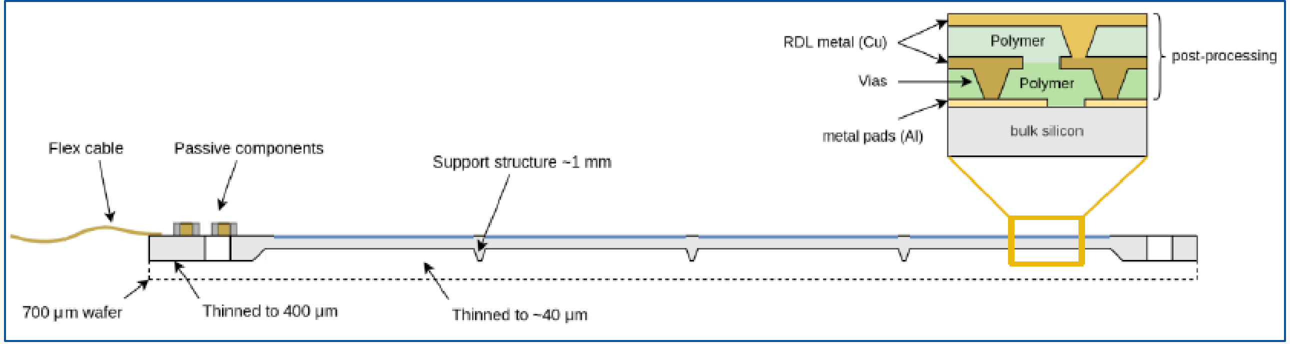
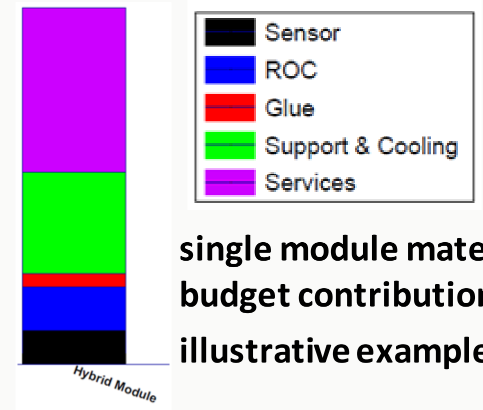
- all-silicon modules
  - significant reduction in X/X_0 possible
    - depends strongly on the requirements for the active part
  - requires high yield on wafer level
  - industry and in-house production possible



M. Vogt et al. CMOS Verbund Meeting 2024



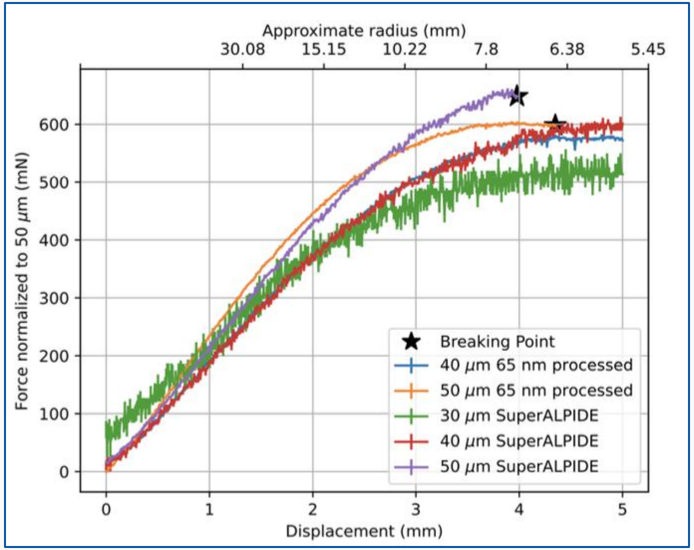


single module material budget contributions

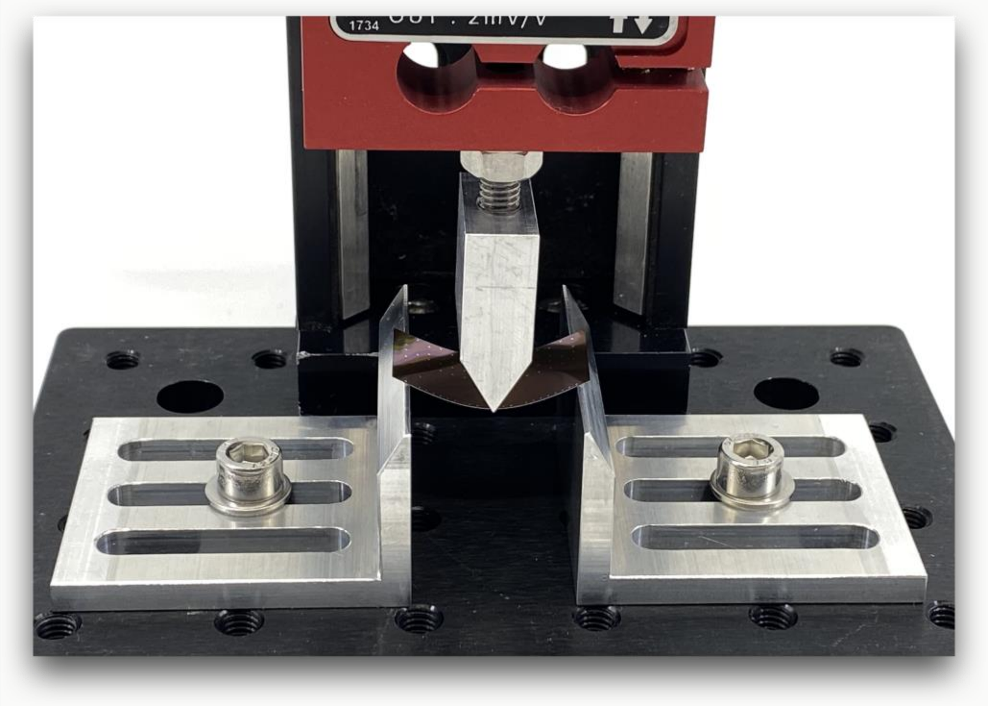
illustrative example!

