Karlsruhe Institute of Technology

Institut für Experimentelle Teilchenphysik

Silicon Detector Technologies

Flavour Workshop, Neckarzimmern, April 7, 2022

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S. Cittolin

Lecture Outline

- Look at modern silicon detector technology from **different perspectives**:
  - Part I – Interactions of particles and matter
  - Part II – Detection principles: solid state detectors
  - Part III – Applications of silicon detectors in particle physics
- Time is rather limited – more focused on **concepts** and **representative examples** than on details

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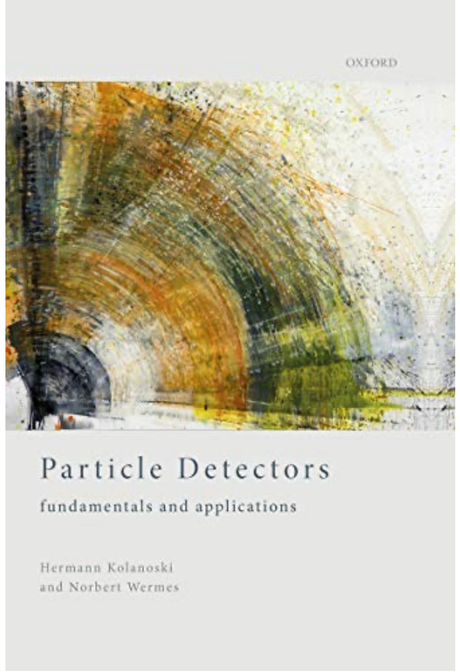
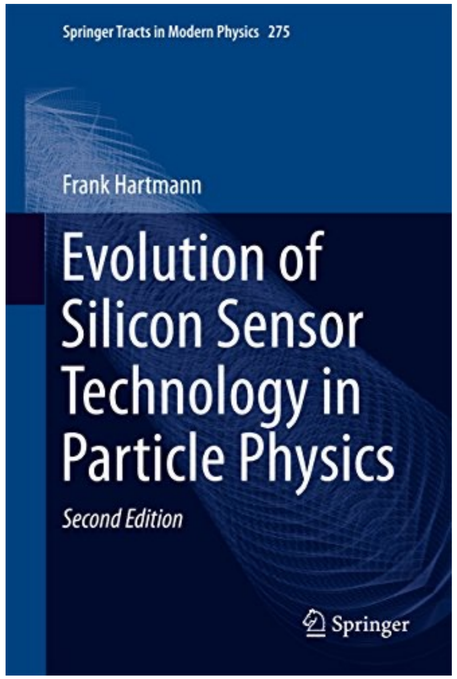
Part I

Interactions of Particles and Matter

Recommended Textbooks

- H. Kolanoski, N. Wermes, *Particle Detectors: Fundamentals and Applications*, Oxford UP 2020
- F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, 2nd Ed., Springer 2017

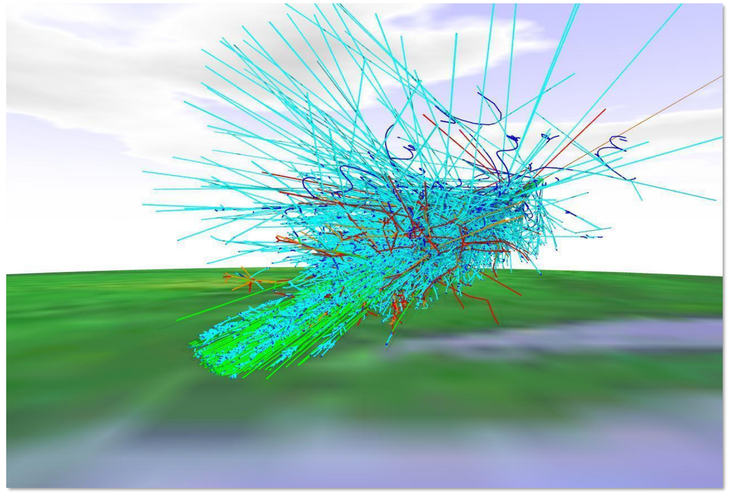




Interactions of Particles and Matter

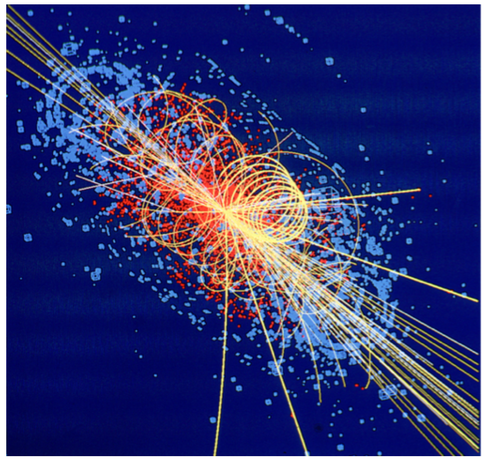
- Many **different physics processes**, depending on particle **type**, **charge**, **energy** range, detector **material**
- **Complicated** interactions: analytical calculations often impossible
  → **simulations** (Monte Carlo method)
- Excellent understanding of interactions
  → best possible design of detectors

Air shower simulation



Bildquelle: Hajo Drescher (U. Frankfurt)

Simulation of a Higgs boson decay in CMS



Bildquelle: Lucas Taylor (CERN)

Charged Particles: $z \neq 0$

Particle Class	Examples	Most Important Processes
charged particles	muons $\mu^{\pm}$, pions $\pi^{\pm}$, protons p, antiprotons $\bar{p}$	**ionization**, excitation of atoms, Cherenkov radiation
very light particles	electrons/positrons $e^{\pm}$	**bremsstrahlung** (→ electromagnetic cascade), ionization
hadrons	pions $\pi^{\pm}$, protons p, antiprotons $\bar{p}$	ionization, **nuclear reactions**

Neutral Particles: $z = 0$

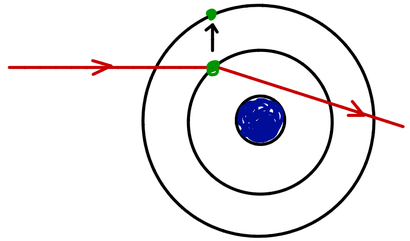
Particle Class	Most Important Processes	Remarks
photons γ	absorption (photoelectric effect), scattering (Compton effect), cascades (pair production)	exponential attenuation, no defined range
hadrons, e.g. neutral kaons K^0, neutrons n	scattering, nuclear reactions ($\rightarrow$ hadronic cascade), decays	
neutrinos ν	only electroweak interactions: charged and neutral currents	

