Radiation detection in particle physics: Development of silicon sensors for future colliders

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Outline

Introduction

- Radiation interaction with matter
- Particle detection:
  - *Tracking*
  - *Timing*

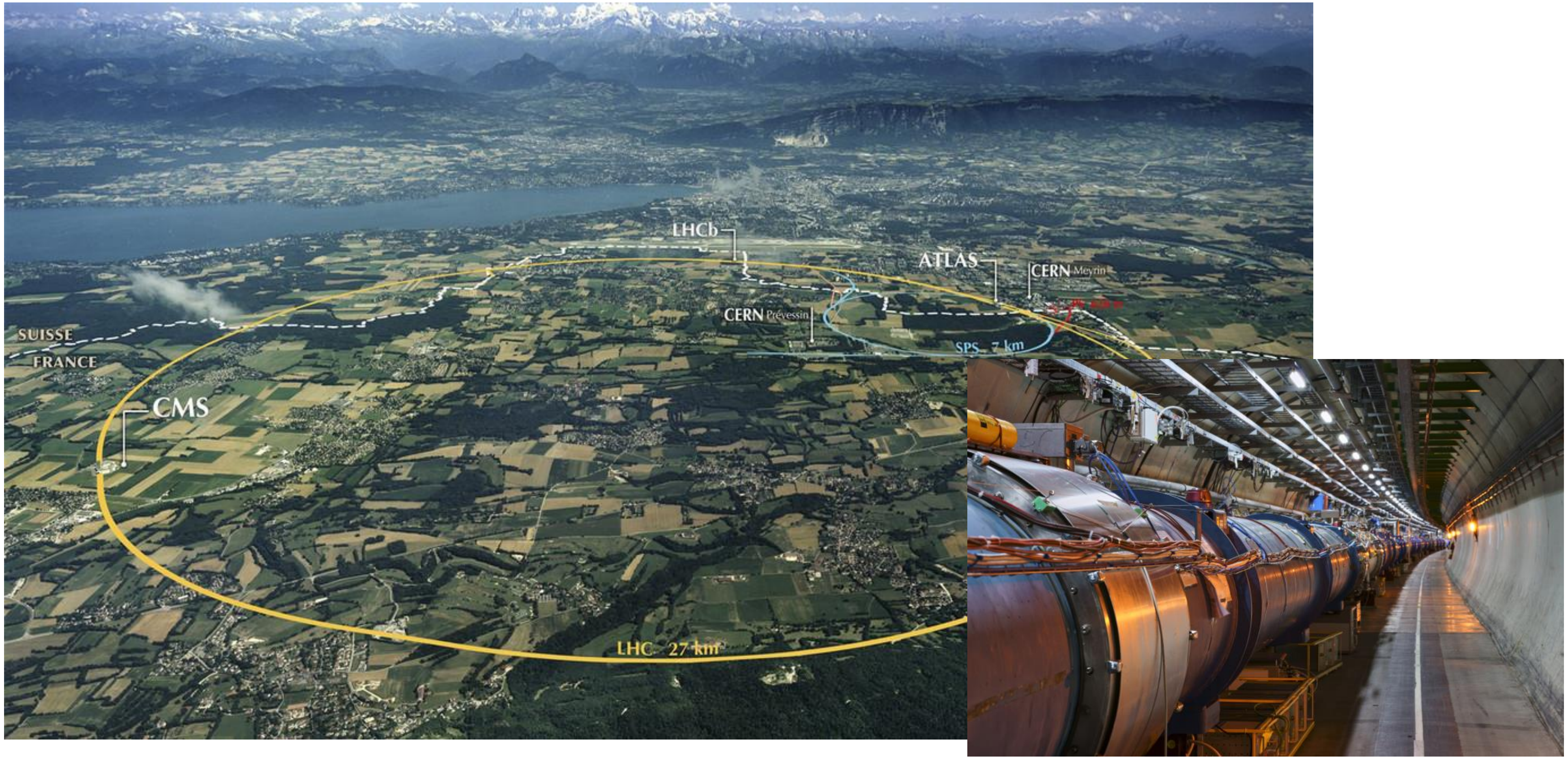
Silicon detectors in high-energy physics

- Operation principle (p-n junction)
- “Conventional” planar pixels and strips, 3D sensors
- **Specific challenge: radiation damage in silicon detectors**
- Low-gain avalanche diodes

Future developments

- Colliders beyond the LHC
- Trends in silicon detectors for future collider experiments

The Large Hadron Collider



Proton-proton (p-p) collisions: 13 TeV

Physics at collider experiments

Precision measurements of the Standard Model of particle physics

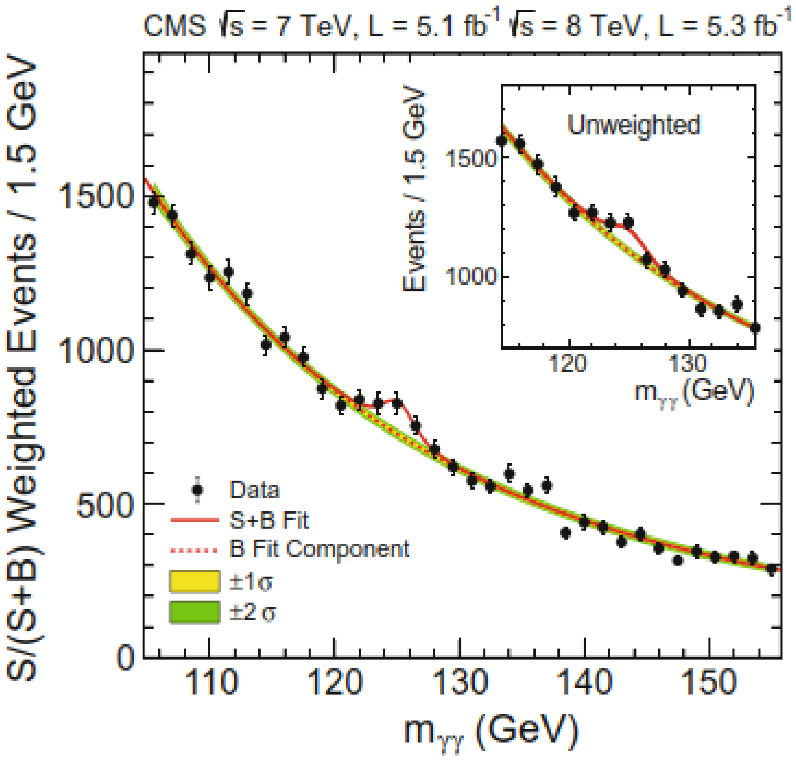
- **Top quark, W/Z bosons**
- **Higgs boson(s)**

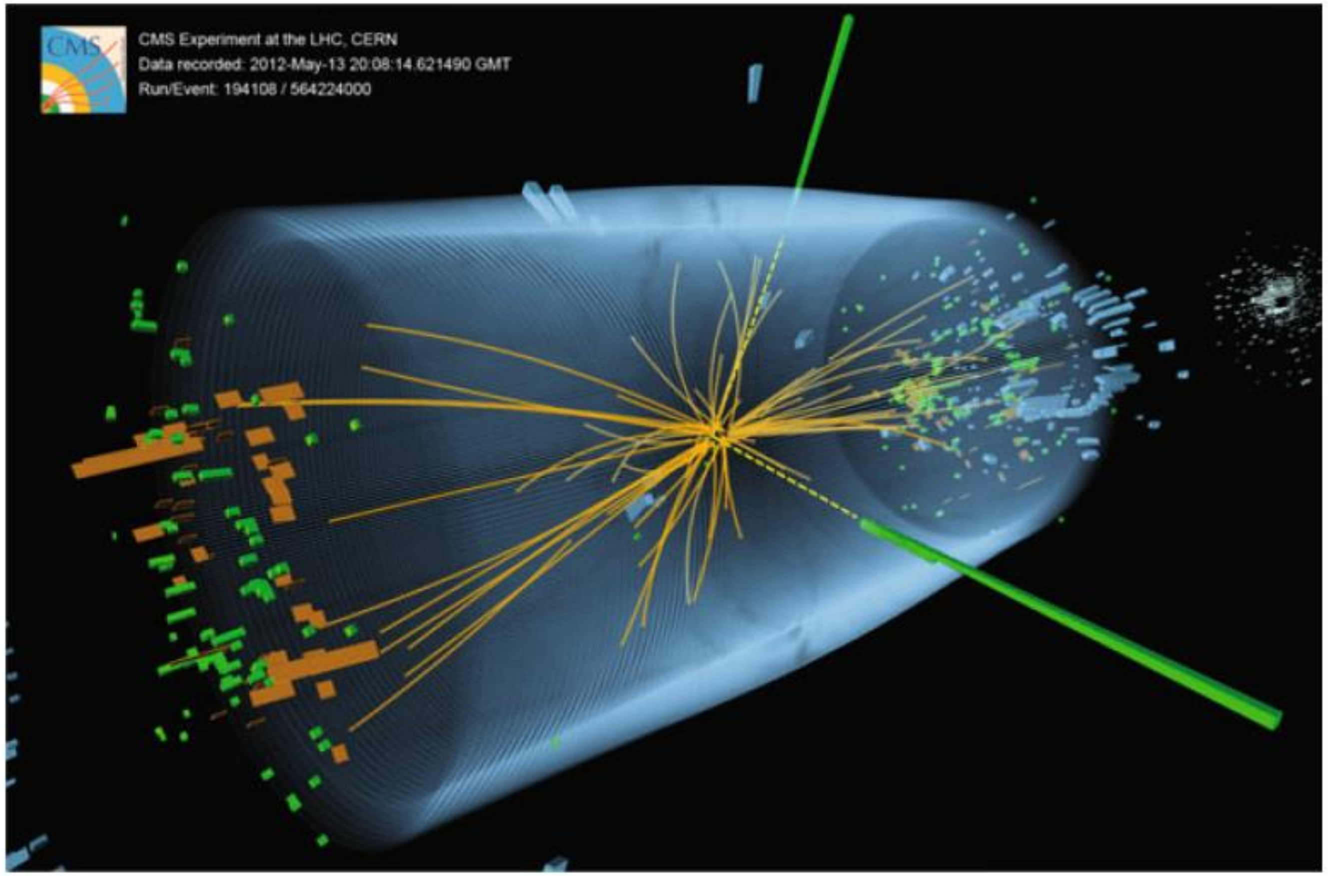
Search for physics Beyond the Standard Model

- **Self-coupling of Higgs boson**
- **Dark matter candidates**
- **Supersymmetry**

Heavy ion physics

- **Extremely dense medium**





Detection of particles!

Radiation detection in high-energy physics

Energy scales in the laboratory: Co-60 gamma ray, 1.1 and 1.3 MeV, or Sr-90/Y-90 beta particle maximum energy, 0.6 – 2 MeV

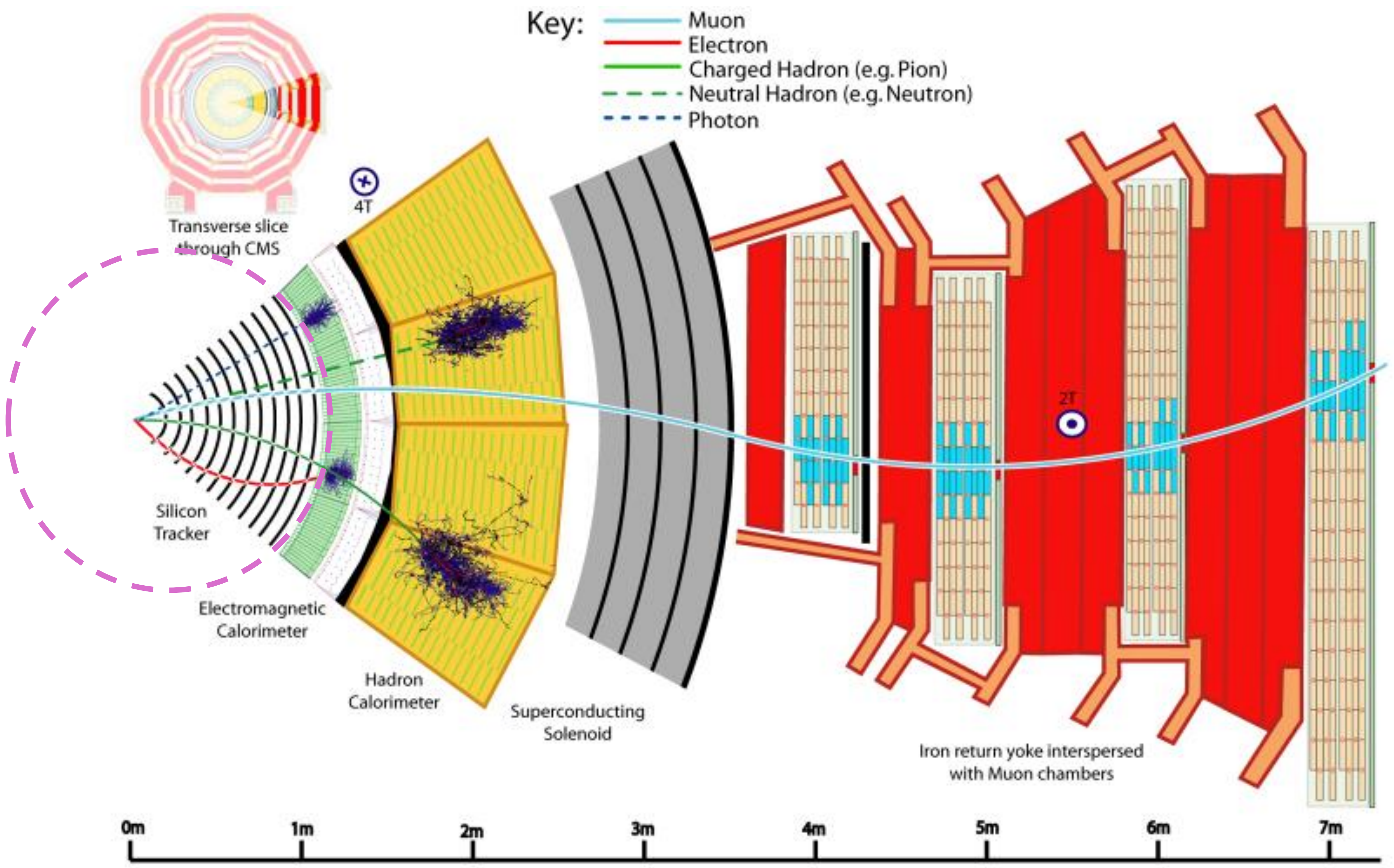
… vs particle physics : TeV c-o-m energies at the LHC - photon and particle energies in the GeV's

- Underlying interaction mechanisms remain, but manifest in specific ways
- High energies require large amounts of absorber material → large detectors
- Some particle species interact so little that they cannot feasibly be stopped (or do not interact at all)

Identification of unstable fundamental particles produced in the collisions relies on precision measurements of their decay products:

- **Energy**
- **Momentum**
- Particle ID

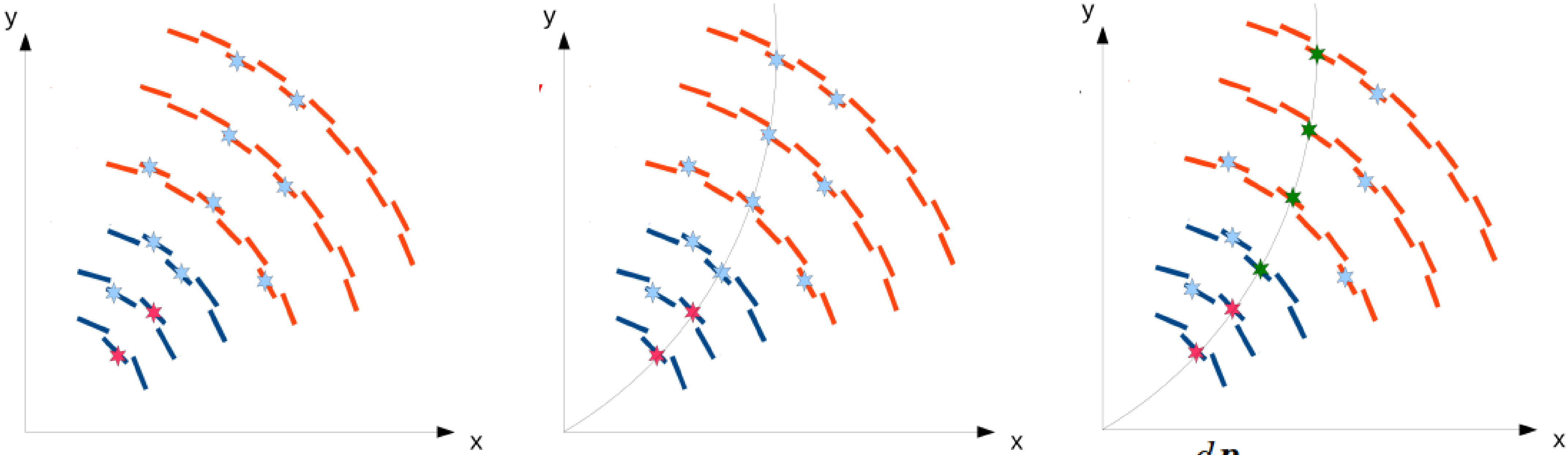
➢ **Experiments consist of several subdetectors with different purposes and specialized technology**