ALL SILICON MODULES

- ALICE ITS3
  - bent wafer-scale tracker with all-silicon modules



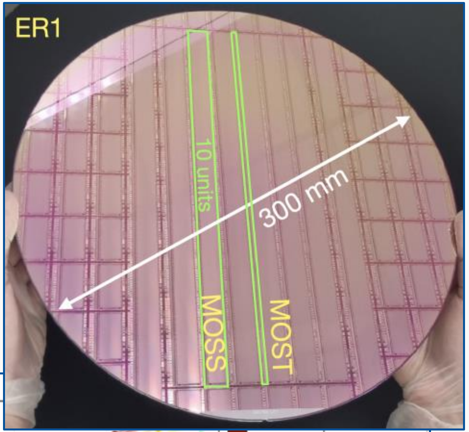
A. Kluge, VCI2025

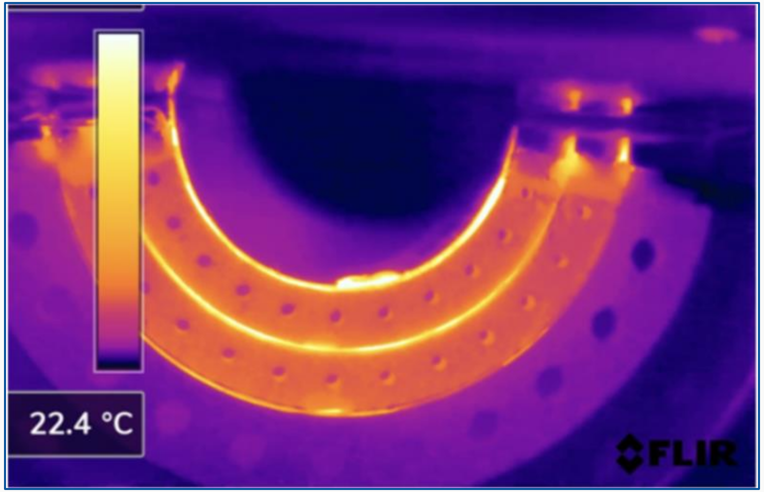


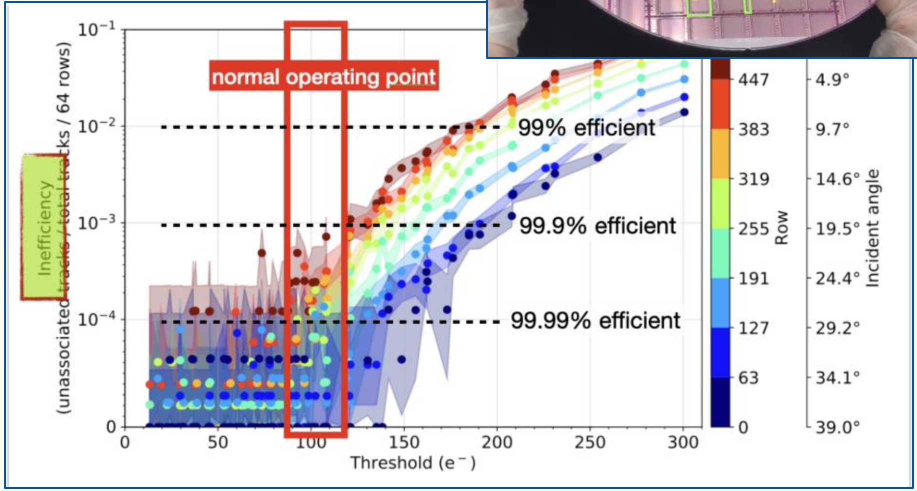
ALL SILICON MODULES

- ALICE ITS3
  - bent wafer-scale tracker with all-silicon modules
  - MAPS produced in TPSCo 65nm
  - good performance after bending & irradiation

A. Kluge, VCI2025

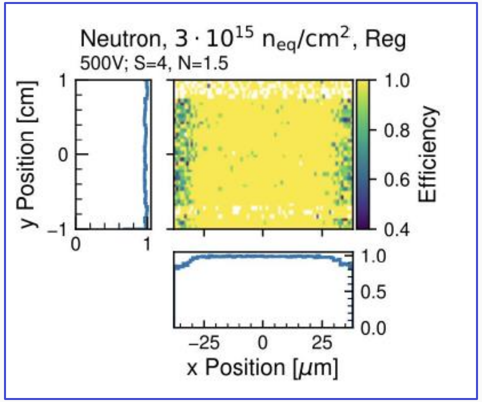


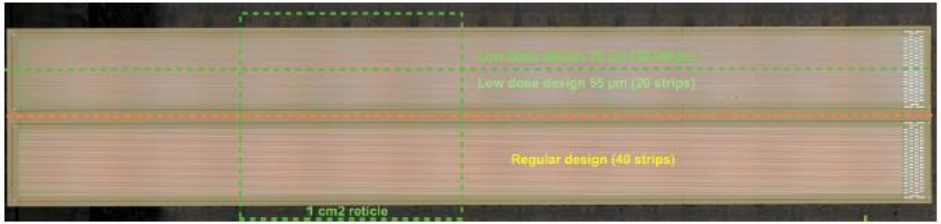


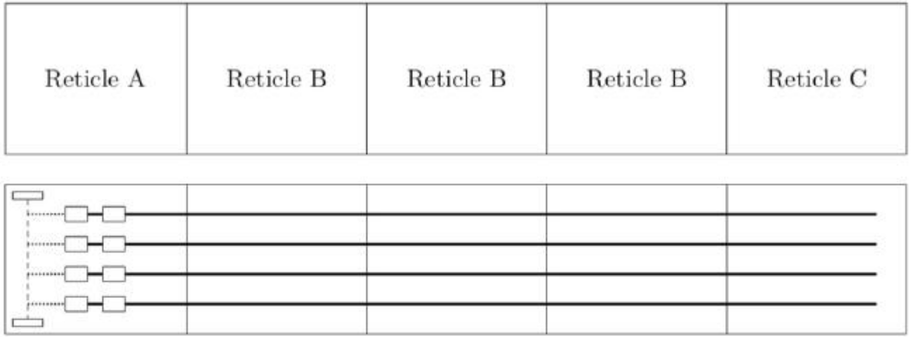


LARGE SCALE SILICON DETECTORS

- cost efficient instrumentation of large areas
  - passive CMOS strip sensors as a first step
  - prototypes produced using stitching
  - good performance up to $10^{15}\ n_{eq}/cm^2$
  - no visible impact of stitching