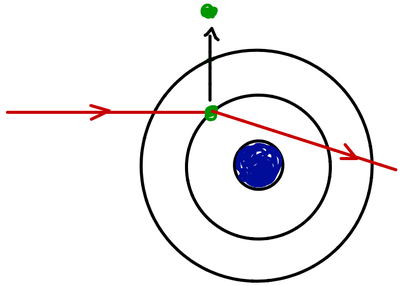
Detection Medium

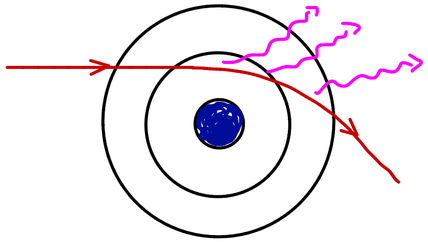
- Interaction of particles with matter influenced by **medium**:
  - **Atomic number *Z***: electromagnetic effects proportional to charge Z^n of nucleus (exponent *n* different for different effects)
  - **Density** and **state of matter**: number of scatterers per area, binding energies of scatterers in medium
  - **Electric** and **magnetic fields** in medium
  - **Conductivity**, e.g. electronic properties of conductors, semiconductors, superconductors

Interactions of Charged Particles

- Basic physics processes:
  - **Excitation** of bound electrons
    (→ deexcitation, e.g. by photon emission)
  - **Ionization** of atoms by inelastic scattering with electrons: dominant effect for **heavy** particles
  - **Radiation** in electromagnetic fields: dominant effect for **light** particles







Bethe Equation

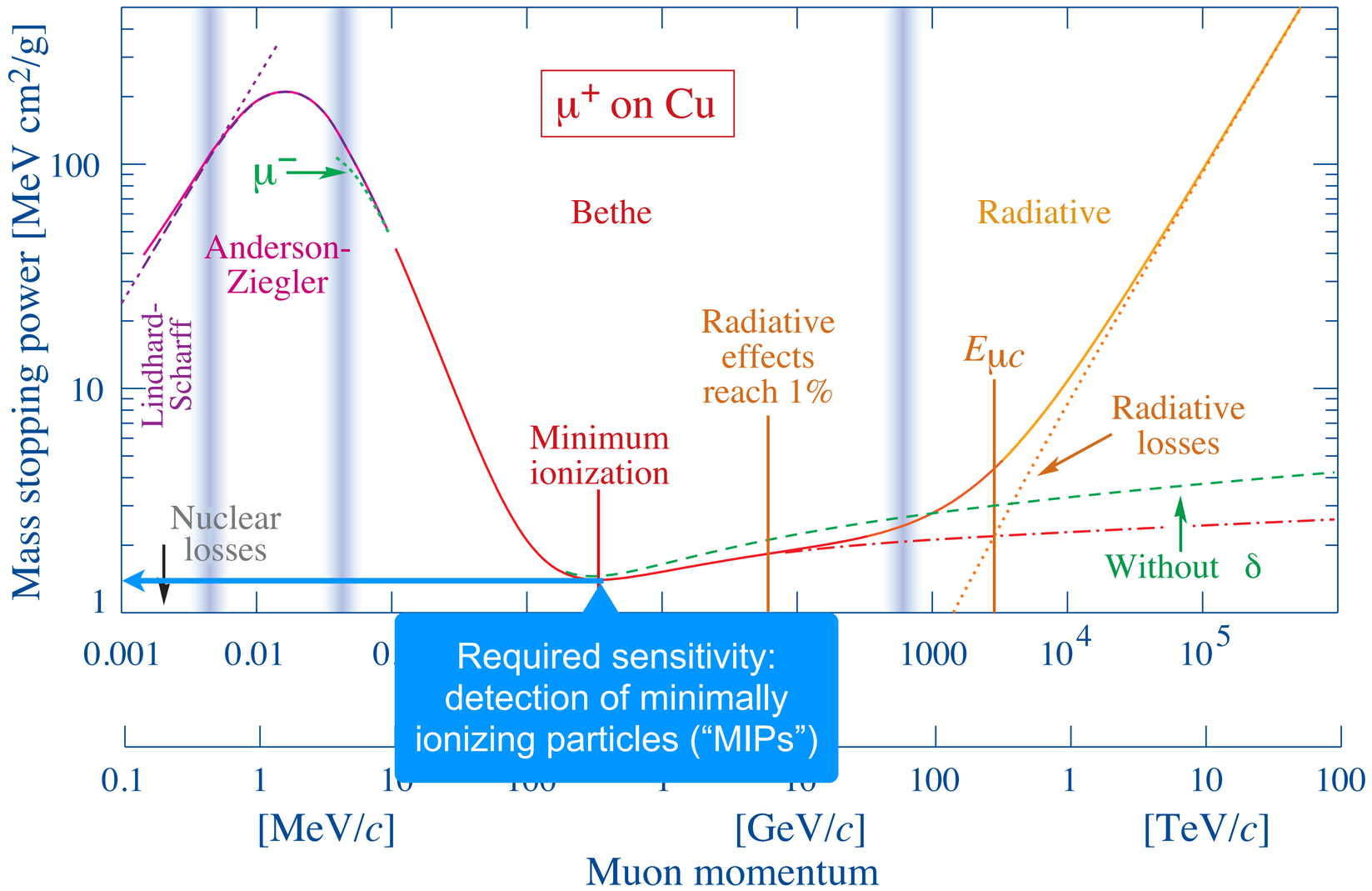
- Ionization: **average energy loss** of heavy particles in matter (aka. “stopping power”) → **Bethe equation**

$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}X} \right\rangle = 4\pi\, N_A r_e^2 m_e c^2\, z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2\, \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- With:
  - z — charge number of incident particle
  - Z, A — charge number (also: atomic number), mass number of medium
  - N_A — Avogadro’s constant
  - $T_{\max}$ — maximum kinetic energy transfer
  - $\delta(\beta\gamma)$ — Fermi’s density correction
  - I — Mean excitation potential → previously: Bloch approximation $I \simeq 10\ \mathrm{eV} \cdot Z$
    today: http://pdg.lbl.gov/2021/AtomicNuclearProperties/