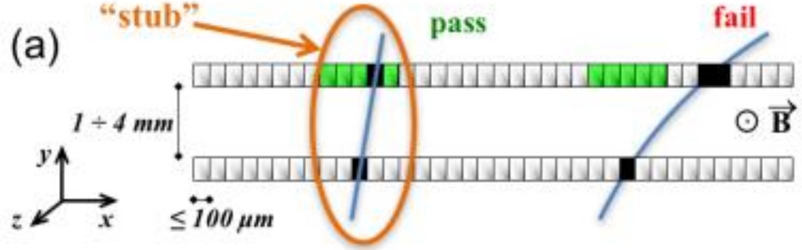
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

Particle tracking

Objective: determine the ‘path’ of a particle, calculate its momentum



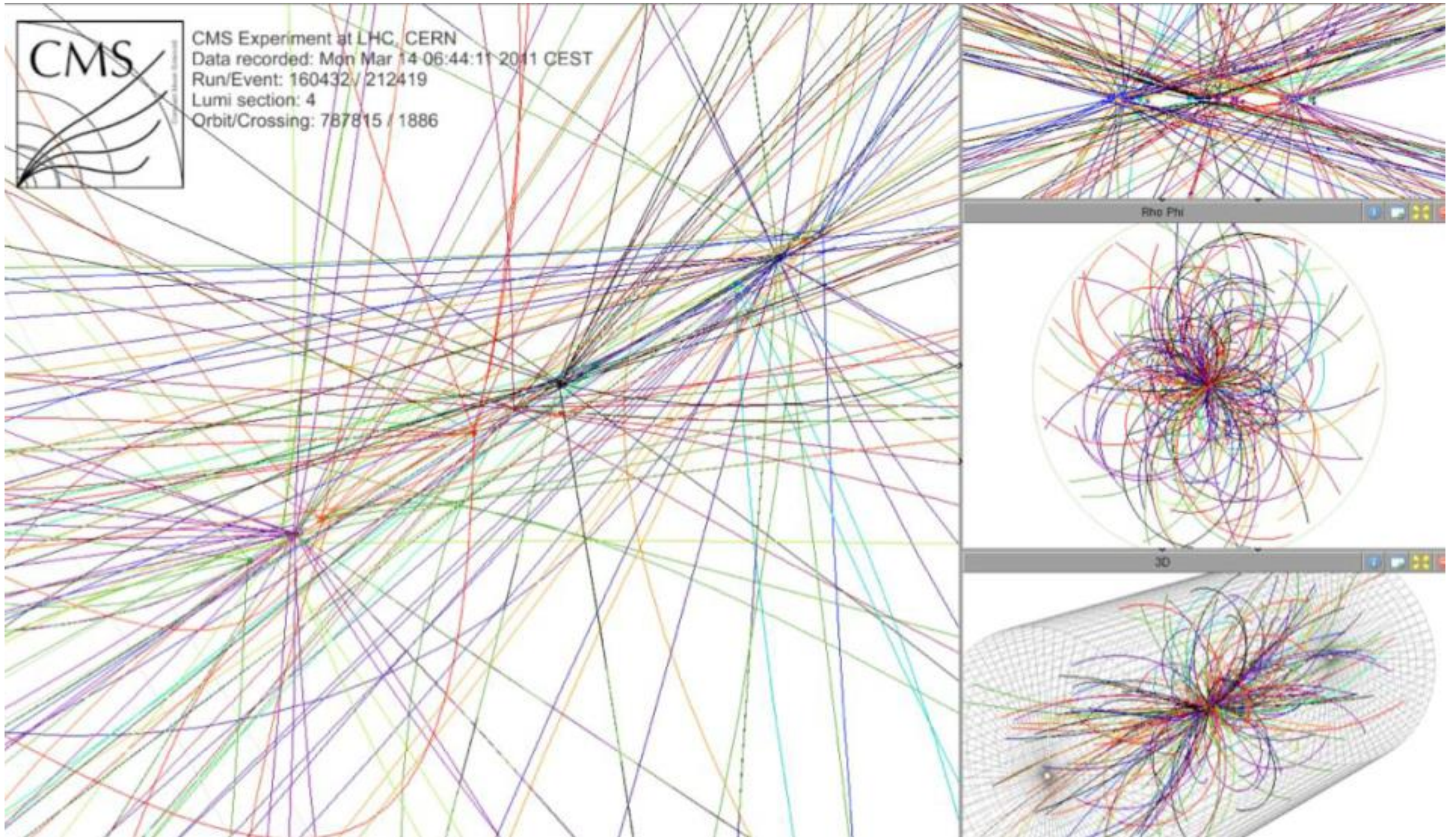
$$\boldsymbol{F_L} = \frac{d\boldsymbol{p}}{dt} = q\boldsymbol{v} \times \boldsymbol{B}$$



$$p_T = \frac{0.3Bl^2}{8s}$$

Particle tracking and vertexing

Vertexing: point / associate a track to the original interaction point



Particle tracking

Objective: determine the ‘path’ of a particle, calculate its momentum - generate a measurable signal, but do not impact energy measurement nor cause excessive scattering

- Multiple layers
- Thin sensors
- Light material
- Capable of detecting small amounts of signal
- High spatial resolution = fine segmentation

➢ **Semiconductor detectors – silicon**
➢ Gaseous detectors

Interaction of radiation with matter

Charged particles

Continuous interaction along the path: *linear energy transfer*

- Dependent on energy and velocity: stronger interaction close to the range of the particle – Bragg peak
- **Bethe-Bloch formula** describing energy loss (stopping power) over distance for a fast charged particle:

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

Mechanisms:

- Electromagnetic interaction: ionization
- Radiative (in the field of a nucleus): bremsstrahlung
- Nuclear / hadronic interaction: nuclear collisions, nuclear reactions, knock-on effect of atoms in a solid-state lattice

At high energies: deposited energy small, ~independent of particle species and energy → *minimum-ionizing particle, MIP*

Photons

On a larger scale: statistical process, exponential decrease of intensity/flux in material depending on mass attenuation coefficient and distance travelled in the medium:

$$\boldsymbol{I_l = I_0}^{-\mu \boldsymbol{l}} \quad // \quad \boldsymbol{I_l = I_0}^{-\frac{\mu}{\rho_m}\rho_m \boldsymbol{l}}$$

Cross-sections for processes depend on photon energy and absorber material

Mechanisms:

- Elastic scattering
- Photoelectric effect
- Compton scattering = inelastic scattering
- Pair production
- (Photonuclear reactions)

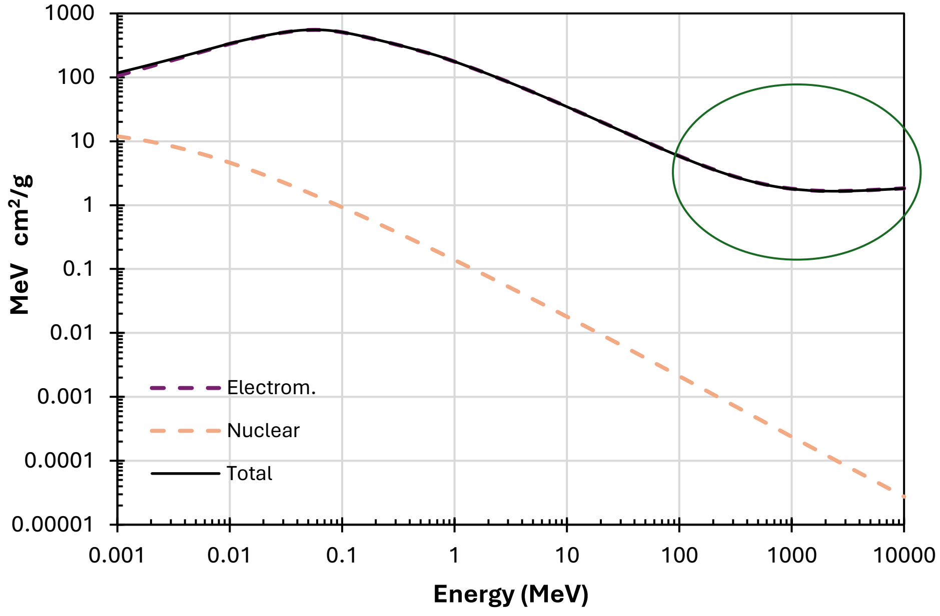
Interaction of high-energy … in silicon

Energy scales: TeV c-o-m energies at the LHC - photon and particle energies in the GeV's

… vs laboratory: Co-60 gamma ray, 1.1 and 1.3 MeV, or Sr-90/Y-90 beta particle maximum energy, 0.6 – 2 MeV

Stopping power / attenuation length in silicon: around 4 MeV cm^{-1} / 0.082 cm^{-1}

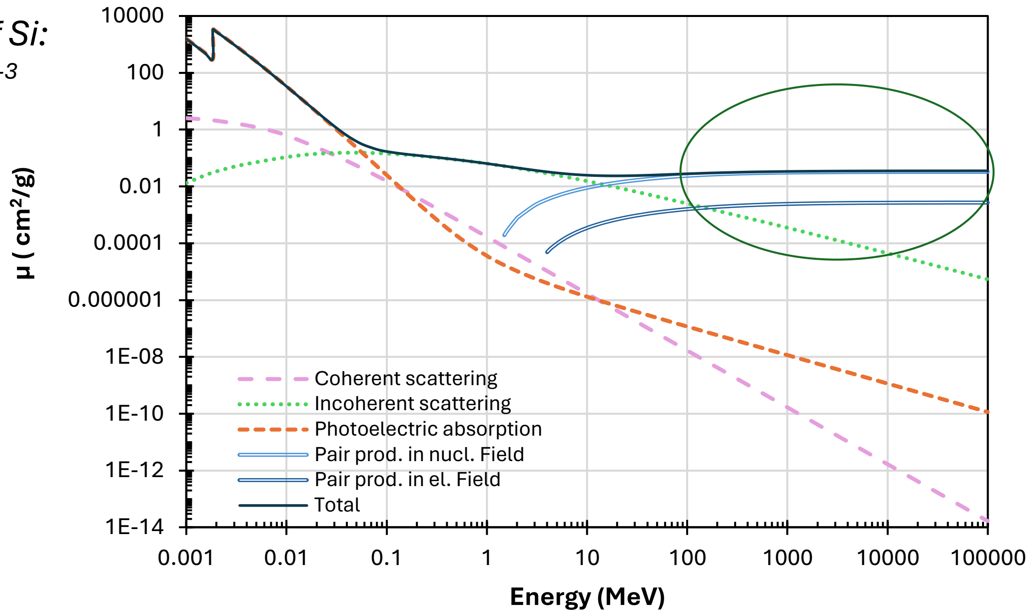
Proton stopping power in Si



https://www.physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

Density of Si: 2.34 g cm^{-3}

Photon attenuation in Si



https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html

Interactions in the Tracker

Photons: minute probability of scattering

Neutral hadrons: small probability of non-ionizing interaction

- ➢ Not detected in the tracker on the level of individual particles, but notable for the sensor in the long run…

Neutrino: no interaction, not detected

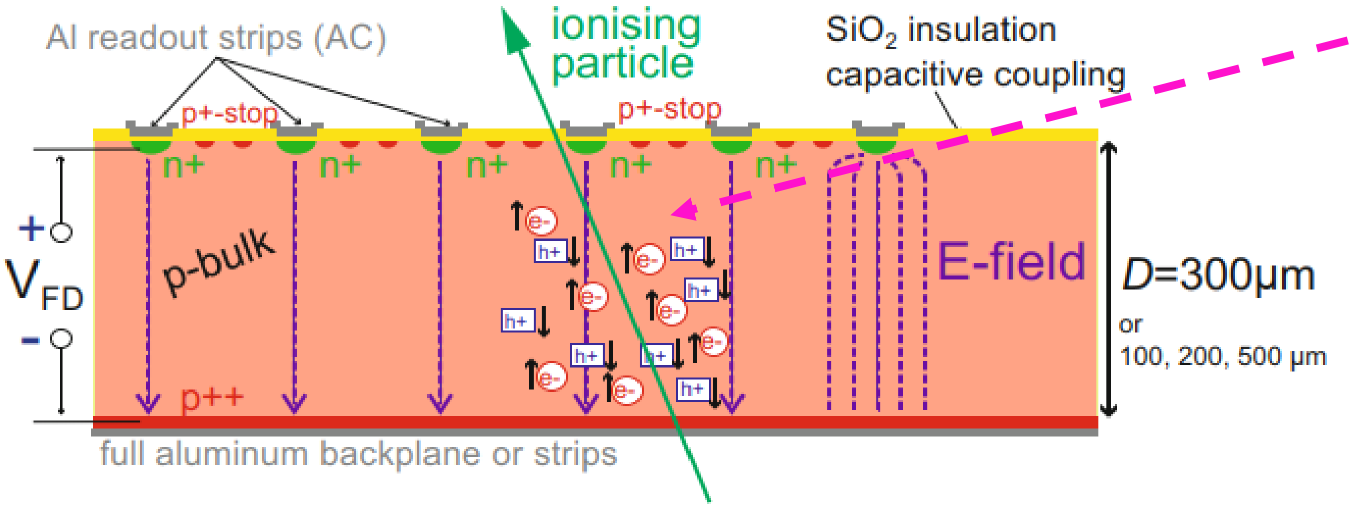
Electron, muon: track of minimum-ionization

Charged hadrons: track of minimum-ionization

Operation of silicon sensors

Semiconductor:

- **Reverse-biased p-n junction → depletion of the silicon bulk**
- **Charge carriers drift to the opposite-polarity electrodes in the electric field**
- **Signal: drifting charges = electrostatic induction on the electrodes**



F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, 2nd Edition, Springer 2017

How many electron-hole pairs are generated by a MIP in silicon?

Energy loss (cf. Bethe-Bloch!) = charge carrier generation is described by a Landau distribution: mean and most probable value are not identical.
Experimental values for Si: ca. 80 (105) e/h pairs per µm → in a 300 µm Si sensor, ca. 24 000 e/h pairs

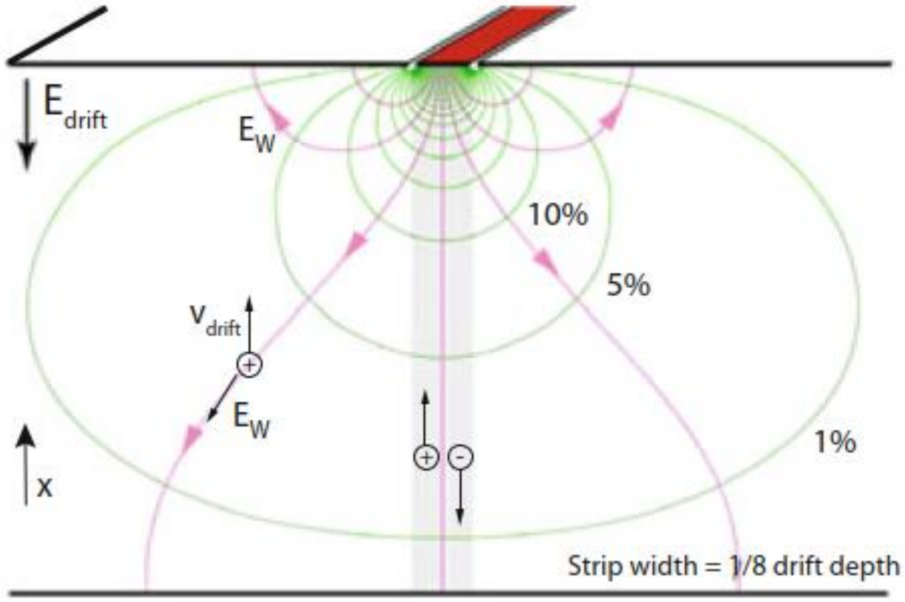
How fast do they drift?