U. Parzefall, Si-D Consortium Workshop, March 2025

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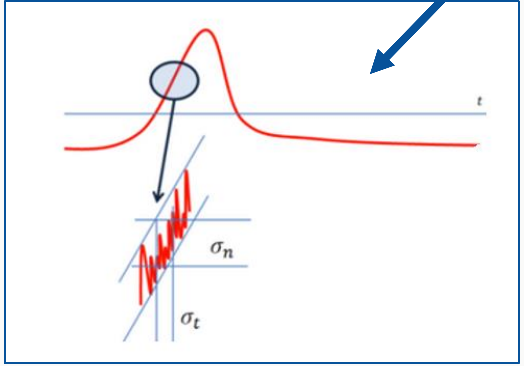
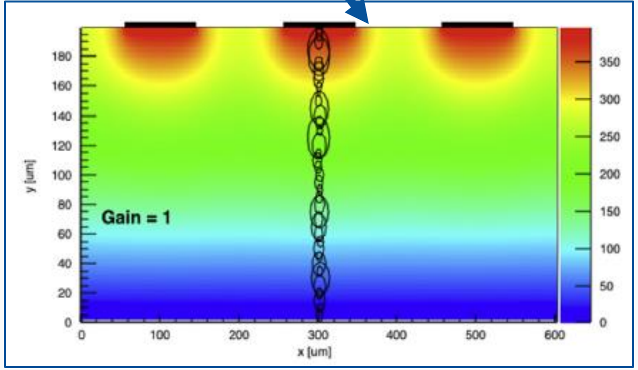
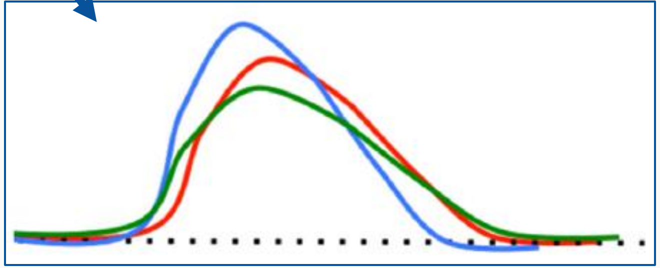
TIMING RESOLUTION

- temporal resolution of a silicon detector, neglecting subleading terms

$$\sigma_t^2 = \left(\frac{\sigma_{\text{noise}}}{dV/dt}\right)^2 + \sigma^2_{\text{ionisation}} + \sigma^2_{\text{shape}} + \text{correlations}$$





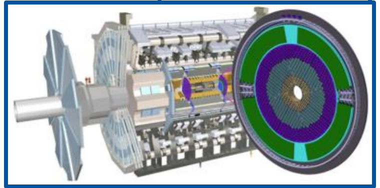


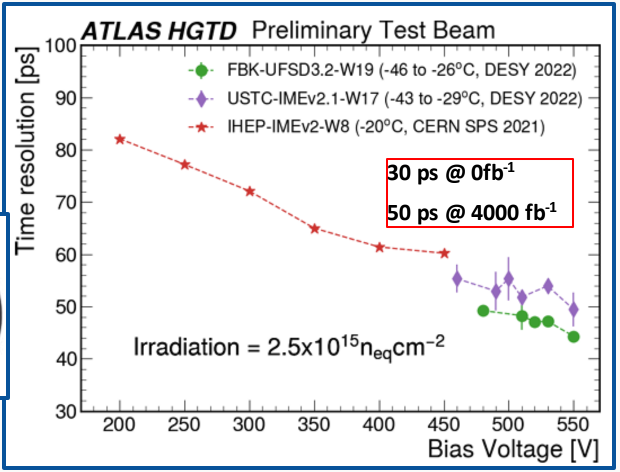
$i\ \mu\ qvE_w$

10.1016/j.nima.2016.05.078

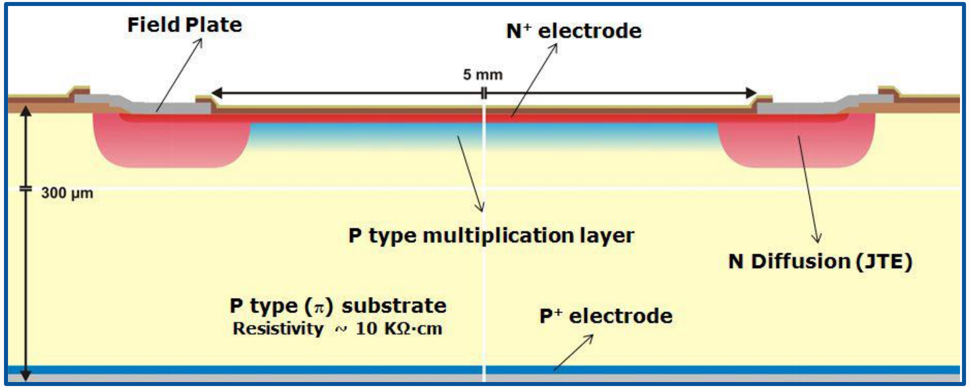
LOW GAIN AVALANCHE DIODES

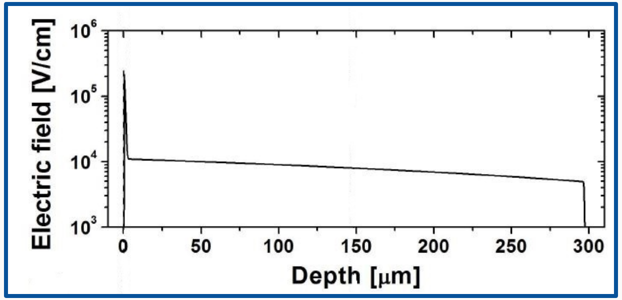
- good candidate: LGADs
  - moderate gain through multiplication layer
  - examples:
    - MTD endcaps in CMS
    - HGTD in ATLAS