Stopping Power

≈ 1.5 MeV cm² g⁻¹

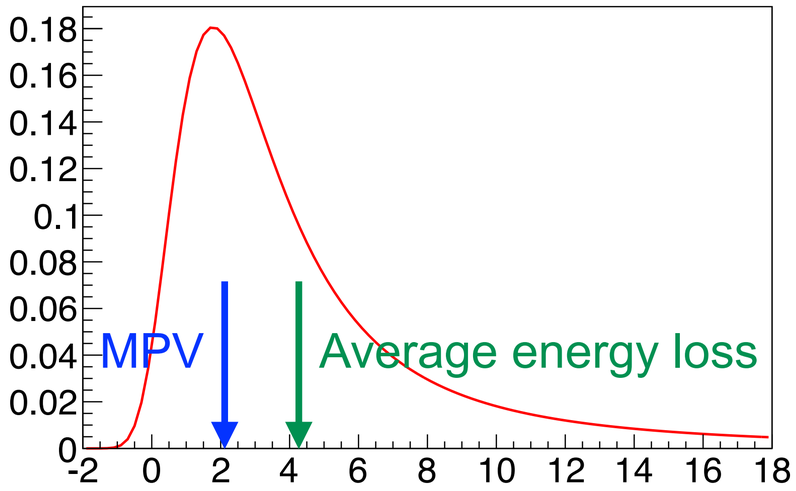


Required sensitivity: detection of minimally ionizing particles ("MIPs")

pdg.lbl.gov

Energy Loss Fluctuations

- Energy loss of charged particles in matter: **stochastic** process
  - Bethe equation: **average** energy loss, but energy loss by single particles can **vary significantly** from average (with tails to very high energy loss)
  - Wanted: **distribution function** of energy loss for fixed $\beta\gamma$ ("straggling function") → use **most probable** energy loss (= maximum of distribution)
- Energy loss distribution:
  - Thick absorbers: **Gaussian** distribution (central limit theorem)
  - Thin (≤ 1–2 mm) absorbers: empirical **Landau(-Vavilov) distribution** (long tails due to knock-on electrons, aka. δ electrons) → expected signal = most probable value (MPV)



Multiple Coulomb Scattering

- Charged particles: **Rutherford scattering** off nuclei (and electrons)
  - **Large number** of scattering processes (at least $N \geq 20$), each with small-angle deflection → net effect: statistical **distribution of scattering angles θ**
  - Expected distribution function: **Gaussian core** (central limit theorem) with **non-Gaussian tails** (few large-angle "hard scatters" ~$\sin^4 \theta/2$)
  - Many approaches, especially "Molière theory" (G. Molière, Habilitation thesis, Tübingen, 1947)
  - **Reduction** of multiple scattering relevant e.g. for **precise position measurement** in particle tracking

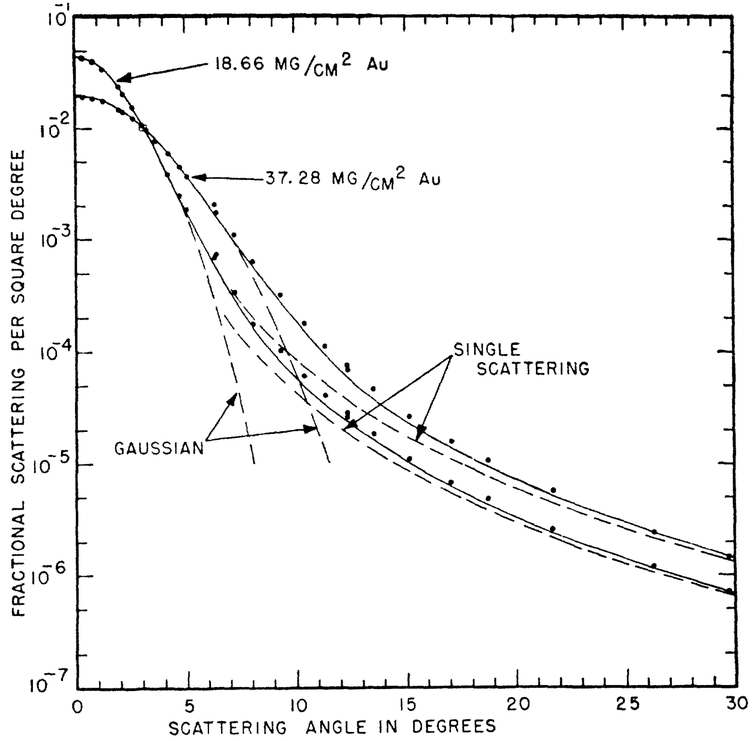


FIG. 3. Angular distribution of electrons from thick and thin gold foils from 0° to 30°. The solid line represents the theory of Molière extrapolated through the region where his small and large angle approximations give different values. The dotted lines at small angles represent the continuation of the gaussians of Fig. 1. At larger angles, the dotted line represents the single scattering contribution.