- depends on electric field = bias voltage. Tens of ns…

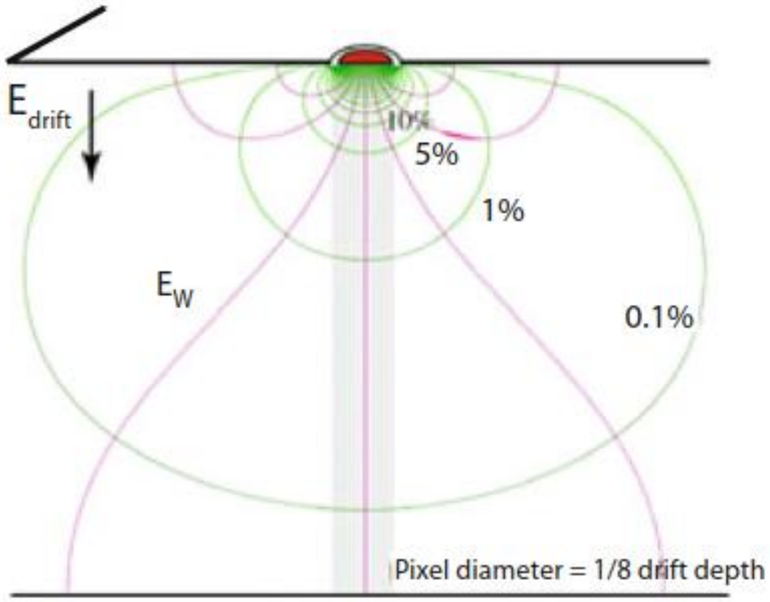
→ Constraints on readout electronics for integration time, signal-to-noise

Planar segmented sensors

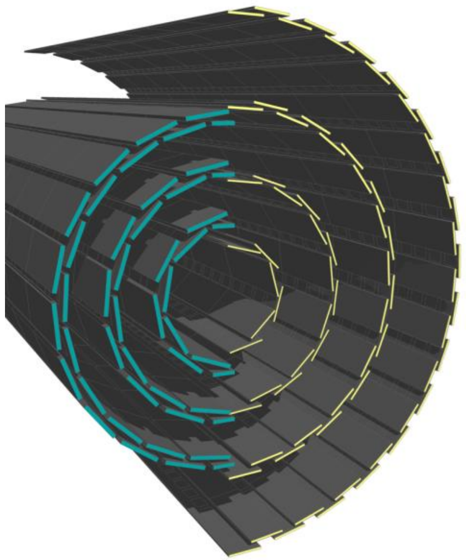
Resolution in 2D: strips

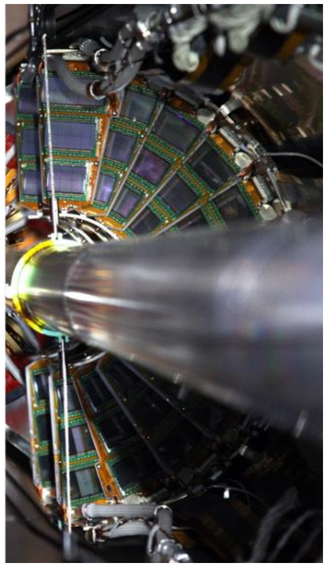


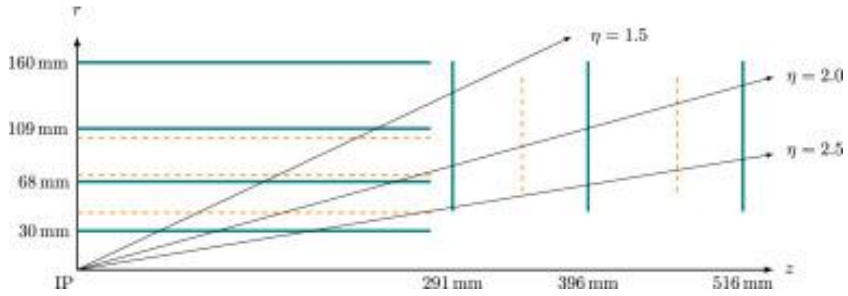
Resolution in 3D: pixels



CMS Phase I pixel detector





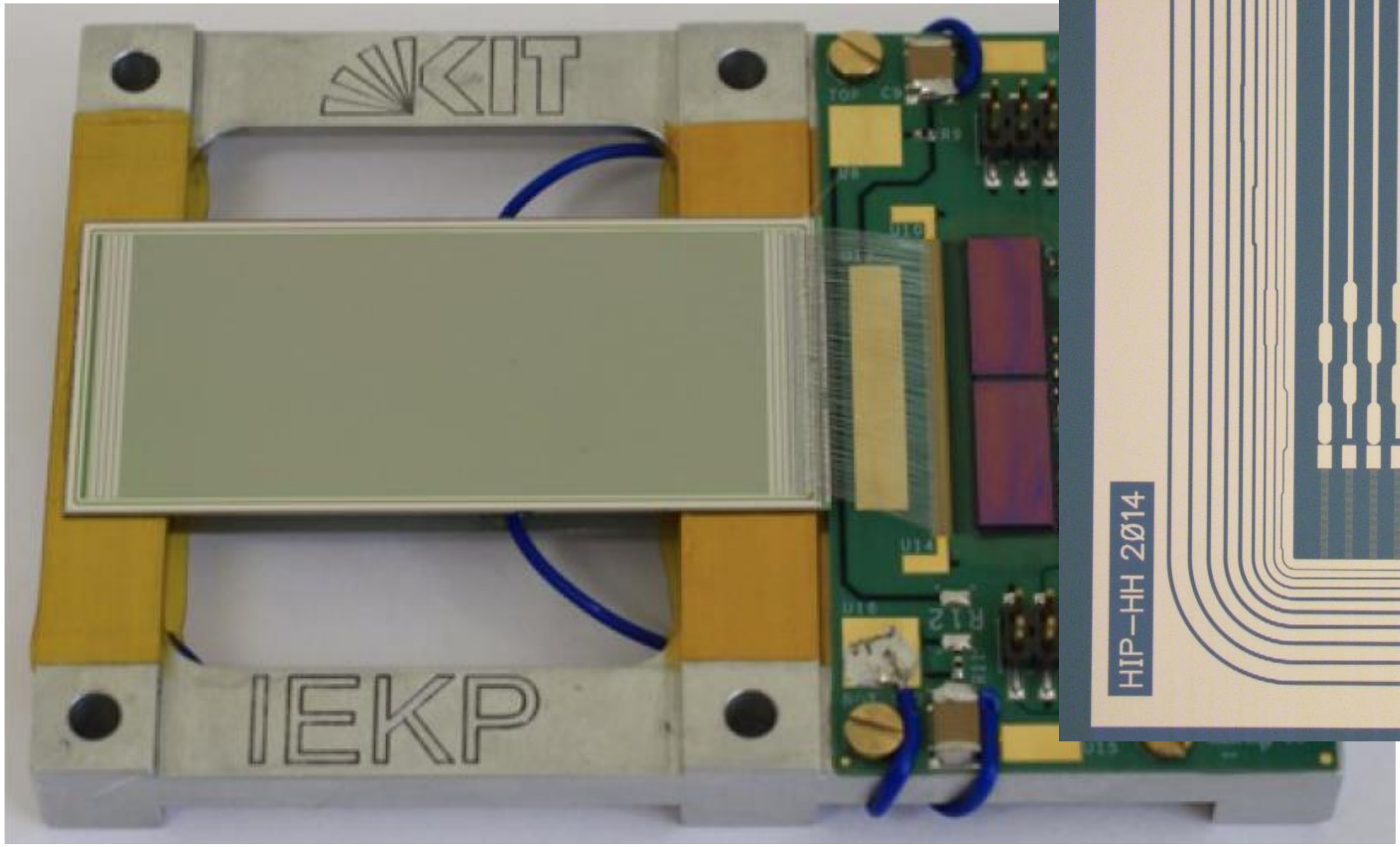


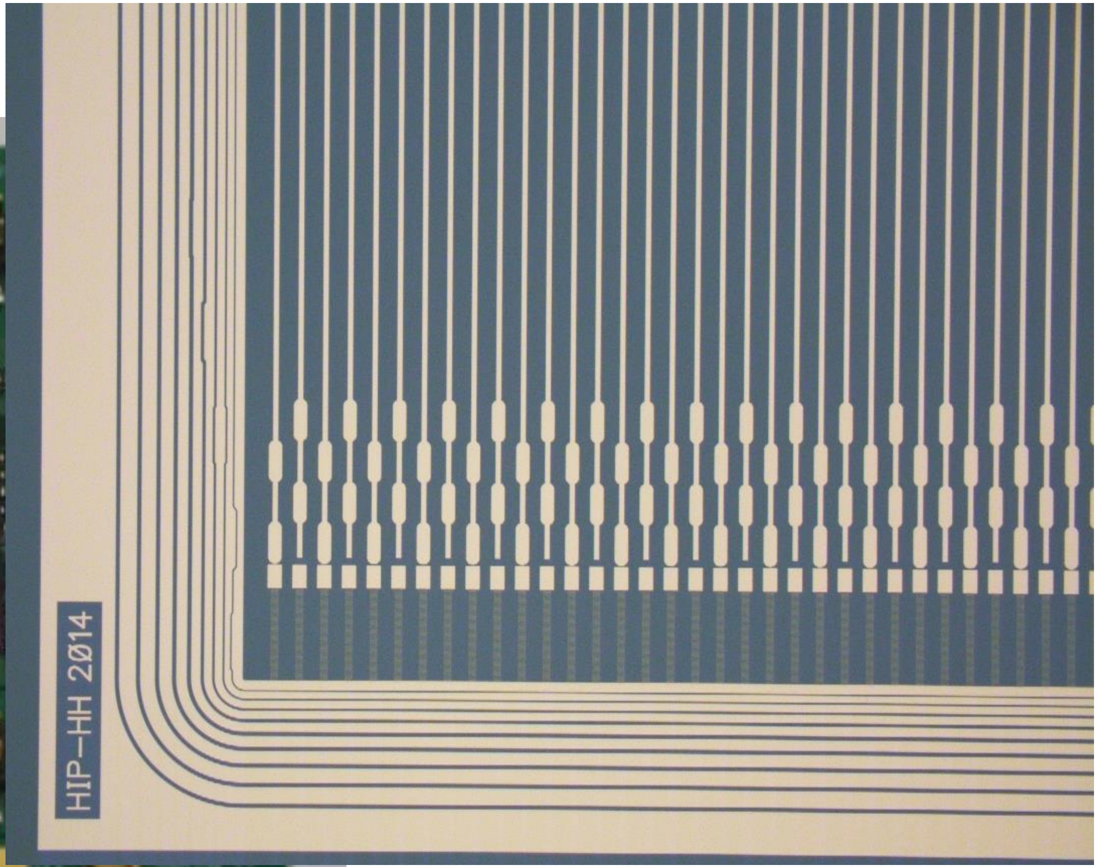
- Innermost component of the CMS experiment
- Main instrument for primary vertex location and precise particle track reconstruction

- Hybrid silicon pixel detector
- 4 barrel layers (BPIX), 2x 3 endcap or forward disks (FPIX)
- 124 M readout channels with 100x150 µm pixel size

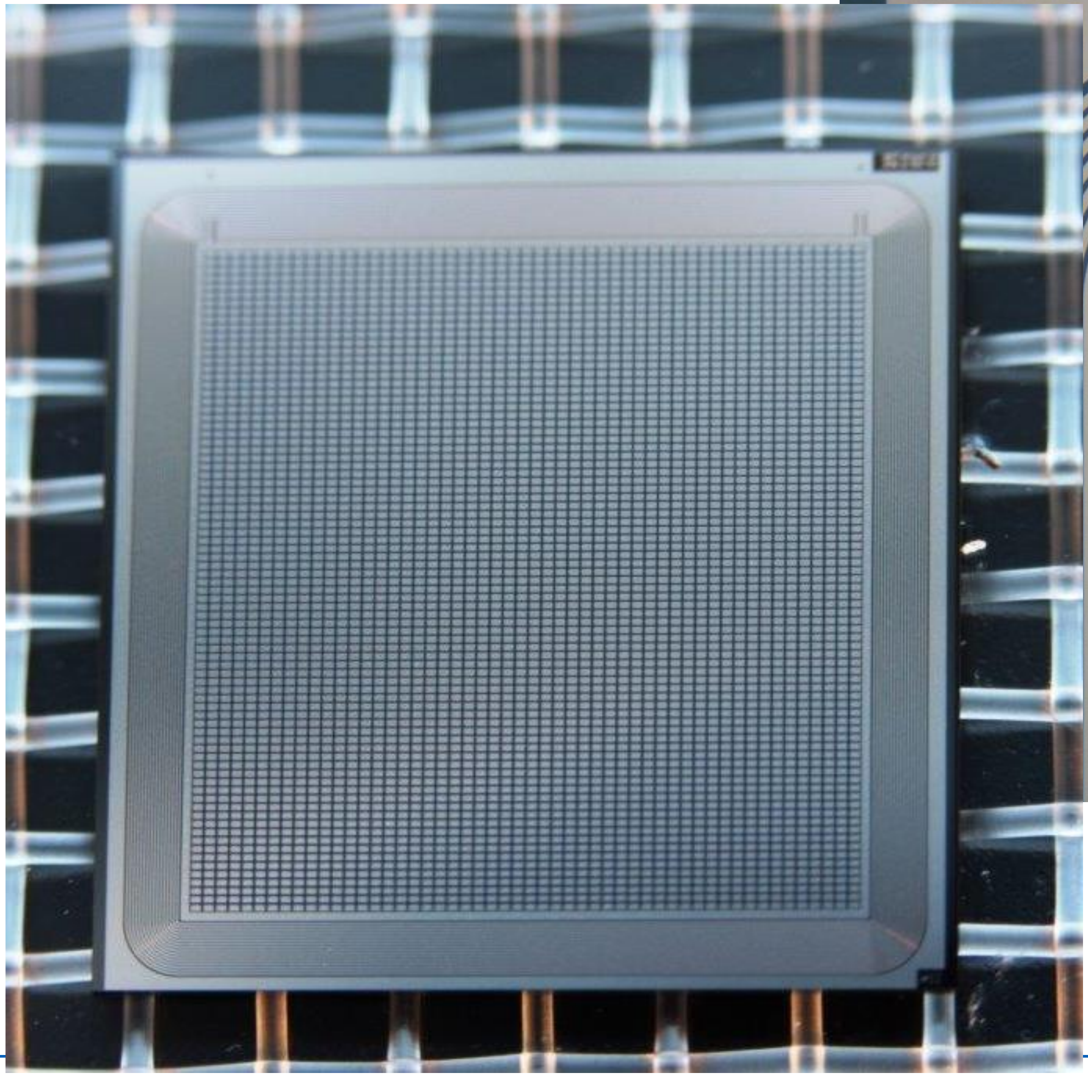
- In operation now for >2 years: experiences with operation, performance and radiation hardness becoming available