M. Missio on behalf of the ATLAS HGTD collaboration 2024 *JINST* 19 C04008



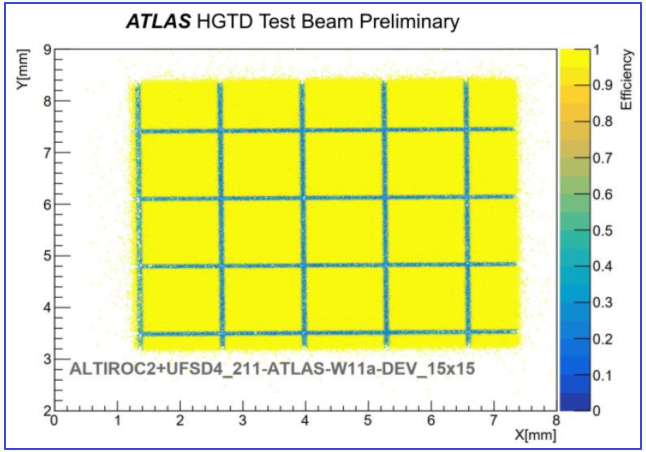


10.1109/CDE.2015.7087475 Proceedings of the 2015 10th Spanish Conference on Electron Devices, CDE 2015

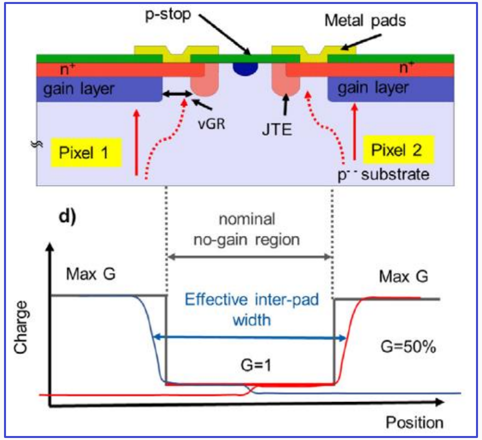
LGAD DEVELOPMENTS

- LGADs for future detectors?
  - increase fill factor for better efficiency

O. Perrin, EPJ Web Conf. Volume 288, 2023



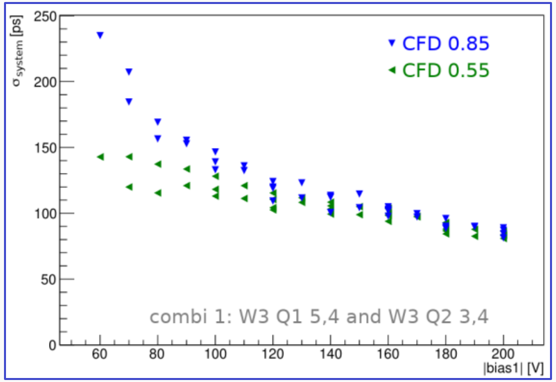
Nuclear Inst. and Methods in Physics Research, A987(2021) 164840



– goal for LGAD developments:
  – increase efficiency
  – maintain/improve spatial resolution
  – maintain/improve temporal resolution

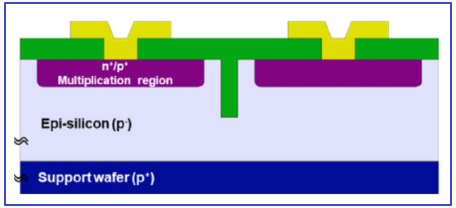
LGAD DEVELOPMENTS

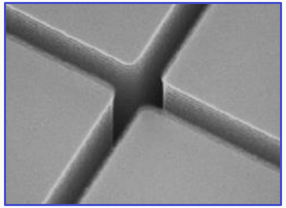
- trench-isolated LGADs
  - etched trenches are filled with SiO_2, Si_3N_4, Polysilicon, …
  - isolation of pixels → better efficiency
  - successfull testbeam at DESY in 2024