Phys. Rev. 84 (1951) 634

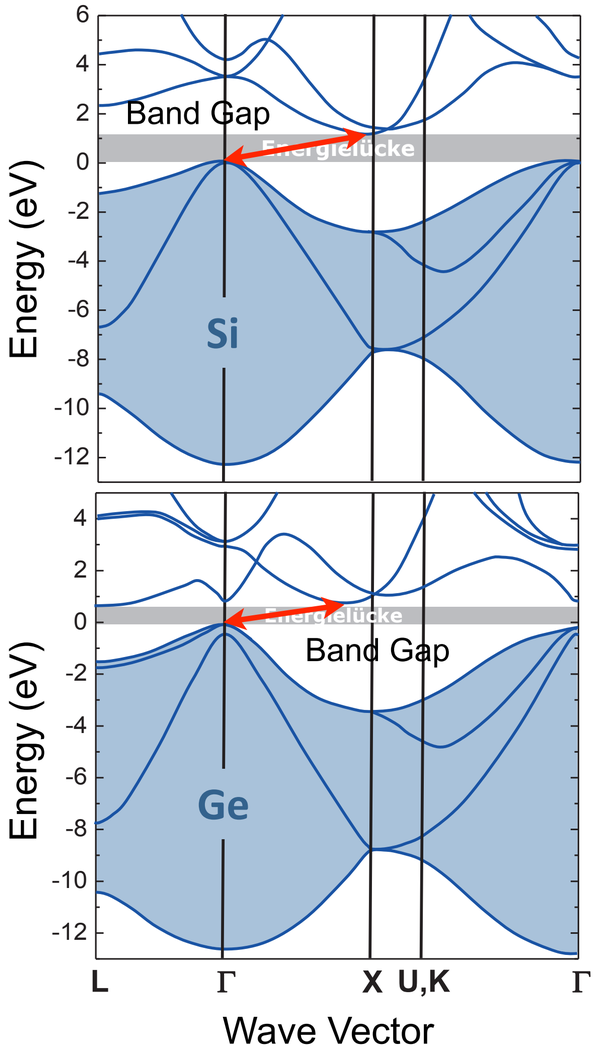
Summary of Part I

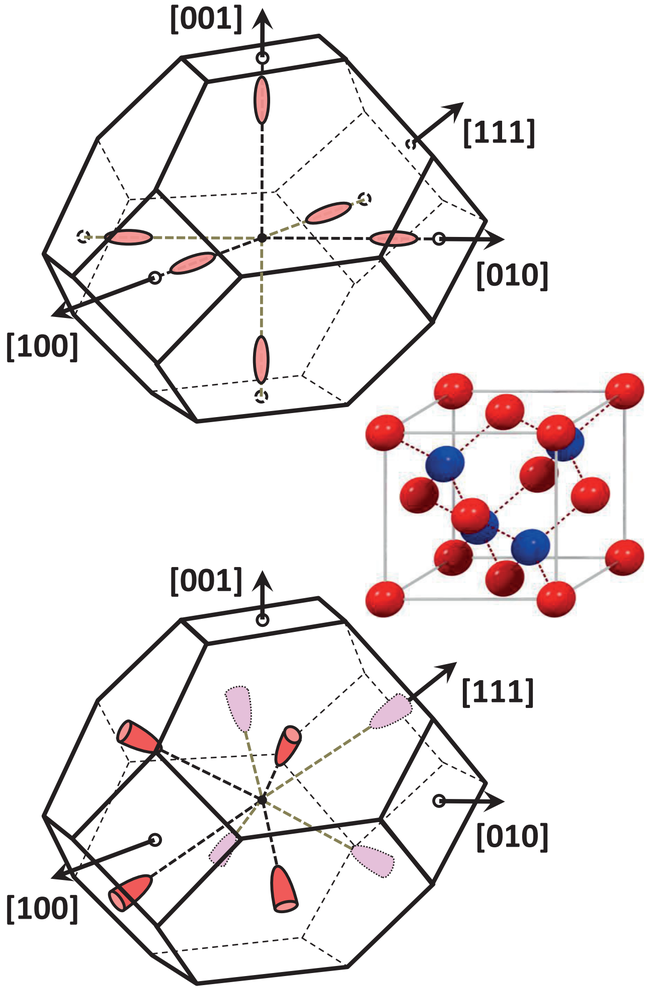
- Interactions of particles in matter depend on various properties of incident particles and medium
- Most relevant for tracking detectors: **charged particles**
  - Main effects: excitation, **ionization**, radiation
  - Heavy charged particles: average stopping power described by **Bethe equation** → design goal: **MIP sensitivity**
  - Energy loss in thin layers: fluctuations around average stopping power → **Landau distribution** (asymmetric, large tails)
  - **Multiple Coulomb scattering**: directions of charged particles smeared

Part II

Detection Principles: Solid State Detectors

Band Structure of Si and Ge





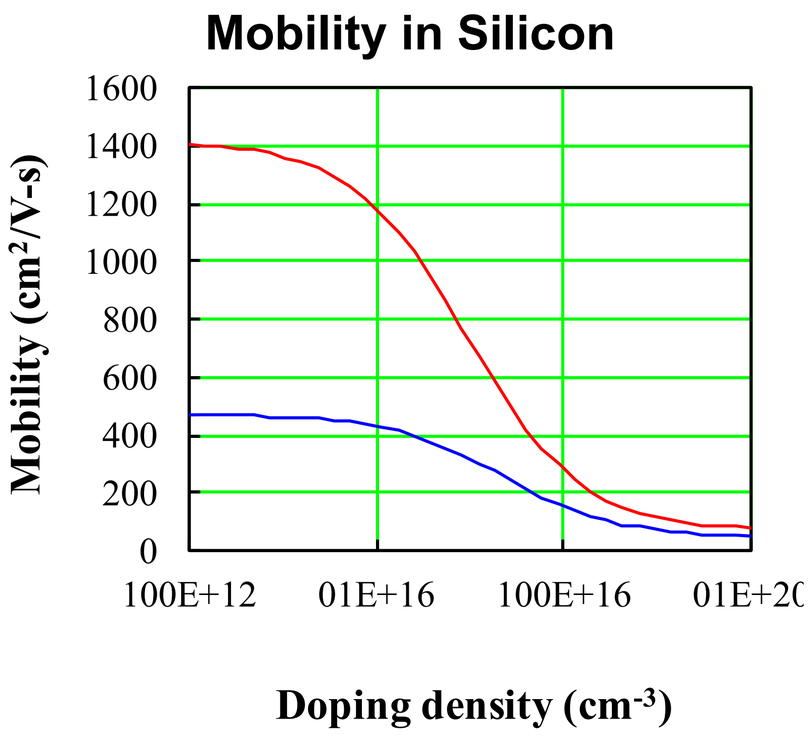
after: Gross, Marx, *Festkörperphysik*, De Gruyter 2012

- Band model: allowed energy levels form bands with characteristic **band gap** between valence band and conduction band
- Si/Ge crystal structure: diamond → **face-centered cubic** (fcc) lattice
- Si/Ge: **indirect** semiconductors
  - Maximum of valence band and minimum of conduction band for **different** wave vectors **k**
  - Transitions would require **three-body process** with phonons → suppressed

Charge Transport in Semiconductors

- Electrons excited to conduction band
  → leave electron hole in valence band
  → charge carriers: **electrons and holes**
- Charge carrier **mobility**: consider quasi-free electrons/holes
  - Electric field **E** applied → **acceleration** of carriers and **scattering** off crystal defects, impurities, phonons → carriers **drift** with velocity **v**
  - Electron and hole **mobilities** μ defined by

$$\mathbf{v}_{e,h} = \mu_{e,h}\,\mathbf{E}$$



B. van Zeghbroeck, Principles of Electronic Devices

Typical values: $|\mathbf{E}| \geq 10^6$ V/m
→ $|\mathbf{v}| \approx 0.1$ m/µs

Properties of Semiconductors

at 300 K

few eV to create electron/hole pair

electrons often more mobile than holes

	$\langle Z \rangle$	ρ (g cm^{-3})	E_g (eV)	W_i (eV)	ε (ε_0)	μ_e (cm^2 V^{-1} s^{-1})	μ_h (cm^2 V^{-1} s^{-1})
Silicon	14	2.33	1.12	3.6	11.7	1350	450
Germanium	32	5.33	0.67	2.96	16	3900	1900
GaAs	31.5	5.32	1.43	4.2	12.8	8000	400
Diamond	6	3.52	5.5	13	5.7	1800	1200