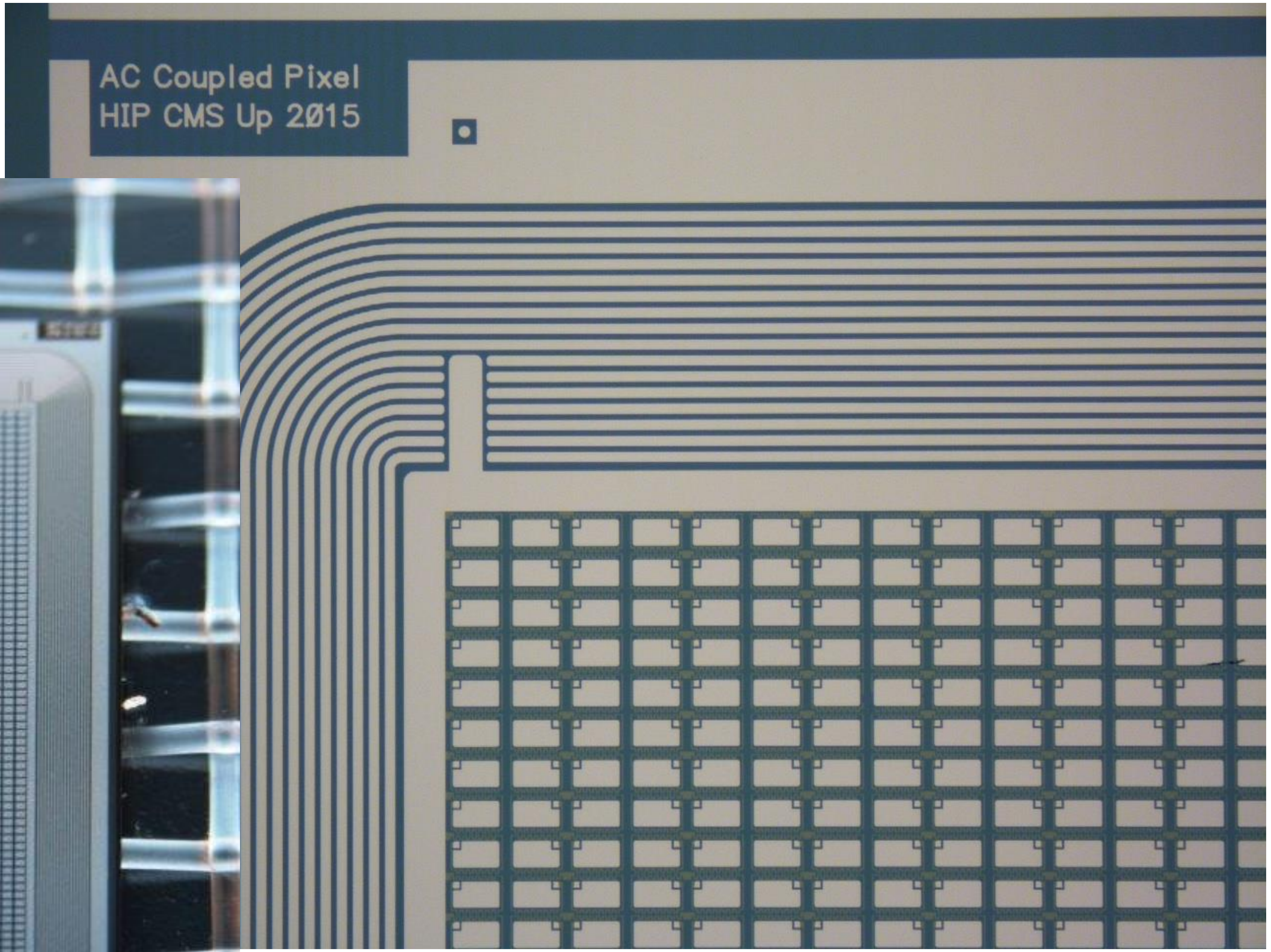
Strip sensors





Pixel sensors



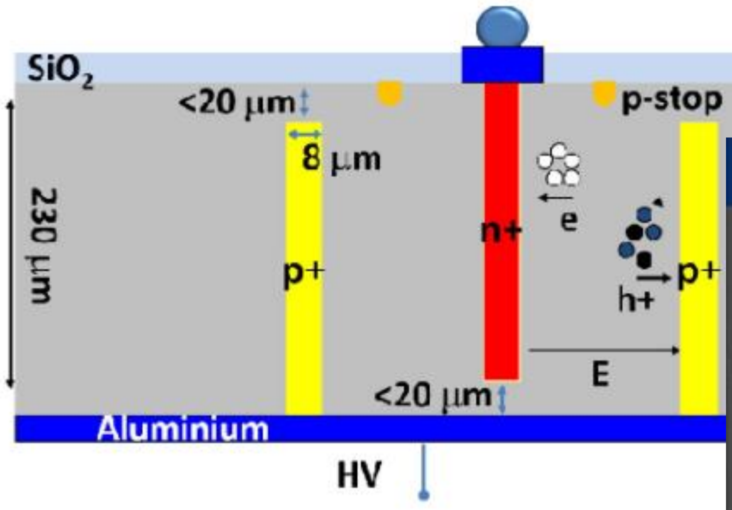


3D sensors

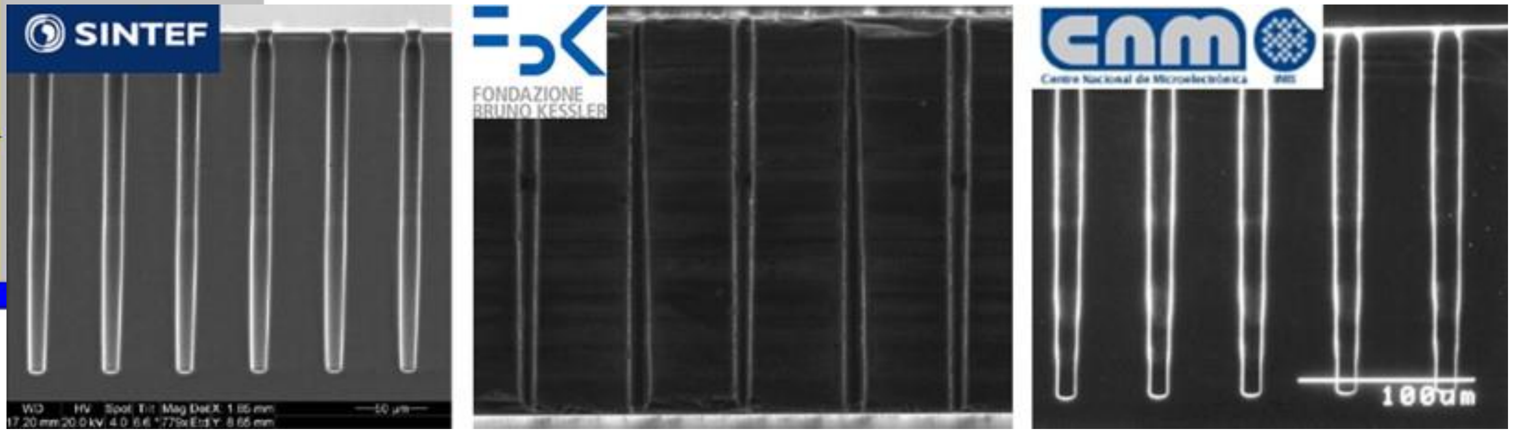
p- and n-electrodes not implemented as patterned sheets on the surfaces of the silicon surface, but as channels through the bulk

→ lower drift distance for charge carriers!

→ faster drift – good timing resolution…



E. Curras 2019



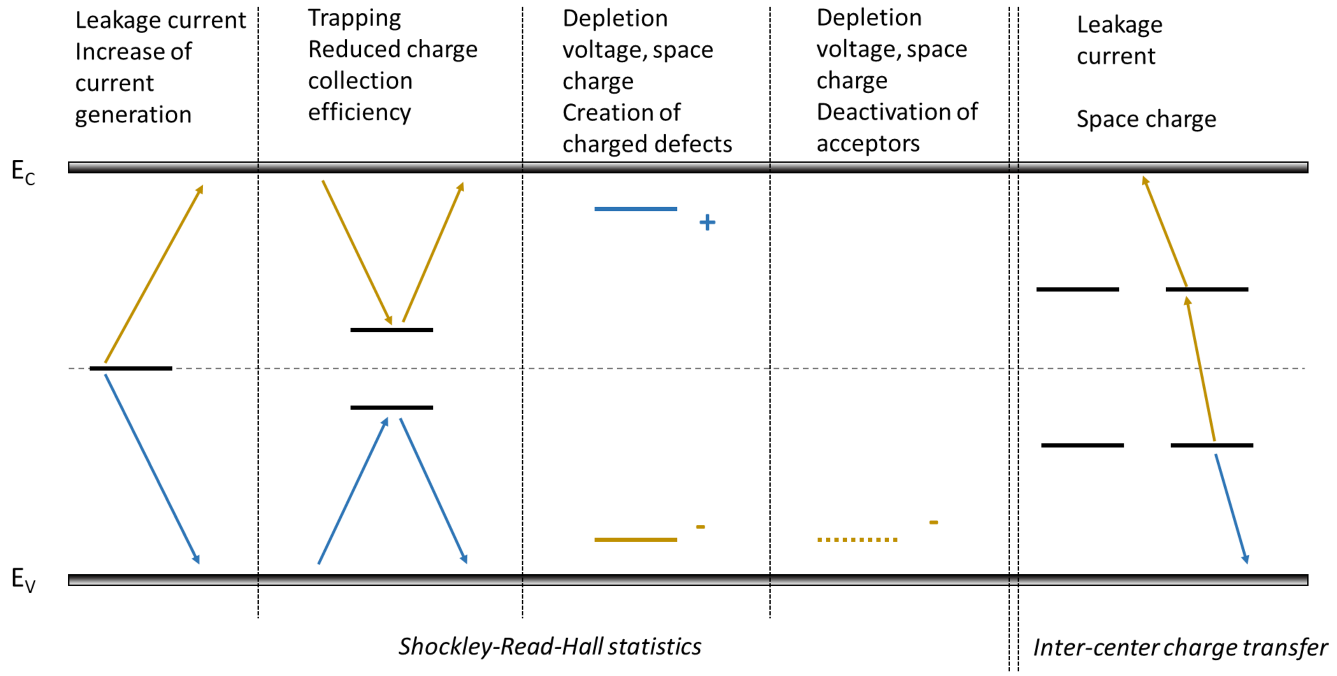
C. Da Via 2012

Silicon sensors in the (HL-)LHC

The challenge: radiation damage

Silicon tracking detectors are placed closest to the particle beams and interactions – are exposed to the highest radiation doses

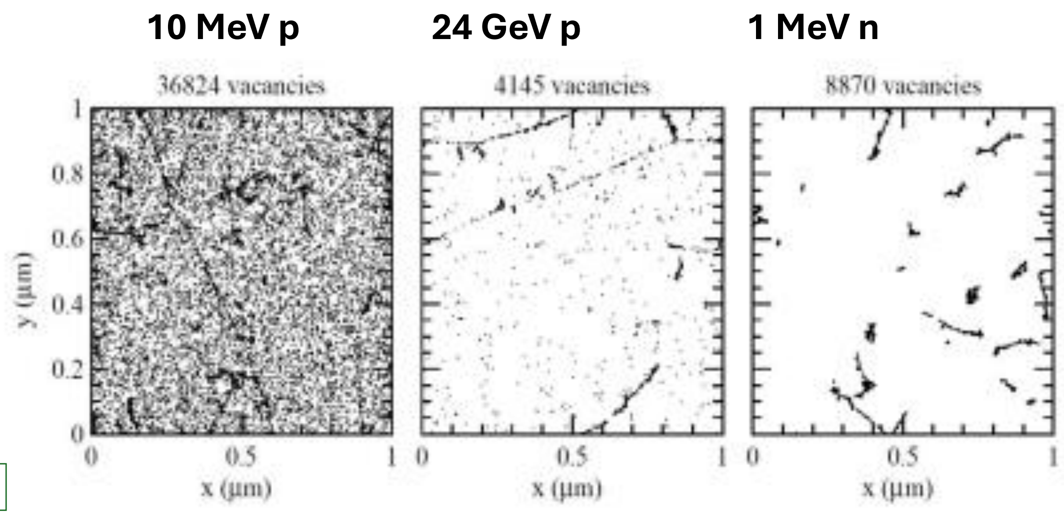
- **Total ionizing dose**
- **'Fluence'**



Evaluation and comparison of radiation damage

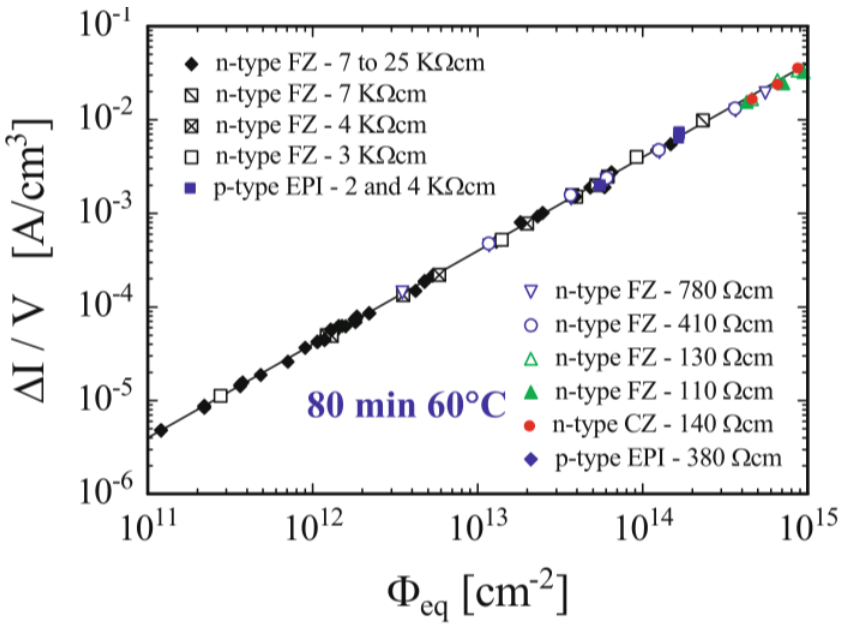
Target: compare and scale damage in silicon caused by different types and energies of radiation

- Introduction of different defect species; point defects vs defect clusters



M. Huhtinen 2002

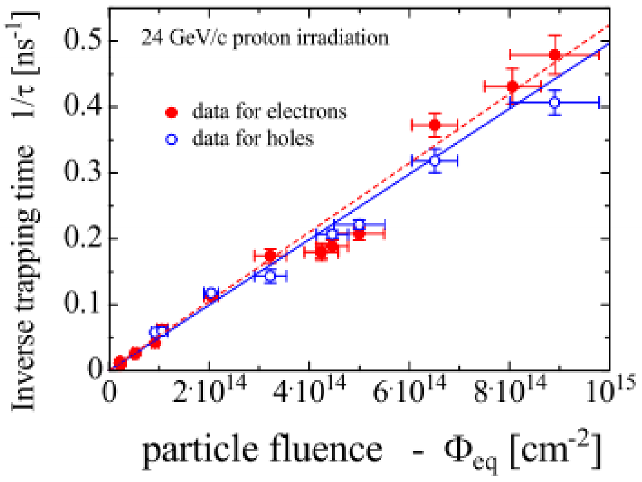
Leakage current

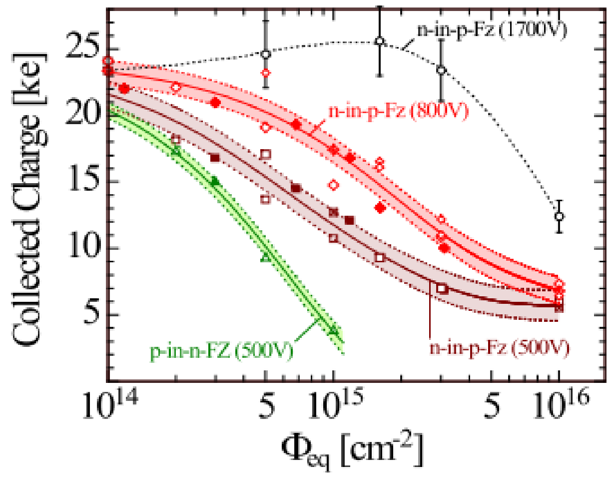


Various deep and shallow level defects → **leakage current** → higher noise, breakdown, higher power consumption

- Introduced in an early model, still valid
- Further studies and larger datasets needed for **p-type** Si substrates

Charge collection and trapping



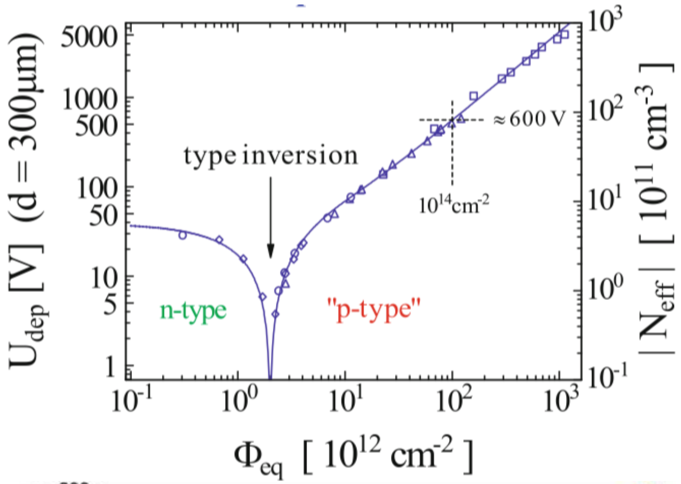


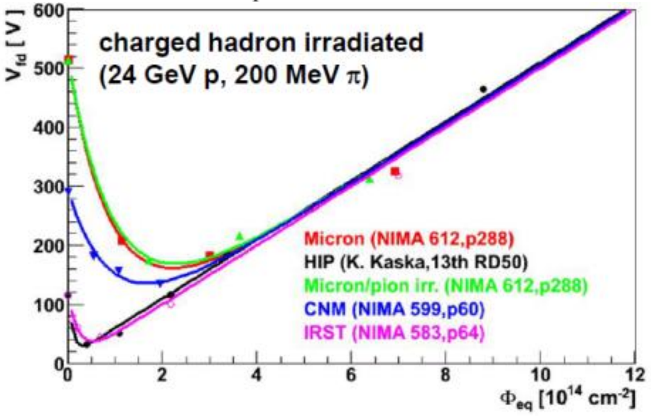
O. Krasel et al, 2004

G. Casse et al, 2010

- Deep-level defects, clusters → charge trapping → reduced **charge collection length** & **charge collection efficiency** → decreased spatial resolution, smaller signal, slower signal
  - Introduced in an early model, additional data collected over the years
  - Evolution and amount of collected charge becomes more relevant than the concept of full depletion at high fluences