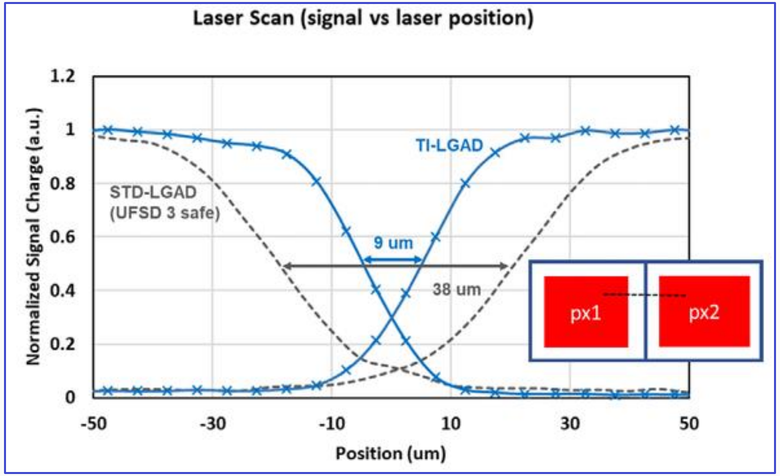


A. Vauth, Si-D consortium workshop, March 2025

Nuclear Inst. and Methods in Physics Research, A987(2021) 164840

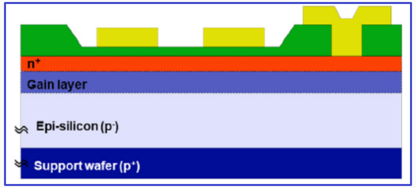


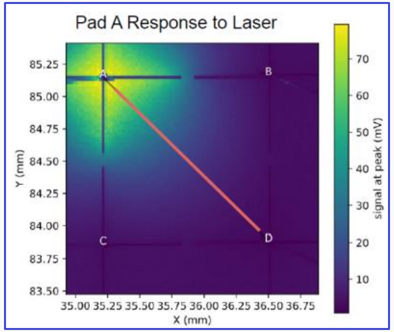


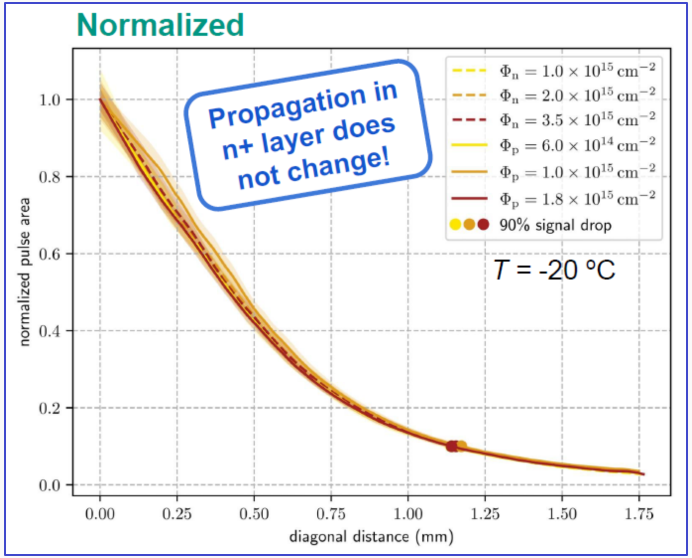


LGAD DEVELOPMENTS

- trench-isolated LGADs
  - etched trenches are filled with SiO_2, Si_3N_4, Polysilicon, ...
  - isolation of pixels → better efficiency
  - successfull testbeam at DESY in 2024
- resistive AC coupled silicon sensors
  - continuous gain layer
  - spatial resolution thanks to charge sharing
  - radiation effects on resistive layer under study
    - signal propagation in resistive layer not affected by radiation damage



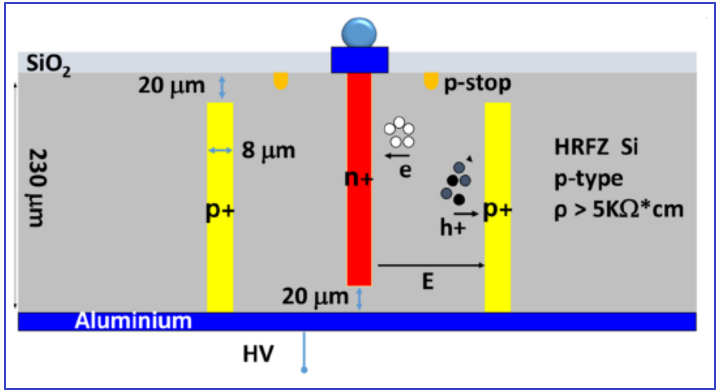




B. Regnery, Si-D consortium workshop, March 2025

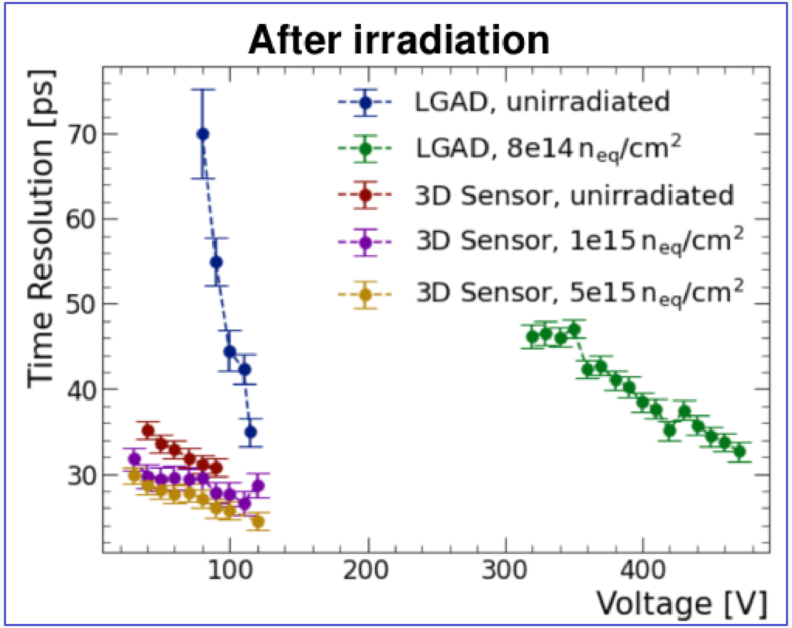
TIMING WITH 3D SENSORS

- 3D sensors
  - temporal resolution competitive with LGADs
  - low depletion voltage
  - possible issues
    - readout ASIC power
    - production (cost, yield)



R. Koppenhöfer,

Si-D Consortium Workshop March 2025



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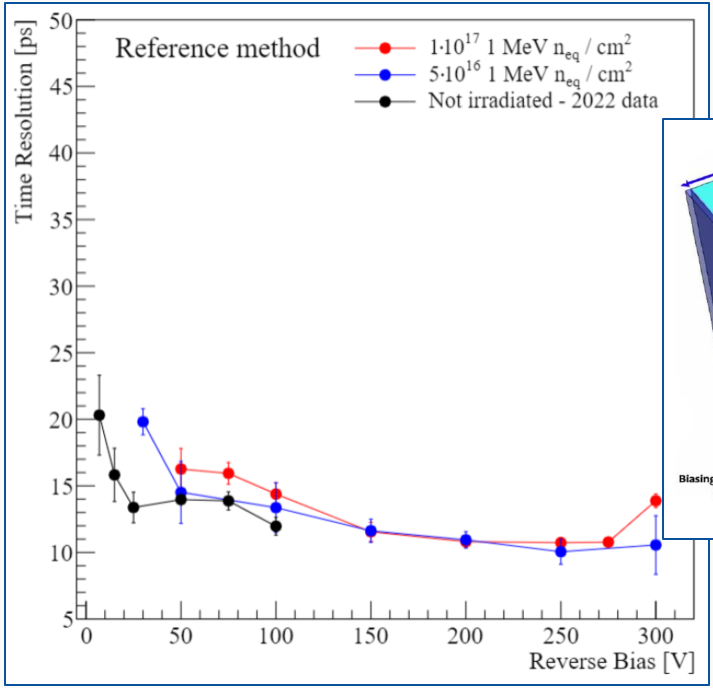
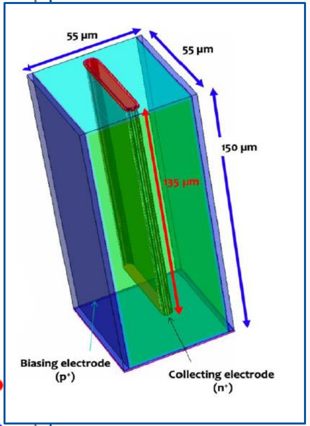
TIMING WITH 3D SENSORS