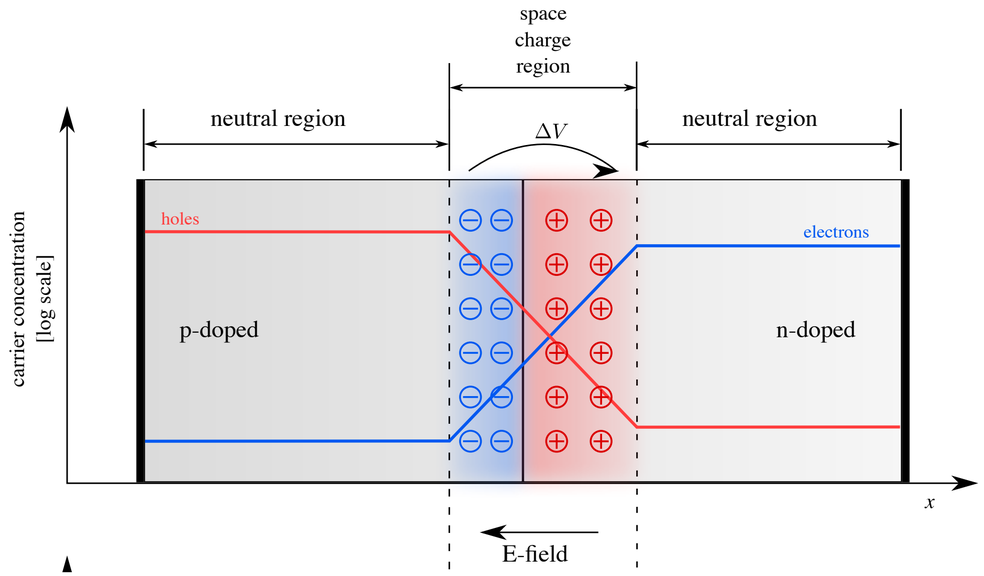
H. Spieler, Semiconductor Detector Systems, Oxford UP 2005

Semiconductors as Particle Detectors

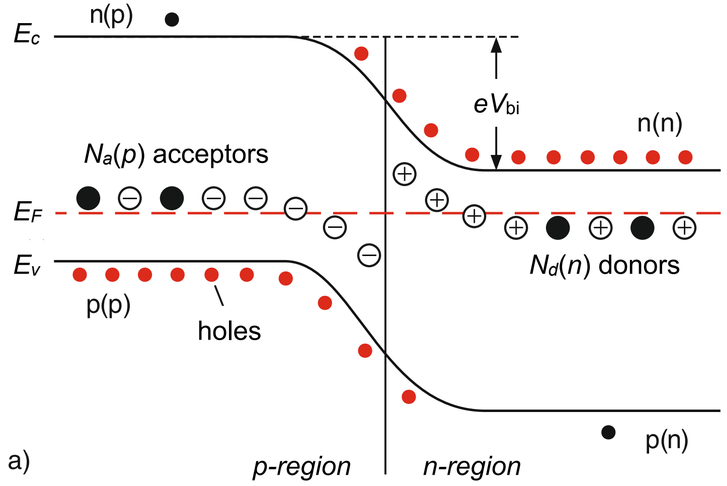
- Advantages of semiconductor detectors:
  - Small ionization energy W_i (e.g. 3.6 eV in silicon, compare 26 eV in argon) → **large signals** even in thin layers (compare 100 e/ion pairs/cm in argon)
  - Numerical example: most probable energy loss for a MIP in thin silicon layer (Bethe/Landau) 1.25 MeV cm^2 g^{-1} = 290 eV µm^{-1}
    → rule of thumb: **80 e/h pairs per µm** (→ 24,000 e/h pairs in 300 µm)
- Problem: **thermal generation** of charge carriers
  - Compare with thermal charge carriers in 1 cm^2 of 300 µm silicon layer at room temperature (n_i = 1.45×10^{10} cm^{-3}): 4.35×10^8 charge carriers
  - Two ways out: operate detector at **cryogenic temperatures** (e.g. pure germanium) or make use of **depletion zone in pn junctions** (e.g. doped silicon)

pn Junction

- Different electron and hole concentrations in p/n-doped region → electron and hole **diffusion**
- Partial **recombination** of electrons in p-type and holes in n-type semiconductor → space charge, building up potential against diffusion (built-in voltage V_{bi})
- Thermal equilibrium: **depletion zone** (also: space charge region) with only few free charge carriers



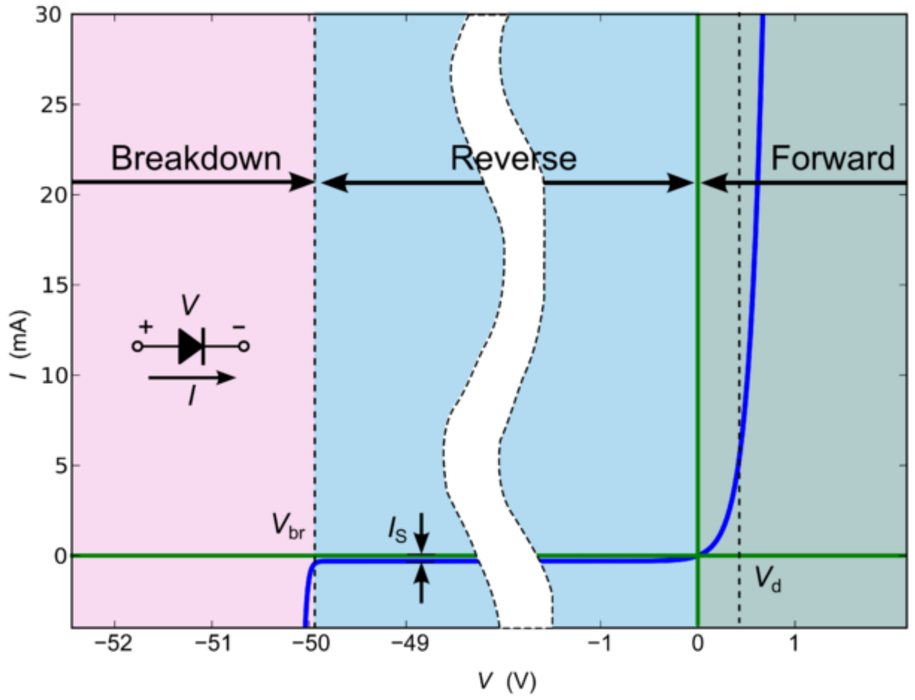
Adunovi, Pn-junction-...svg, CC BY 3.0



after Demtröder, Experimentalphysik 3, Springer 2010

Biased pn Junction

- **External** bias voltage → departure from thermal equilibrium:
  - **Forward bias**: positive potential in p-doped region → potential barrier reduced
  - **Reverse bias**: positive potential in n-doped region → potential barrier increased, larger depletion zone