Effective doping concentration





- Change in states of of dopant atoms, creation of charged defects → change in N_{eff}
- n-type: space charge sign inversion → higher V_{bias} required
  - Introduced early on
- p-type: **acceptor removal** → (space charge sign inversion), reduced gain → (higher V_{bias} required), worse timing resolution
  - Has risen to attention in recent years due to the increase of interest in p-type substrates and LGADs with a p-type gain layer

The High-Luminosity LHC

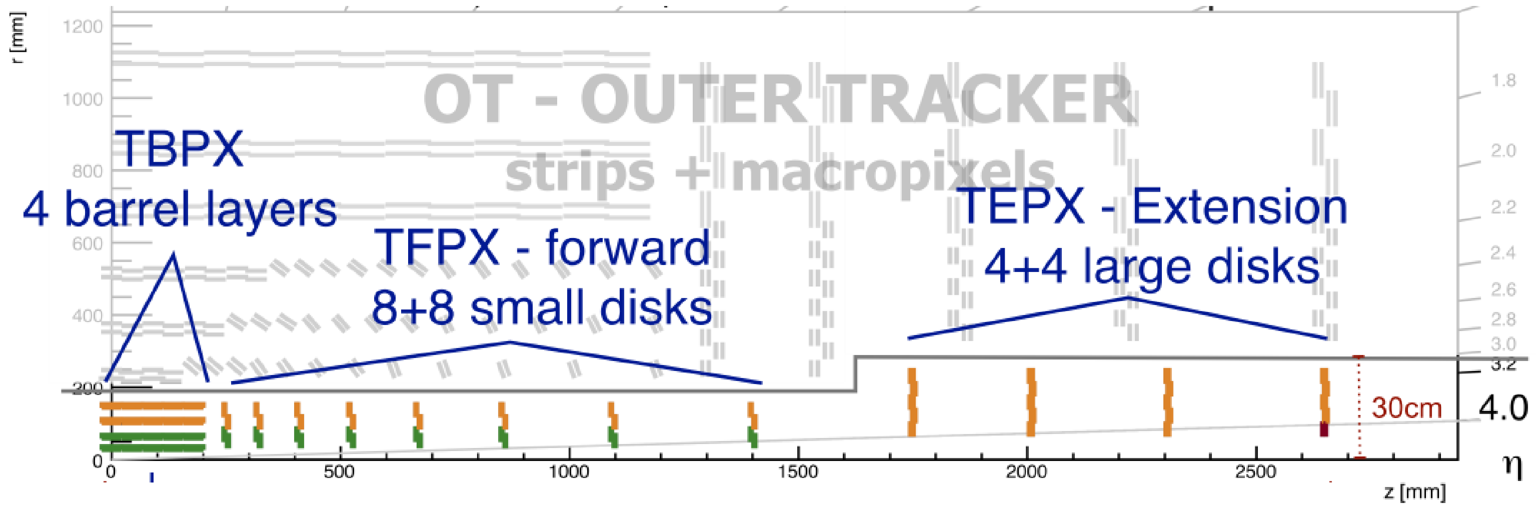
- Long shutdown in years 2024-~~2026~~ **2028**: installation of Phase II upgrades and transition to High-Luminosity LHC
- Collision center-of-mass energy 14 TeV

- Luminosity up to $7x10^{34}$ $cm^{-2}s^{-1}$ (LHC: $2x10^{34}$ $cm^{-2}s^{-1}$)
- Up to 200 p-p collisions per bunch crossing (”pile-up”)
- Fluence, i.e. radiation dose, to the innermost silicon detector layers: $2x10^{16}$ n_{eq} cm^{-2}

- In the pixel tracker: ~ 140 000 pixels / chip (as compared to present 4160)
- Total number of channels: 1 924 M

CMS Phase II pixel detector upgrade

- Structure of the upgraded pixel detector:
  - 4 barrel layers, 2x 8 inner endcap disks, 2x 4 extended endcap disks (these are also used for beam luminosity monitoring, instead of separate instrumentation)

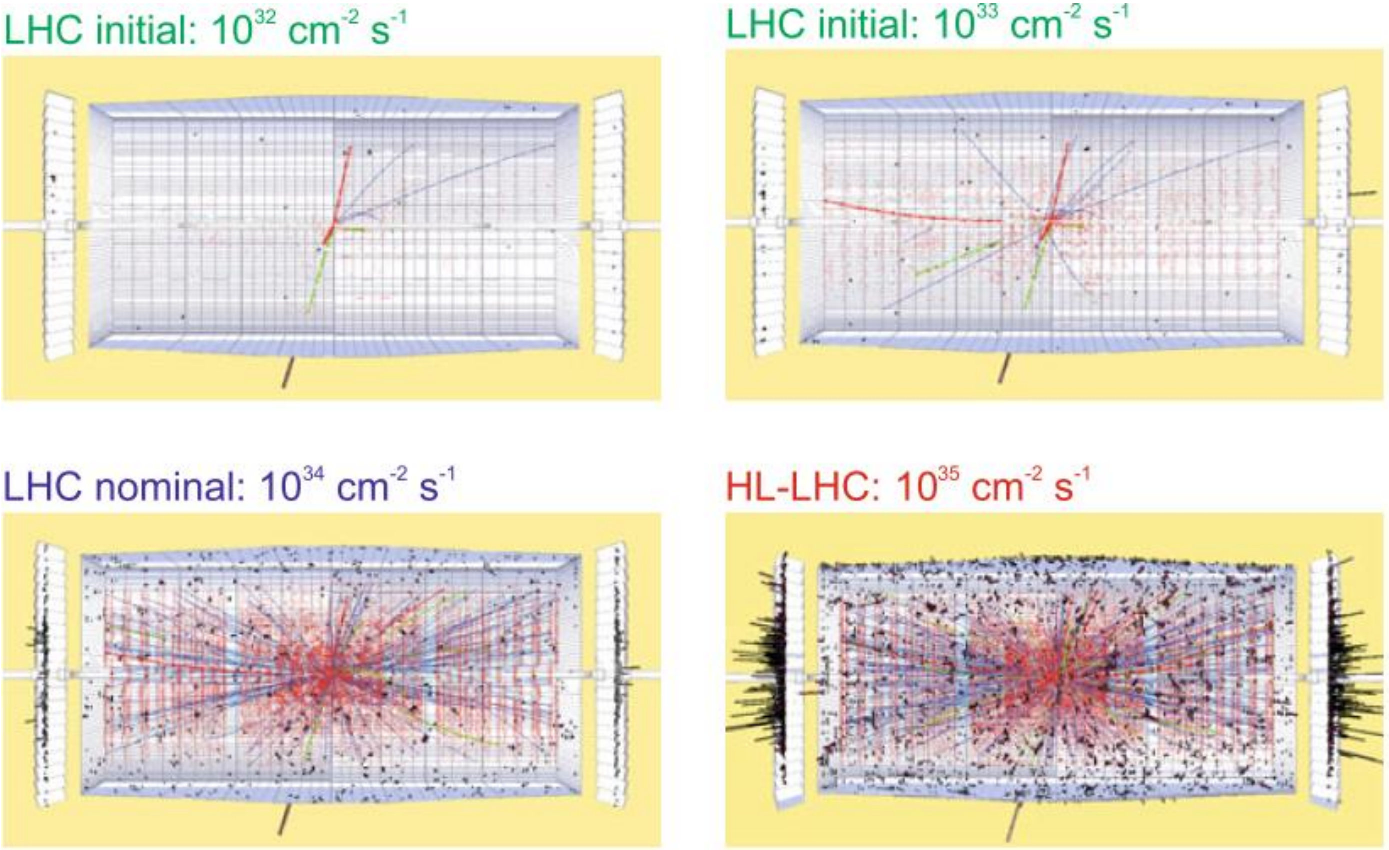


Timing

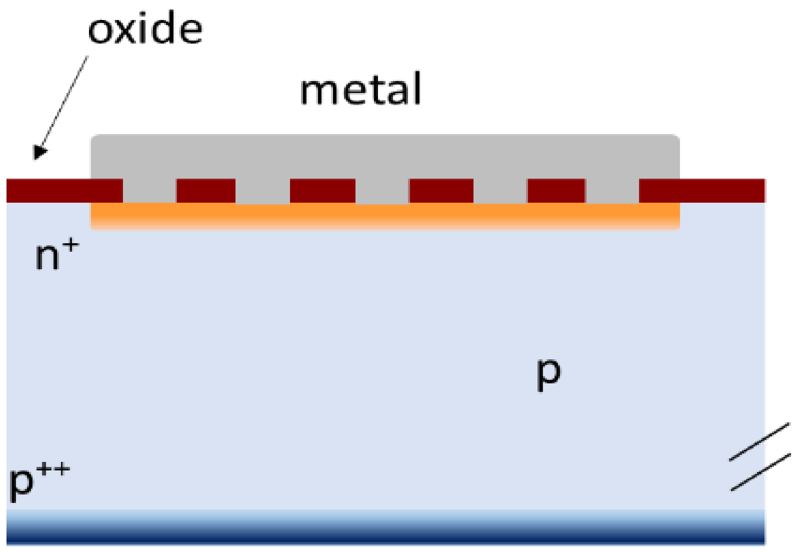
In a collider with high luminosity, there is not just one collision at a time

From LHC to HL-LHC: Pile-up of collisions increases to ~200

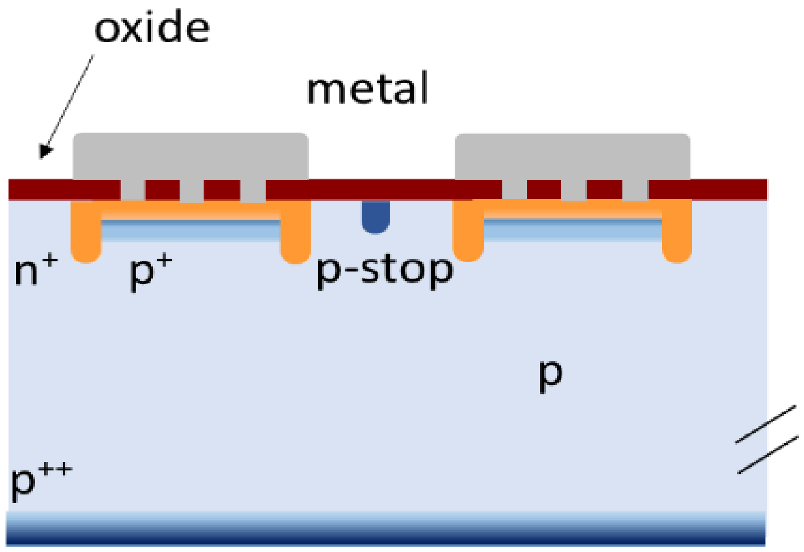
Separation of primary vertices, pointing of tracks not possible without timing information