- 3D sensors
  - temporal resolution competitive with LGADs
  - low depletion voltage
  - possible issues
    - readout ASIC power
    - production (cost, yield)
- alternative electrode designs being studied
- trench-like electrodes tested up to FCC-hh like fluences
  - good timing resolution up to $10^{17}\ n_{eq}/cm^2$
  - setup limitations have impacted evaluation of samples at highest fluences





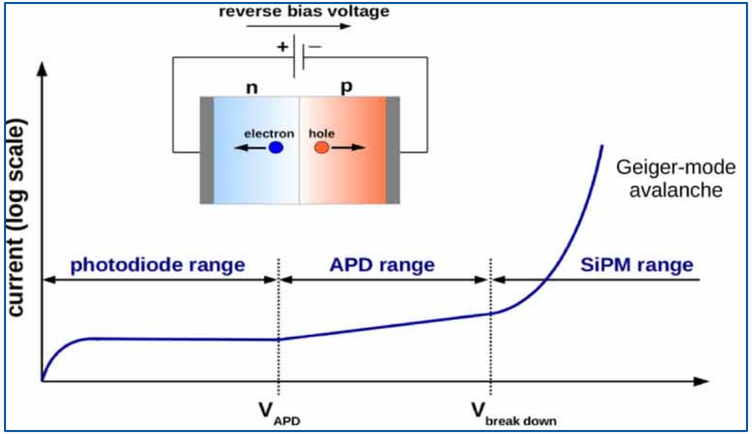
Adriano Lai, VCI 2025

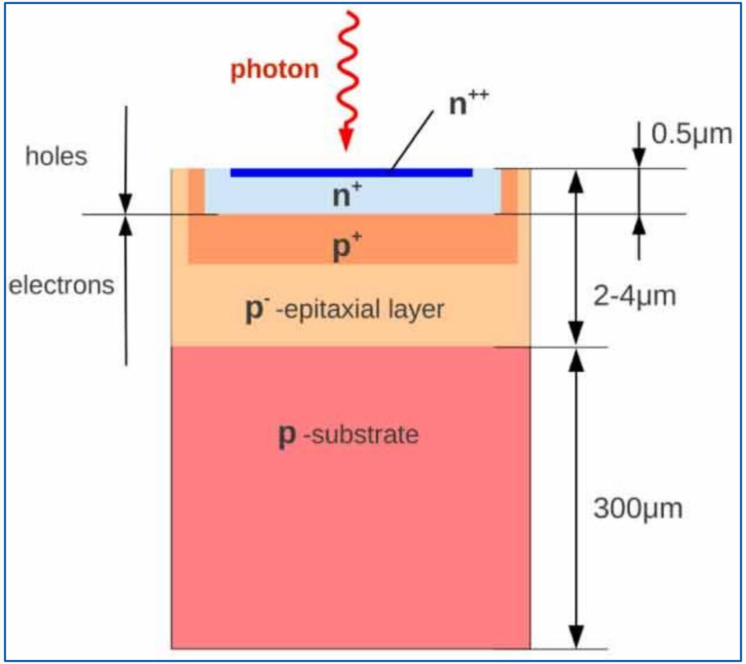
OUTLINE

- Introduction
- State of the Art
- **Future Detectors**
  - Low Mass Detectors
  - Silicon Timing Detectors
  - **Calorimetry with Silicon Sensors**
  - Further R&D and Other Applications

SILICON PHOTO MULTIPLIERS

- use scintillators with silicon photon detectors: SiPM
- p-n junction operated in Geiger regime
- self-sustained avalanche due to strong electric field
  - quenching mechanism required

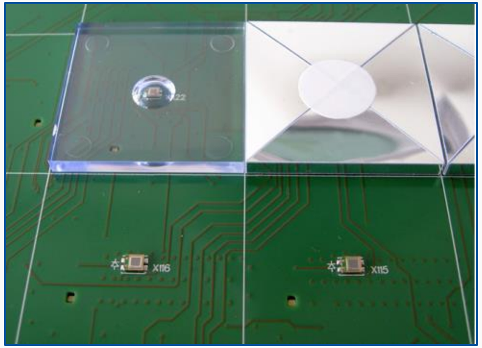




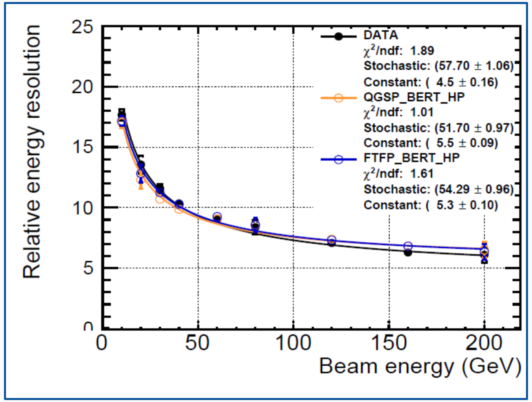
Phys.Med.Biol.65(2020)17TR01

ANALOG HADRON CALORIMETER

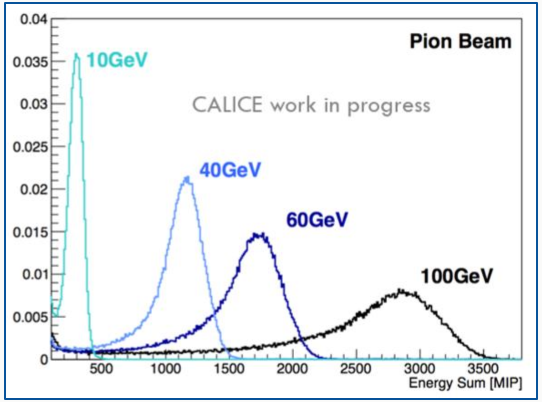
- CALICE AHCAL prototype and beamtests
  - 38 layers with 72x72 cm^2 active area each
  - 3x3 cm^2 cells, each 3mm thick
  - steel as absorber (1.7cm)
  - power pulsing capable