Spinningspark, Diode_current_wiki.png, GFDL

- Current flow through pn junction at voltage V: **Shockley equation**

$$I(V) = I_0 \left(\exp\left[\frac{eV}{k_B T}\right] - 1 \right)$$

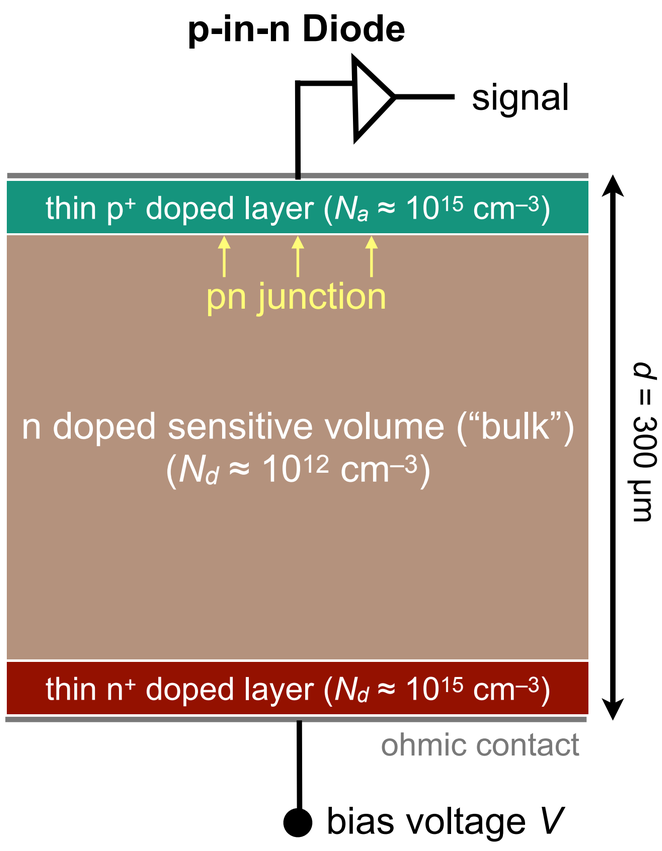
- **Width** of depletion region grows with reverse bias:

$$w(V) = \sqrt{\frac{2\epsilon(V_{bi} - V)}{e} \frac{N_a + N_d}{N_a N_d}}$$

N_a, N_d: number densities of acceptors, donors

Basic Semiconductor Detector

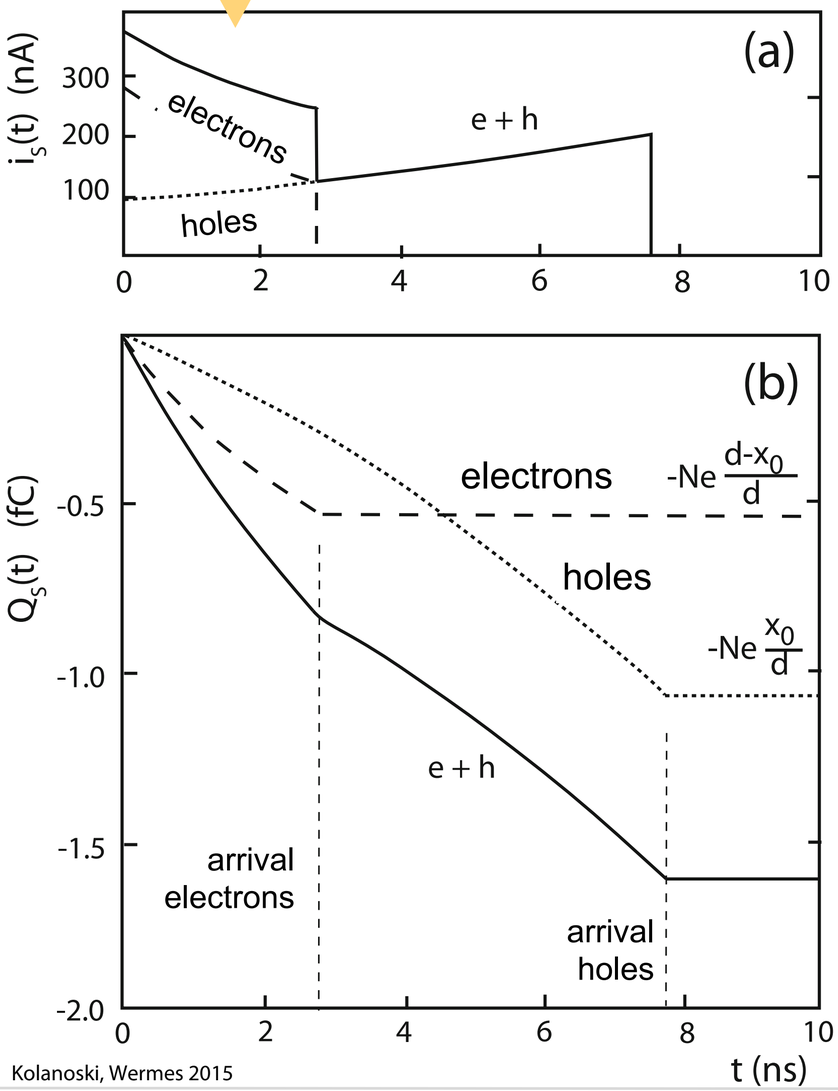
- Basic setup: semiconductor **diode** (here: p-in-n, but also: n-in-p, p-i-n) ≈ **solid state ionization chamber**
- Maximum detector sensitivity: depletion zone extends to **entire bulk** → **depletion voltage** V_{dep} (often "over-depleted" operation: $|V| > |V_{dep}|$)
- Small **leakage current** due to minority charge carriers randomly generated in bulk, depending on band gap → increased by orders of magnitude due to impurities, defects, surface effects



Charge Collection

- Physics effect: moving charges
  → **electrostatic induction** on electrodes
- Semiconductor detectors:
  - Electric field: **linear increase** with position in depletion zone (~parallel plate capacitor with dielectric)
  - Simplified example: point charge of 10000 e/h pairs in 300 µm of silicon with V = 150 V (overdepleted operation, V_{dep} = 100 V)
  - Charge carriers **accelerated** towards detection electrodes → electric **current**
  - All charge carriers collected: current stops

Typical time scale for charge collection: <10 nanoseconds



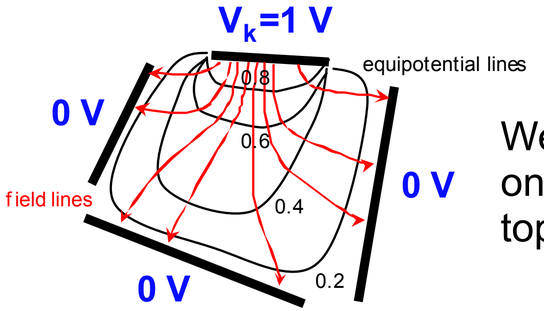
Kolanoski, Wermes 2015

Shockley-Ramo Theorem

- Problem: exact calculation of induced currents depends on **full knowledge of electric field** due to all charges at all times
- Approximation: **Shockley-Ramo theorem** (W. Shockley 1938, S. Ramo 1939)
  - Induced current I on detection electrode for drift with velocity v_D

$$I(t) = q\,\mathbf{E}_w \cdot \mathbf{v}_D(\mathbf{E}(\mathbf{r}, t))$$

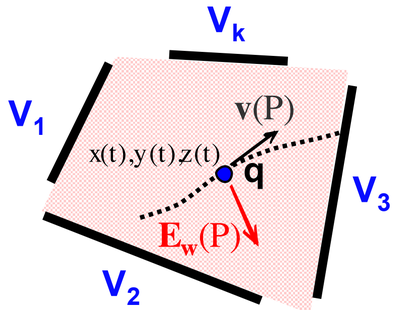
  - $\mathbf{E}_w$: **weighting field**, only given by potential of electrode k, all other electrodes on ground potential