Low-gain avalanche diodes

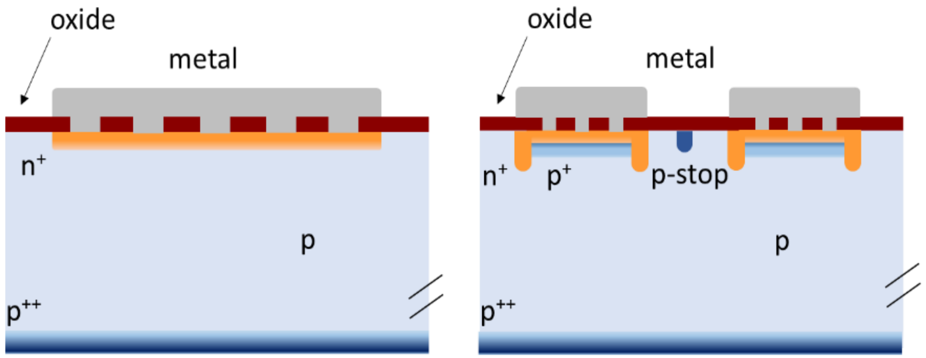


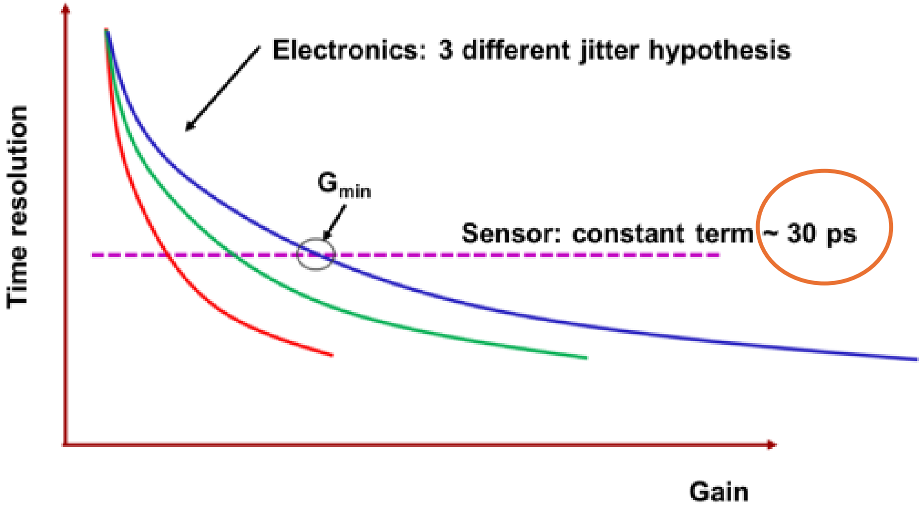
n-in-p

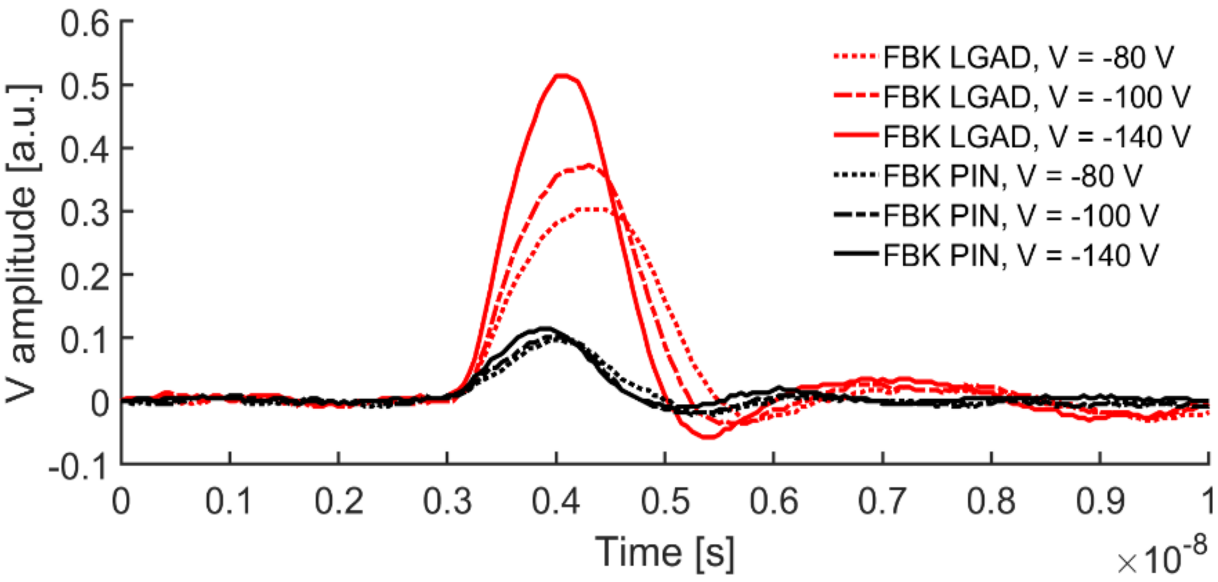


LGAD

Low-gain avalanche diodes







Summary: evelopments in silicon sensors

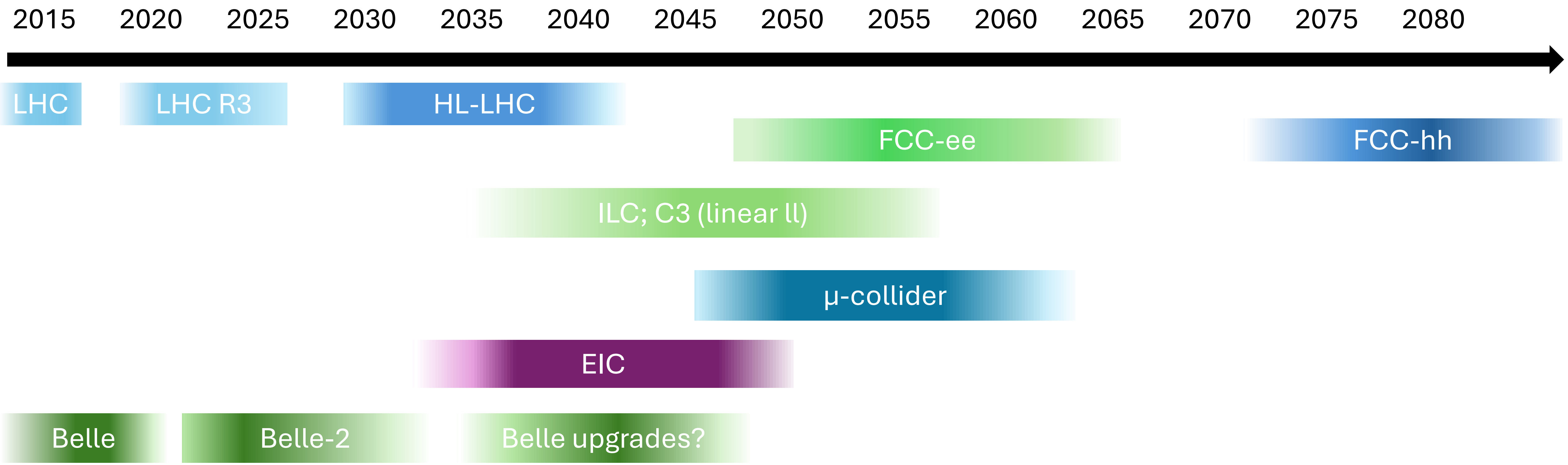
- **Radiation hardness**
  - P-type sensors – using electron drift to pixels
- **Sensor design**
  - Smaller pitch
- **Fast timing: LGADs in HL-LHC upgrades**
- **3D sensors incorporated in pixel detector upgrades inner layers – also strong potential for timing**

Silicon detectors in future particle physics experiments

Efficient tracking (in 4D)

- **Timing resolution**
  - Silicon sensors with gain
  - 3D detectors
- **Improved spatial resolution**
  - Small pixels
  - 3D detectors
- **Operation at extreme fluences**
  - Radiation tolerance of material
  - Sensor design (incl. thickness)
- **Efficient manufacturing and operation**
  - Low mass
  - Large area, low cost, low power consumption
  - Challenging interconnection technology

Silicon sensor development for future colliders


2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
2075
2080
LHC
LHC R3
HL-LHC
FCC-ee
FCC-hh
ILC; C3 (linear ll)
μ-collider
EIC
Belle
Belle-2
Belle upgrades?

Extreme conditions in future colliders

HL-LHC

- Max. fluence on silicon detectors ~$3x10^{16}$ n_{eq}/cm^2
- Pileup ~200, for mitigation: timing resolution < 50 ps

Future colliders

- Fluence on inner layers up to $7x10^{17}$ n_{eq}/cm^2 (FCC)
- Similar pileup conditions to HL-LHC
- Desired resolution: 1-3 µm (lepton colliders)
- Material budget: down to 1% X_0

“Near-future” colliders other than the (HL-)LHC

Several candidates: (ILC), (CLIC), C3, CEPC, FCC-ee

Ongoing / to be built: SuperKEKB / Belle-2, EIC

- **Further: muon collider, FCC-hh**

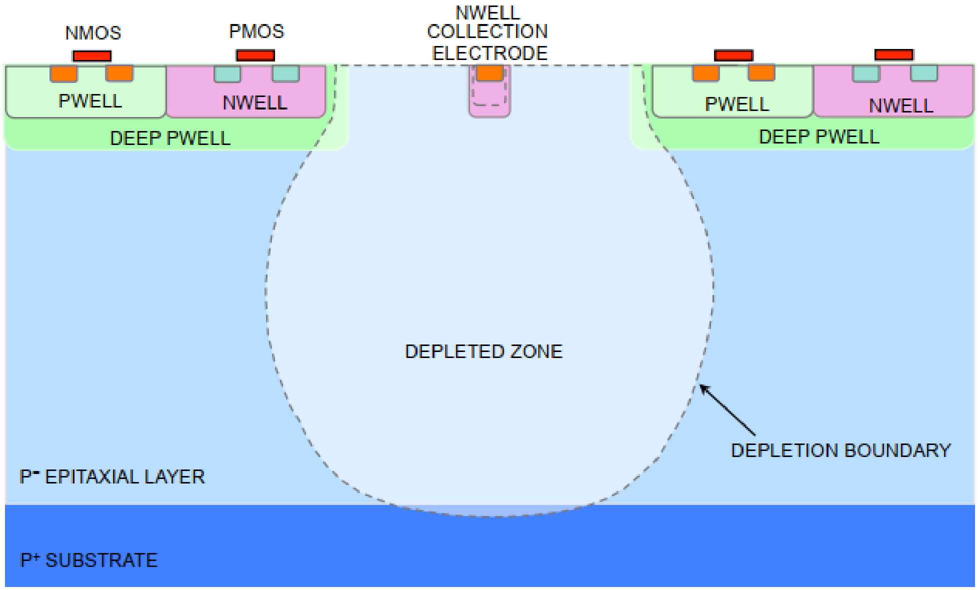
- **All near-future colliders are lepton or lepton-hadron colliders, at the Intensity Frontier**
  - No q-q, g-g interactions in the collisions, no QCD background – ‘clean’
- **Developments / trends for silicon tracking and timing detectors are turning to some extent!**

“Near-future” colliders other than the (HL-)LHC

- **All near-future colliders are lepton or lepton-ion colliders, at the Intensity Frontier**
  - No q-q, g-g interactions in the collisions, no QCD background – ‘clean’
- **Developments / trends for silicon tracking and timing detectors are turning to some extent!**

- **Radiation levels significantly lower**
- **Fewer vertices and tracks, little to no pileup – timing less essential**
- **Tracking resolution needs to improve: reduce material budget to minimize scattering**
- **Large area and low cost, low power consumption increasingly important**

Monolithic CMOS detectors



Active CMOS / MAPS

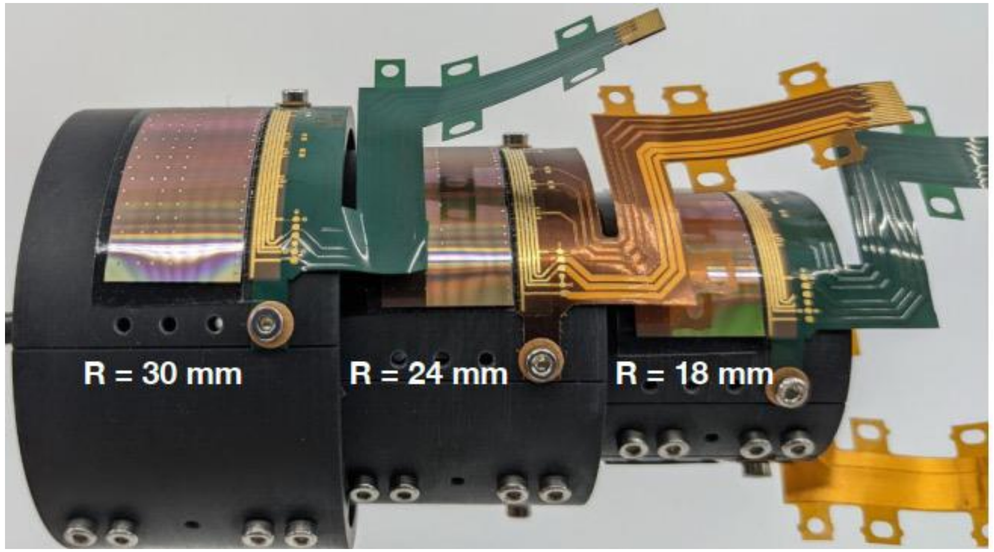
- With/without gain

- **Small pixels, better spatial resolution, do not require elaborate interconnection**
- **Commercial large vendor process**
- **Showstopper for p-p colliders so far: radiation levels**

“Massless” detectors

Thin stitched detectors: ALICE ITS-3 for the HL-LHC upgrade

➢ *Example for inner tracker and vertex detector at most future colliders: EIC, FCC-ee, etc*



Timing detectors

Do not lose expertise and R&D motivation here: Energy Frontier experiments will require extreme radiation tolerance and timing resolution!!

Some timing information (imaging of particles) from time projection chambers

Particle ID: separation and identification of charged particles (incl charged hadron species) by time-of-flight

T0 timestamp for vertexing, tracking, other particle-ID detectors, TPC

- this is exactly the approach in the Electron-Ion Collider
- similar case could be made in FCC-ee

Add advanced timing capabilities to strip sensors?

Some variants of fast-timing sensors also provide precise spatial resolution with lower pitch; higher signal also helps readout electronics…

Fast timing

Timing capabilities for MIPs to <20 ps (< 5ps electronics jitter)

3D integration

Not only in silicon trackers!

- Timing of calorimeter showers
- Fast light readout from scintillator / Cherenkov detector: also down below 100 ps!

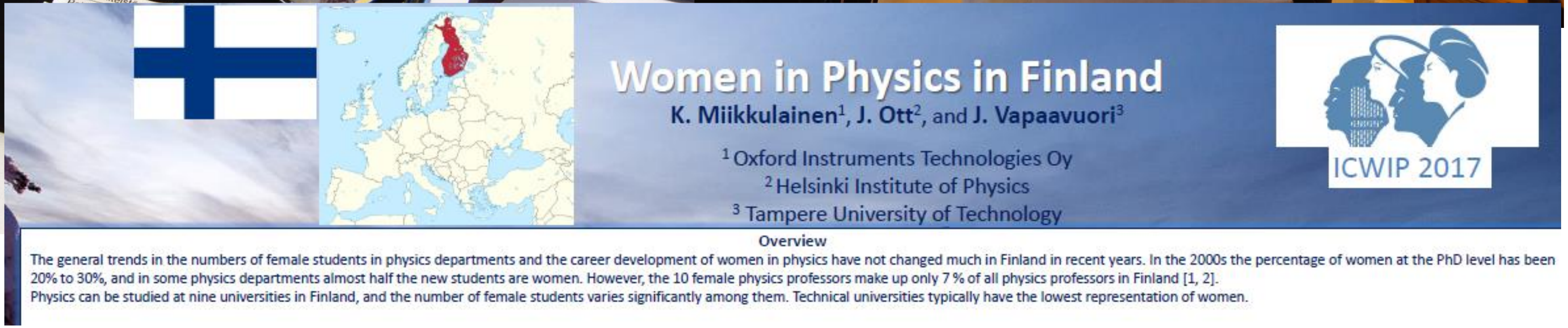
Detectors with gain: not only high-energy physics: nuclear physics, photon science, medical imaging (e.g. positronium decay PET)

Thank you!

Backup

Outreach

"Making the invisible visible"


Women in Physics in Finland

K. Miikkulainen[1], J. Ott[2], and J. Vapaavuori[3]

[1] Oxford Instruments Technologies Oy
[2] Helsinki Institute of Physics
[3] Tampere University of Technology

ICWIP 2017

Overview

The general trends in the numbers of female students in physics departments and the career development of women in physics have not changed much in Finland in recent years. In the 2000s the percentage of women at the PhD level has been 20% to 30%, and in some physics departments almost half the new students are women. However, the 10 female physics professors make up only 7 % of all physics professors in Finland [1, 2].
Physics can be studied at nine universities in Finland, and the number of female students varies significantly among them. Technical universities typically have the lowest representation of women.

References

Technical design reports

- detailed information on physics background, detectors, electronics, mechanics etc

CMS Collaboration, *The Phase-2 Upgrade of the CMS Tracker*, CERN-LHCC-2017-009, CMS-TDR-0141, 2017

CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, CMS-TDR-020, 2019

CMS Collaboration, The Electromagnetic Calorimeter Technical Design Report, CERN-LHCC-97–33, CMS-TDR-4,1997

Book:

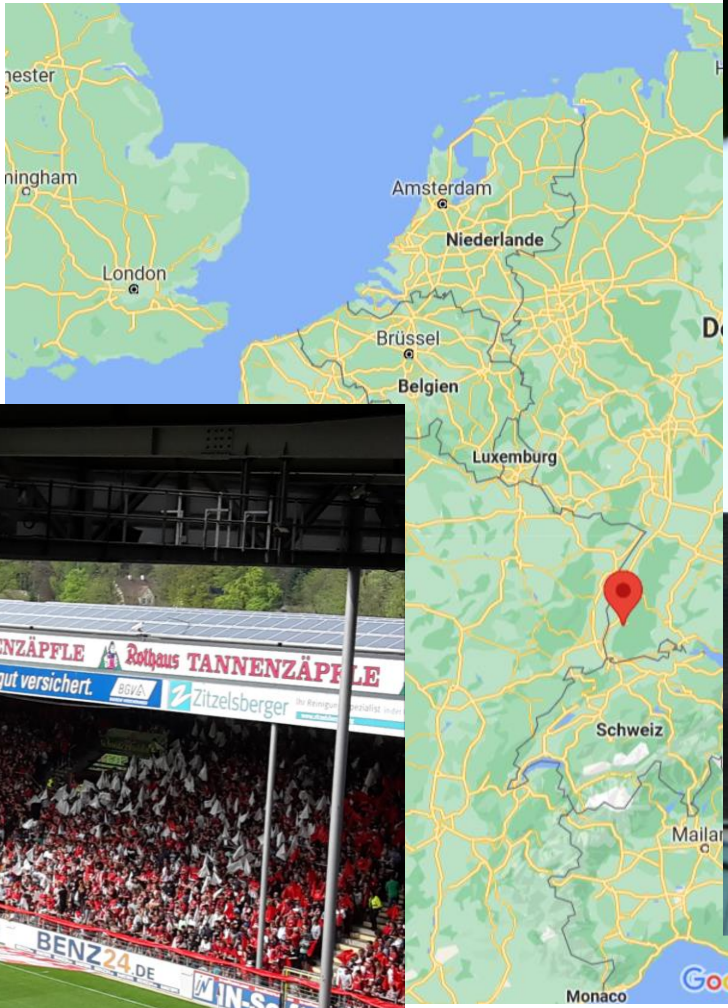
F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, 2nd Edition, Springer 2017

Introduction

Jennifer Ott

Born in Freiburg,

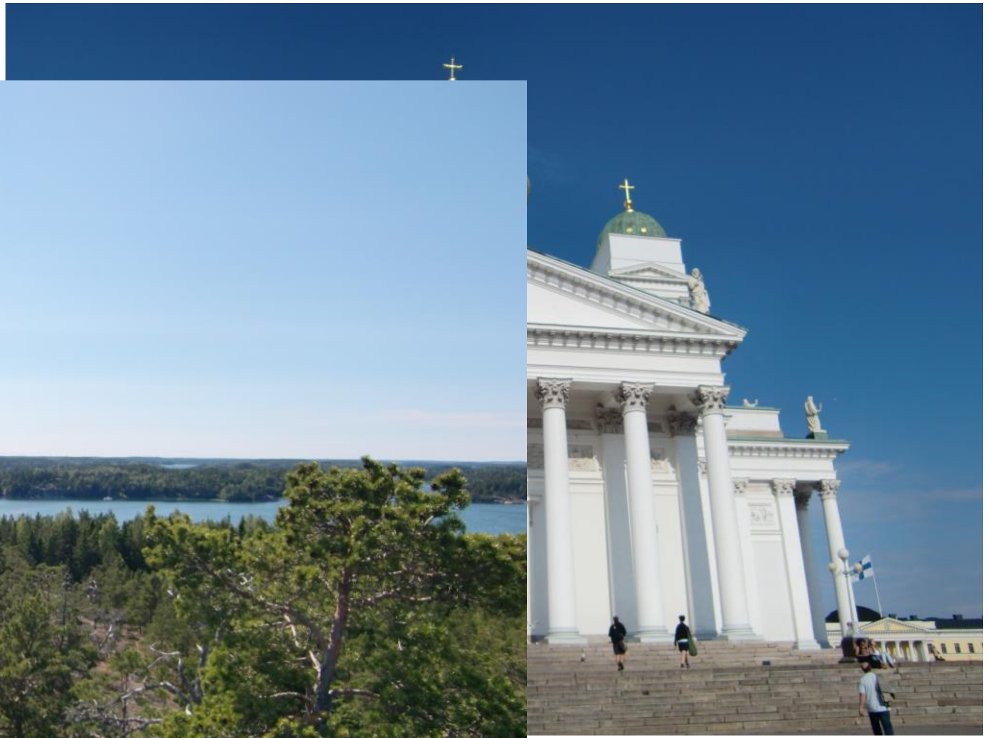
Germany



Introduction

High school student exchange year to Finland in 2009/2010

… stayed there!