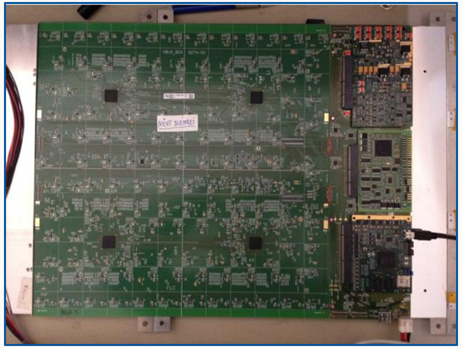
A. Laudrain, Journal of Physics: Conference Series 2374 (2022) 012017



O.L. Pinto, Shower Shapes in a Highly Granular SiPM-on-Tile Analog Hadron Calorimeter



M. Roblez Manzano, 8th Beam Telescope and Test Beam Workshop



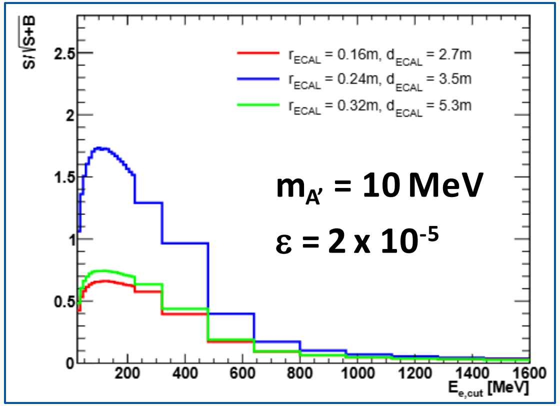
L. K. Emberger, Precision Timing in Highly Granular Calorimeters and Applications in Long Baseline Neutrino and Lepton Collider Experiments

OUTLINE

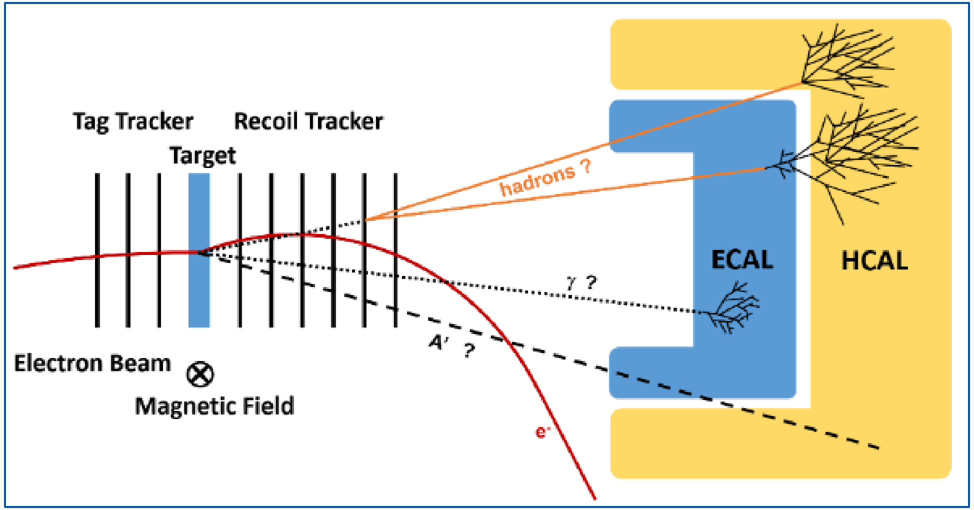
- Introduction
- State of the Art
- **Future Detectors**
  - Low Mass Detectors
  - Silicon Timing Detectors
  - Calorimetry with Silicon Sensors
  - **Further R&D and Other Applications**

OTHER EXPERIMENTS AND CHALLENGES

- example for high rates: Lohengrin @ ELSA
  - dark photon search in a fixed target setup
  - 100 MHz single electron tracking
  - low energy electrons in final state
  - high occupancy in single pixels