Weighting field: only device topology

(V_k=1 V, all others grounded)

Drift: full field



A. Castoldi

Summary of Part II

- **Semiconductors** as particle detectors:
  - Small ionization energy (≲5 eV), high charge carrier mobility
  - Tracking detectors: **doped** semicondurctors → avoid thermal charge generation by employing **space charge region** in pn junction
- Optional (not discussed here): **radiation damage** in silicon detectors
  - Surface: ionization effects
  - Bulk: ionization reversible, but **non-ionizing** energy loss leads to defects in crystal lattice → new energy levels in band gap
- **Charge collection** by electrostatic induction: **Shockley-Ramo theorem**

Part III

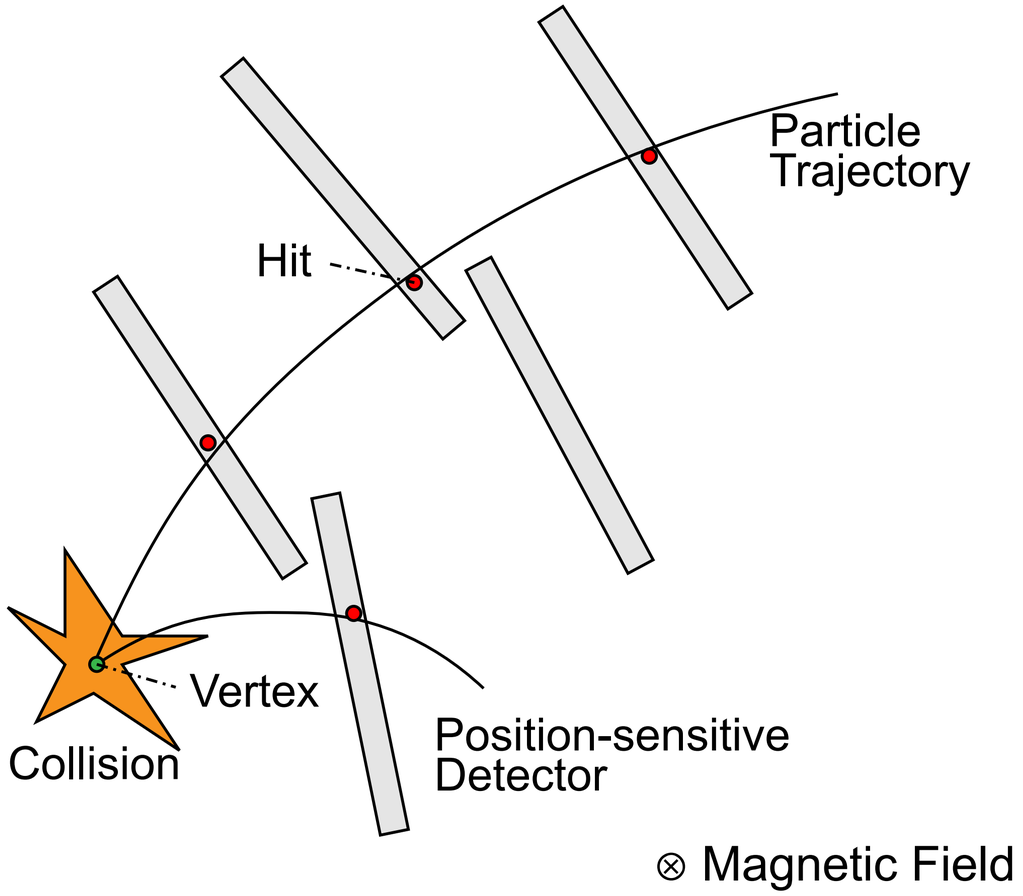
Applications of Silicon Detectors in Particle Physics

Applications: Overview

- Silicon detector technology in particle physics: **wide range** of applications
  - Charged particle tracking
  - Fast timing
  - Imaging calorimetry
- Not a comprehensive list, just my **personal selection** of a few examples of current trends

Application I: Particle Tracking

- Key application of silicon detectors in HEP: **tracking** of charged particles and **vertexing**
- Several layers of 1D or 2D **position-sensitive detectors**, often in **magnetic field**
  - Solution for large-area (100s of m^2) coverage: silicon **microstrip** detectors (1D measurement)
  - Solution for high granularity: silicon **pixel** detectors (2D measurement)