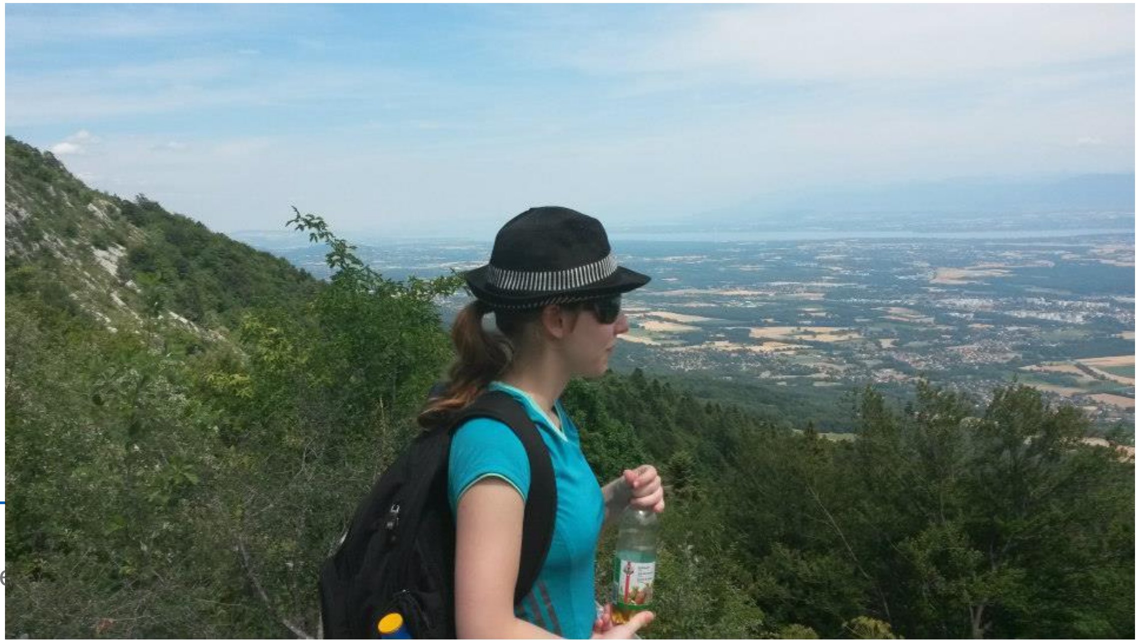
Introduction

Graduation from high school ('lukio') in Järvenpää, Finland, in 2011

B.Sc., University of Helsinki, chemistry (2014)

M.Sc., University of Helsinki, radiochemistry (2015)

- Fabrication of biasing resistors for pixel detectors
- Including 3 months at CERN



Introduction

Jennifer Ott

M.Sc. University of Helsinki, radiochemistry (2015)

D. Sc. (Tech.) Helsinki Institute of Physics & Aalto University

(spring 2021)

Development, processing and characterization of silicon pixel and timing detectors for the CMS Experiment

Especially: using thin films grown by atomic layer deposition in semiconductor detectors

Thesis publications

I. J. Härkönen, **J. Ott** et al, *Atomic Layer Deposition (ALD) grown thin films for ultra-fine pitch pixel detectors*, Nuclear Instruments and Methods in Physics Research A (2016), 831, 2–6

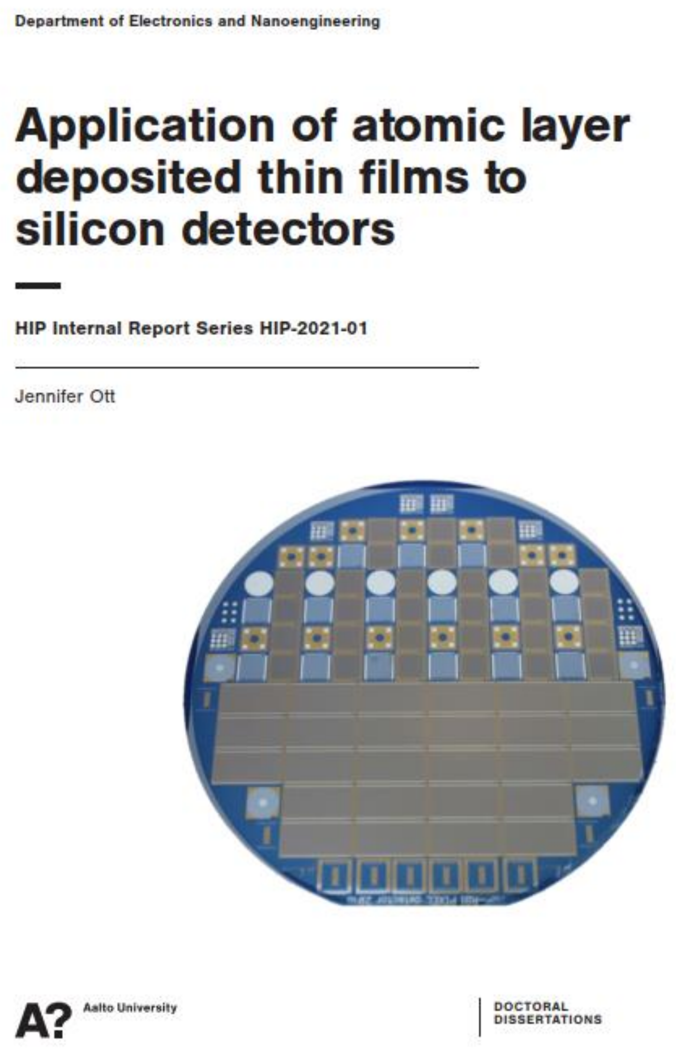
II. **J. Ott** et al, *Passivation of Detector-Grade Float Zone Silicon with Atomic Layer Deposited Aluminum Oxide*, Physica Status Solidi A (2019), 1900309

III. **J. Ott** et al, *Impact of doping and silicon substrate resistivity on the blistering of atomic-layer-deposited aluminium oxide*, Applied Surface Science (2020), 522, 146400

IV. **J. Ott** et al, *Characterization of magnetic Czochralski silicon devices with aluminium oxide field insulator: effect of oxygen precursor on electrical properties and radiation hardness*, Journal of Instrumentation (2021), accepted

V. **J. Ott** et al, *Processing of AC-coupled n-in-p pixel detectors on MCz silicon using atomic layer deposition (ALD) grown aluminium oxide*, Nuclear Instruments and Methods in Physics Research A (2020), 958, 162547

VI. A. Gädda, **J. Ott** et al, *AC-coupled n-in-p pixel detectors on MCz silicon with atomic layer deposition (ALD) grown thin film*, Nuclear Instruments and Methods in Physics Research A (2021), 986, 164714


Department of Electronics and Nanoengineering

Application of atomic layer deposited thin films to silicon detectors

HIP Internal Report Series HIP-2021-01

Jennifer Ott

Aalto University

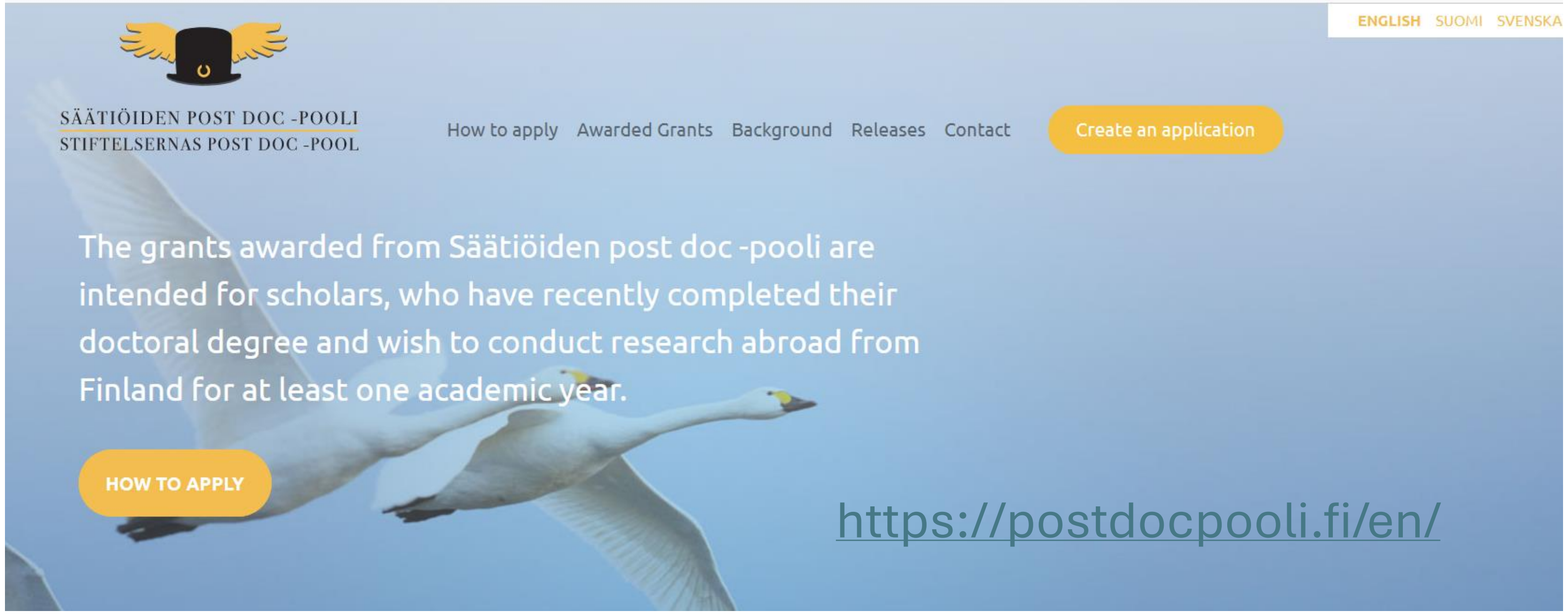
DOCTORAL DISSERTATIONS

http://urn.fi/URN:ISBN:978-952-64-0277-2

Introduction

1st September 2021 → 31st August 2023: postdoctoral researcher at UC Santa Cruz with a scholarship from the Finnish Cultural Foundation

Continuing as postdoctoral researcher at UCSC



https://postdocpooli.fi/en/

Interaction of radiation with matter

= transfer of energy to a medium

Typically presented from a viewpoint of radiation safety: focus on absorption and shielding, and radiation that can be more commonly encountered

Photons and particles: gamma rays and x-rays; alpha particles, beta particles (electron/positron), protons…

Ionizing vs non-ionizing?

- Yes, but not exclusively – neutrons and other neutral hadrons!
- *Electromagnetic vs hadronic interaction*

➢ **How does this relate to particle physics experiments?**

Radiation detection in high-energy physics

Energy scales: TeV c-o-m energies at the LHC - photon and particle energies in the GeV's

… vs laboratory: Co-60 gamma ray, 1.1 and 1.3 MeV, or Sr-90/Y-90 beta particle maximum energy, 0.6 – 2 MeV

- Underlying interaction mechanisms remain, but manifest in specific ways
- High energies require large amounts of absorber material → large detectors
- Some particle species interact so little that they cannot feasibly be stopped (or do not interact at all)

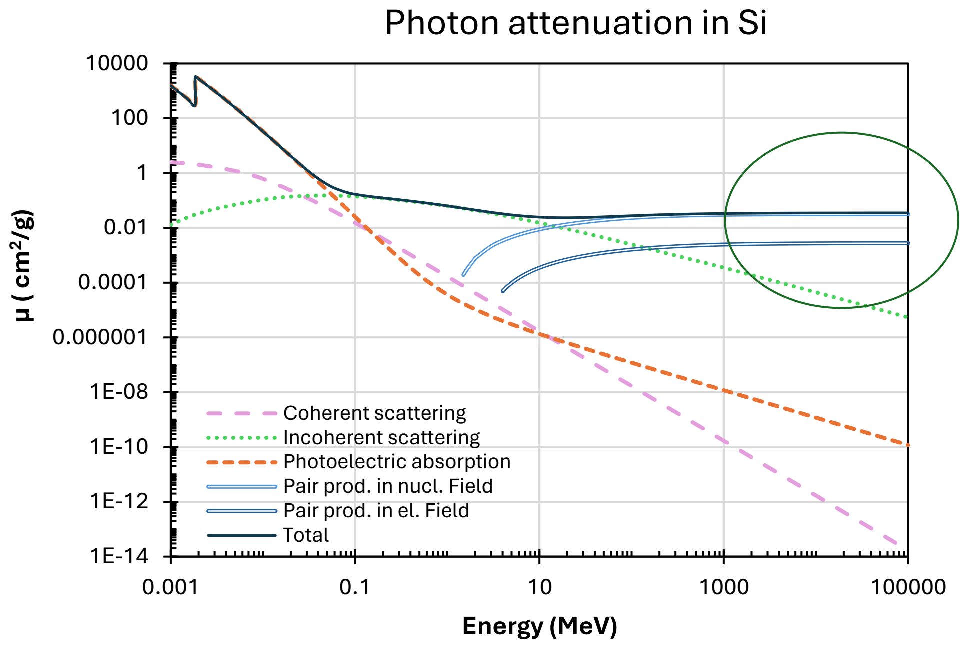
Interaction of radiation with matter: photons

On a larger scale: statistical process, exponential decrease of intensity/flux in material depending on mass absorption coefficient and absorber thickness

$$I_l = I_0^{-\mu l} \quad // \quad I_l = I_0^{-\frac{\mu}{\rho_m}\rho_m l}$$

Mechanisms:

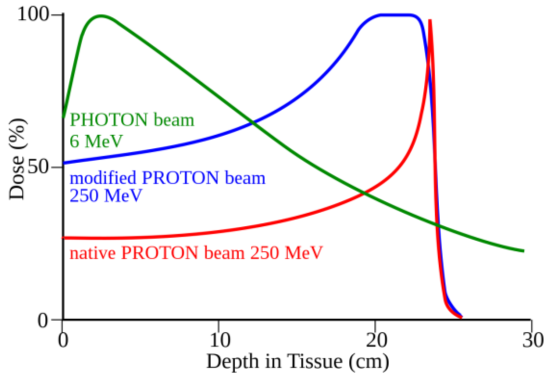
- Elastic scattering
- Photoelectric effect
- Compton scattering (inelastic scattering)
- Pair production
- (Photonuclear reactions)



Cross-sections for processes depend on photon energy and absorber material

https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html

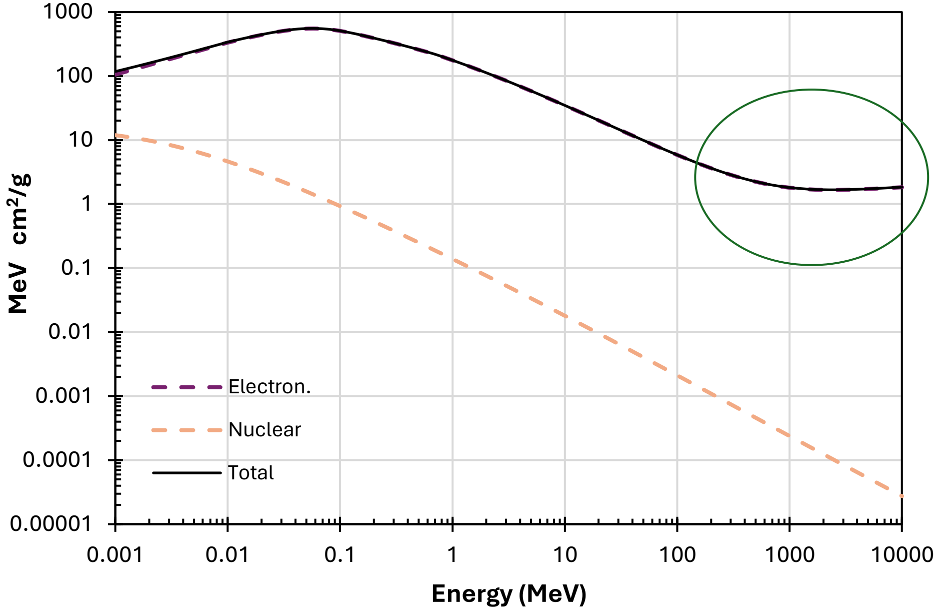
Interaction of radiation with matter: charged particles



Mechanisms:

- Electromagnetic interaction: ionization
- Radiative (in the field of a nucleus): bremsstrahlung
- Nuclear / hadronic interaction: nuclear reactions, knock-on effect of atoms in a solid-state lattice

Proton stopping power in Si



https://www.physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

Bragg peak: energy-dependent energy transfer

- High energy deposit can be made use of – e.g. hadron therapy!!