arXiv:2410.10956v2

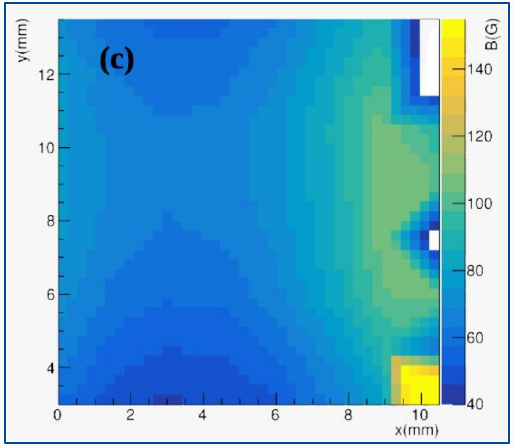


telescope like detector

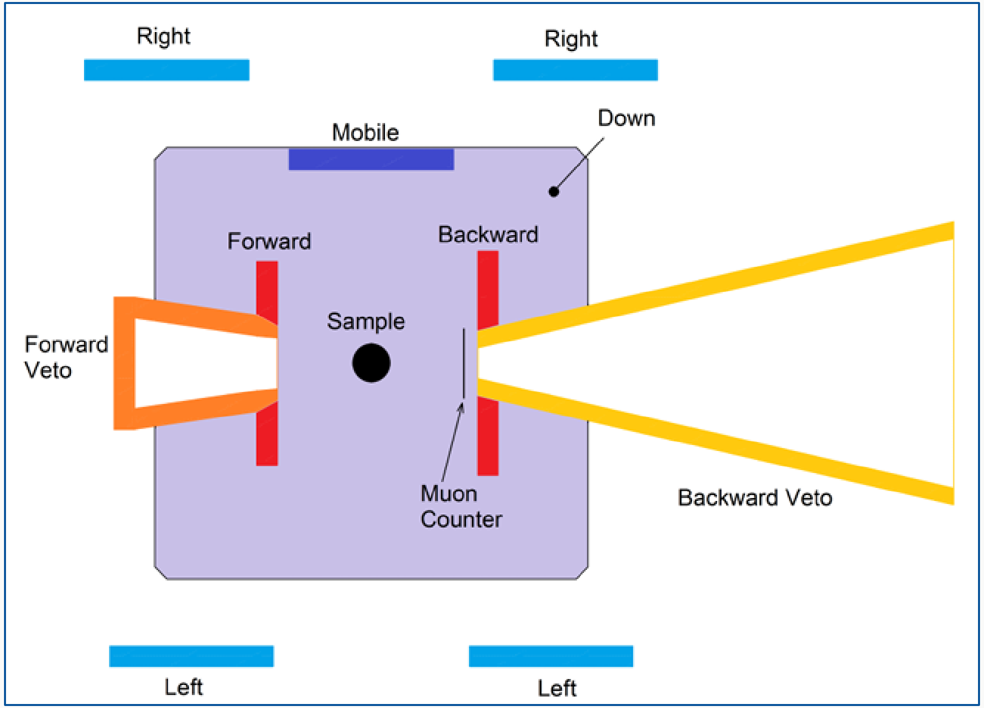
high rate capable CMOS detector with minimal local services

OTHER EXPERIMENTS AND CHALLENGES

- material sciences: muon spin rotation
  - measurement of material properties
  - HV-MAPS as positron detectors
    - increase in muon rate
    - provide better spatial resolution

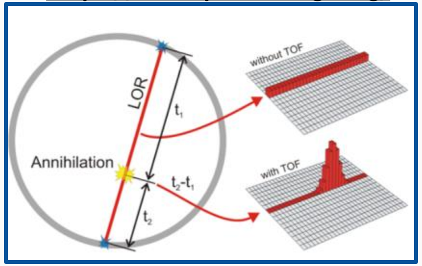


Marius Köppel, VCI 2025

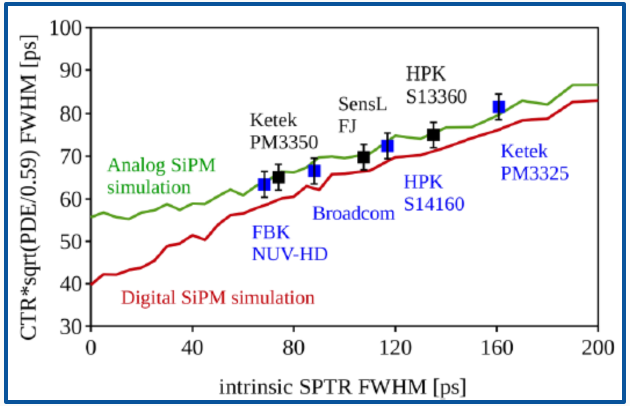


OTHER APPLICATIONS

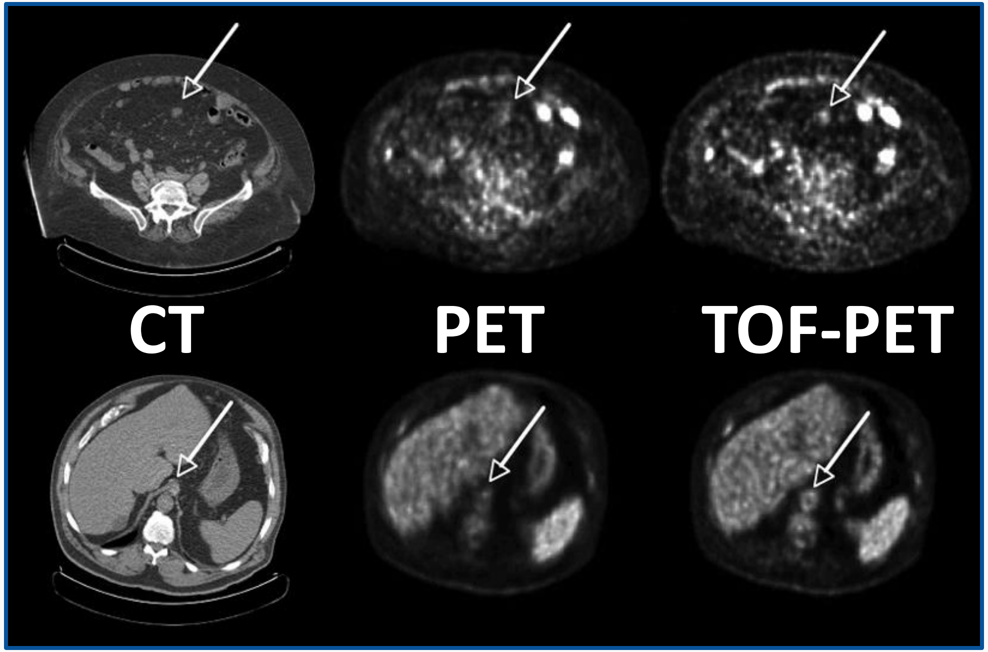
https://the10ps-challenge.org/



- TOF-PET
  - TOF-PET scanners using SiPMs since 2014
  - 210 ps time resolution achievable
  - push for 10-30 ps
  - attractive candidate: digital SiPMs



2019 Phys. Med. Biol. 64 055012



J Nucl Med. 2008 March ; 49(3): 462–470

SUMMARY

- challenging detector R&D ahead in order to enable the full physics potential of future experiments

- future collider experiments:
  - material budget
  - granularity
  - radiation hardness
  - power management
  - data transmission

- other applications:
  - non-collider experiments
  - medical applications
  - . . .

- solutions meeting individual requirements already exist in many cases
- no single solution that meets all requirements for a given experiment yet

- many topics not covered in this presentation:
  - efficient power regulation on modules (DC/DC, Serial Powering)
  - in-silicon optical transceivers
  - CMOS LGADs
  - . . .