Bethe-Bloch formula describing energy loss (stopping power) over distance for a fast charged particle:

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

At high energies: deposited energy small, ~independent of particle species and energy → *minimum-ionizing particle, MIP*

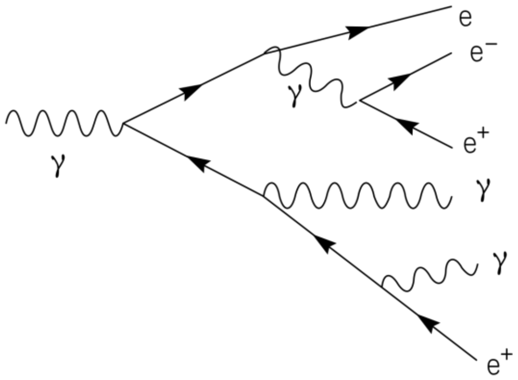
Radiation detection in high-energy physics

Measurement / signal:

- Heat
- **Charge**
- **Light**
- Structural changes

Radiation length X_0 (cm, (g cm^{-2})): energy of a charged particle is reduced to 1/e AND 7/9 of the mean free path for an interaction of a photon leading to pair production

Nuclear interactions: nuclear interaction length, nuclear collision length



Calorimetry

Objective: determination of total energy – contain the particle

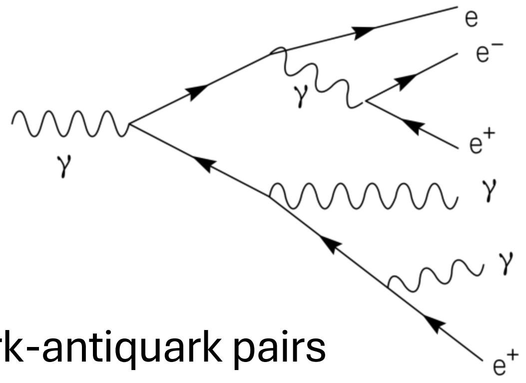
Here the particle should interact, eventually stop, transfer its energy to the detector.

Radiation length X_0 (cm, (g cm^{-2})): energy of a charged particle is reduced to 1/e AND 7/9 of the mean free path for an interaction of a photon leading to pair production

Photons: nearly exclusively interact by high-energy transfer Compton scattering or pair production – electrons (‘delta rays’) cause secondary ionization, new gamma rays through bremsstrahlung when deflected off an atom, which in turn scatter or create pairs…

Electrons: effectively the same as photons

➢ **Electromagnetic showers**



Equivalent for nuclear interactions**: nuclear interaction length, nuclear collision length**

Hadrons: energy transfer to atoms in material; gluons interact with each other, form pairs of quark-antiquark pairs

➢ **Hadronic showers, hadronization - jets**

Calorimeter design

Showers should be contained in the detector

- For spatial resolution, within a small segment of the detector

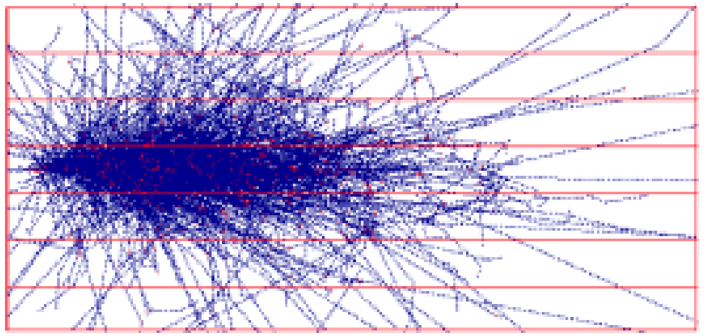
Shower length (depth): cf. radiation length

$$X \approx X_0 \frac{ln(\frac{E_0}{E_c})}{ln(2)}$$

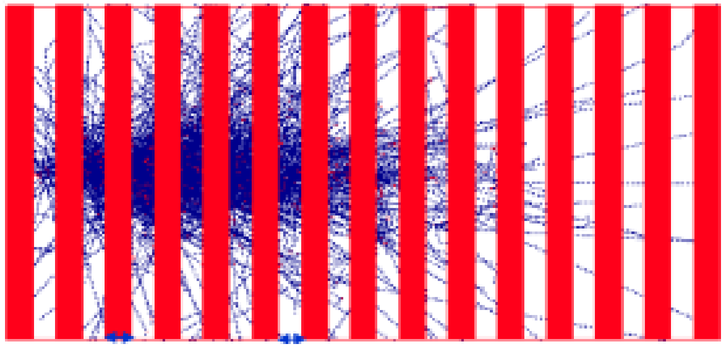
Transverse containment: Molière radius

$$R_M \approx 0.0265\, X_0\, (Z + 1.2)$$

Slightly different materials and different architectures for electromagnetic and hadronic calorimeter



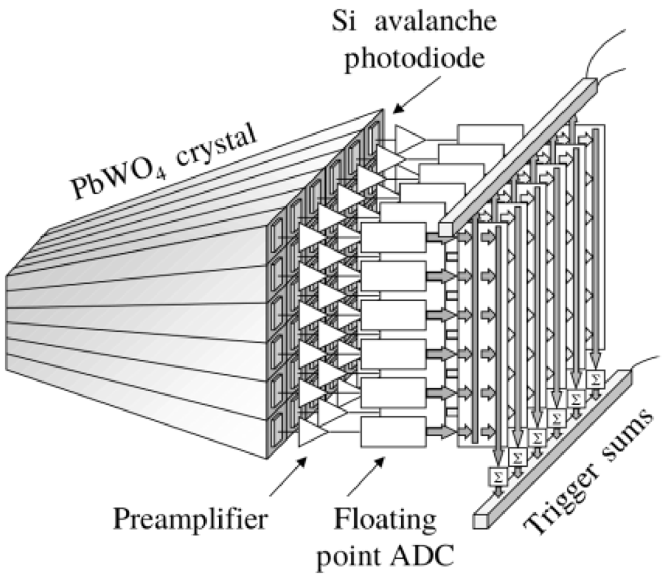
Homogeneous calorimeter

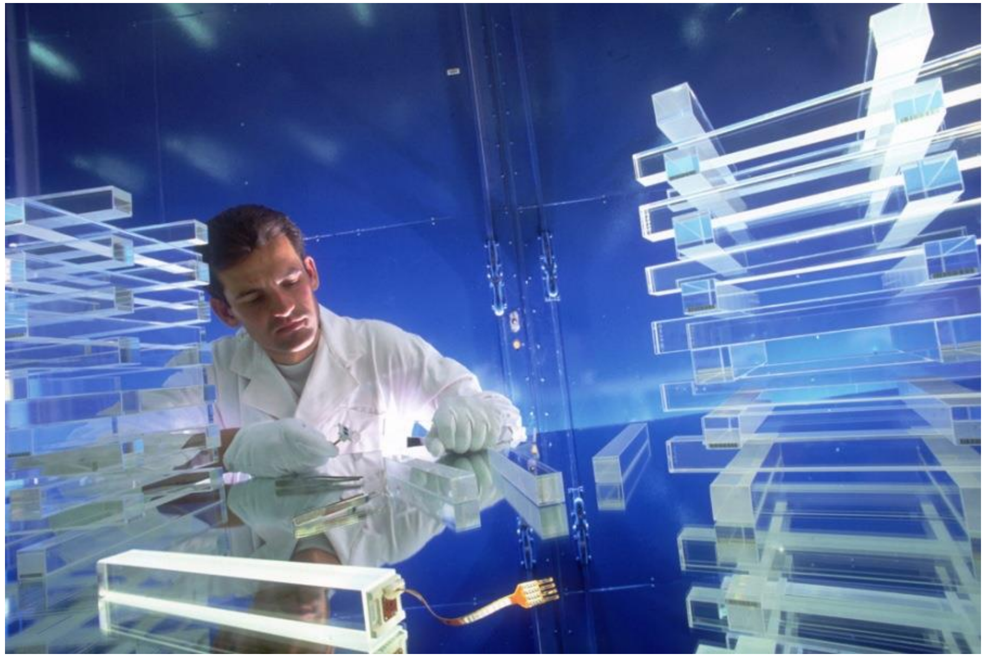


Sampling calorimeter

Scintillators + silicon detectors

Electromagnetic calorimeter (ECAL) of CMS: homogeneous calorimeter





Silicon photomultipliers

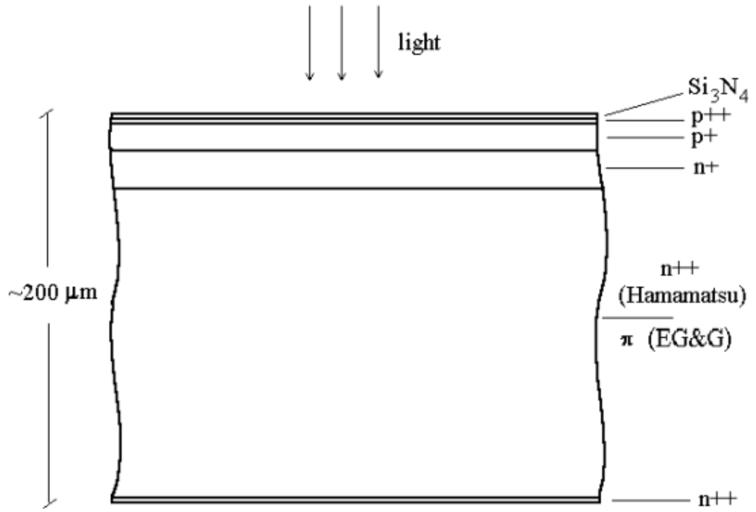
Avalanche photodiodes (and variations thereof)

Dependence of gain with…

- Temperature
- Bias voltage

Direct ionization

- Spikes, discharges
- Noise, dark current

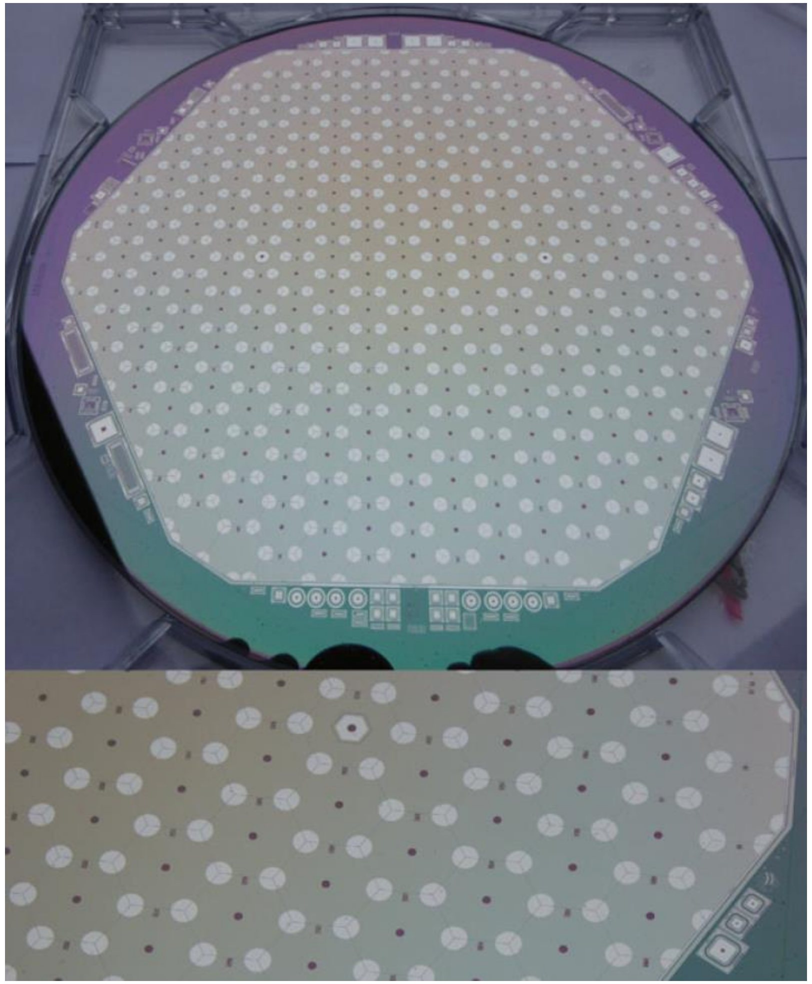


Silicon sensors in calorimetry: pad sensors in HGCAL

= High-granularity calorimeter

Sampling calorimeter based largely on silicon (with brass/copper/tungsten as inactive absorber materials)

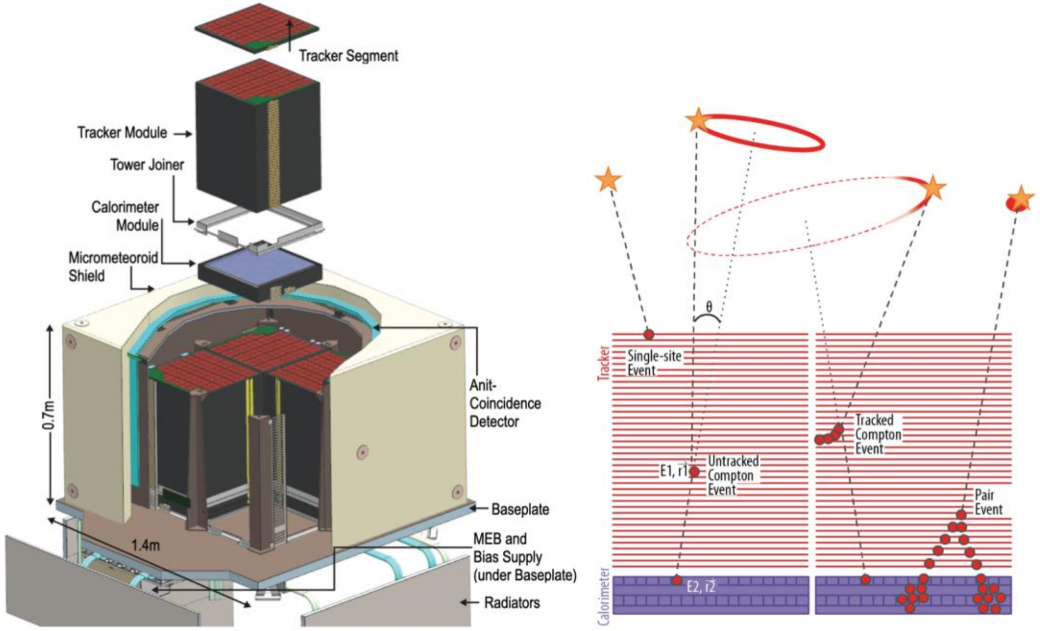
Larger area of silicon than tracking detectors!



Silicon detectors in (partial) calorimetry: Astropix

AMEGO-X satellite: Gamma ray telescope with stacks (towers) of segmented silicon detectors

- Tracking of Compton scattering and pair production events
- Energy measurement of scattered electron; single interaction < 100 keV



R. Caputo et al, *The All-sky Medium Energy Gamma-ray Observatory eXplorer (AMEGO-X) Mission Concept*, https://arxiv.org/abs/2208.04990

Inner layers in EIC ePIC barrel ECAL

- thicker sensor – 700 µm bulk

500x500 um pixel pitch

Currently: Astropix v3 fabricated and being tested; challenges with depletion and leakage current in high-resistivity substrate – some laser edge-TCT studies at UC Santa Cruz