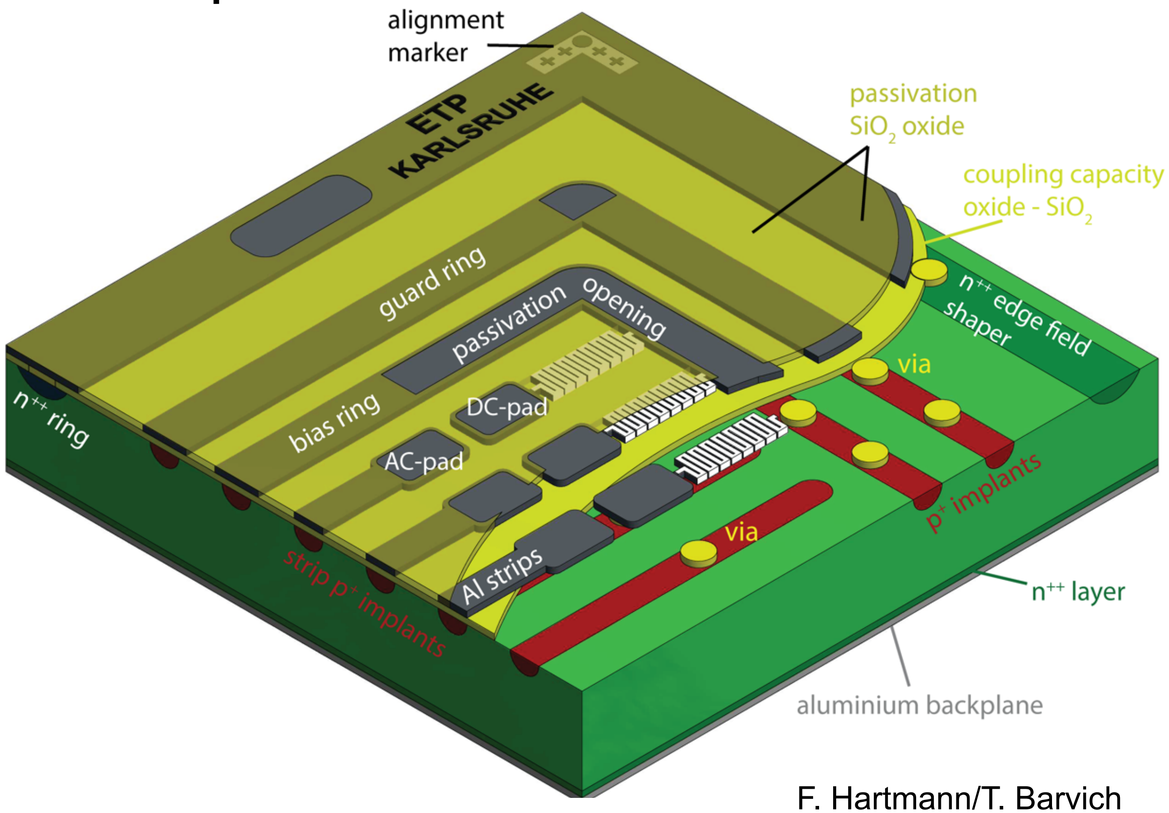


Tracking: Requirements

Goal	Measures
High momentum resolution	Strong, homogeneous magnetic field Large detector volume High granularity (many readout channels)
Fast timing (sub-nanosecond)	Fast and well defined detector signals + matching electronics
Low disturbance of particle trajectory (multiple scattering, radiation)	Low material budget
Separation of individual particles	High granularity
Vertex reconstruction	First layer close to interaction point (IP)
dE/dx measurement	Charge deposition measurement (in addition to position)
Radiation hardness	Choice of material: radiation-hard silicon (diamond)

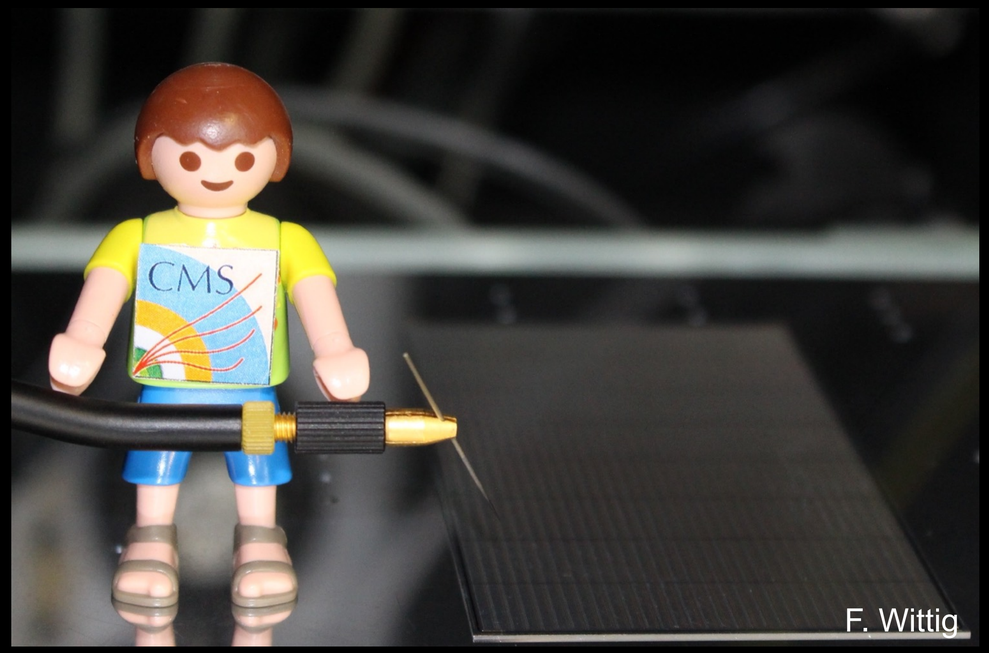
Silicon Microstrip Detectors

- Realistic silicon microstrip detectors: typical structures
  - **Bias ring**: distribution of bias voltage to all strips
  - **Biasing**: polysilicon resistor (alternative: punch-through biasing)
  - **Guard ring(s)**: shaping of fields at sensor edges → **homogeneous potential** in full sensitive area
  - **n^{++}-doped** ring: protection against leakage current from crystal defects due to silicon cutting
  - Pads for **wire bonding** and **sensor probing** with needles (“probe station”)



F. Hartmann/T. Barvich

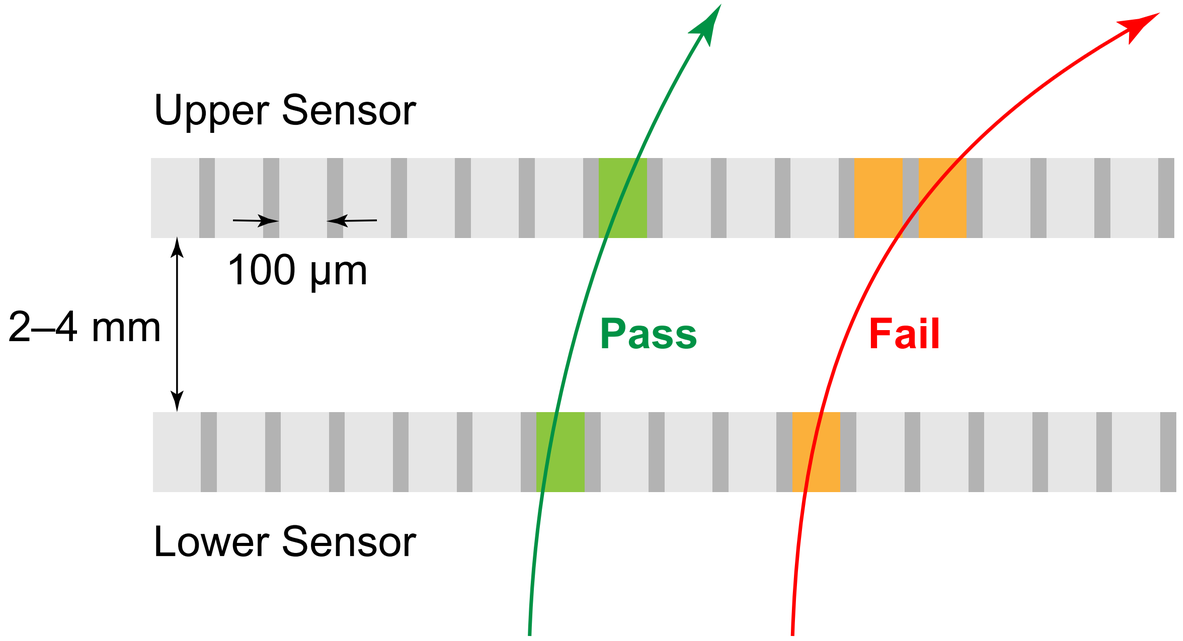
Probe Station & Clean Room

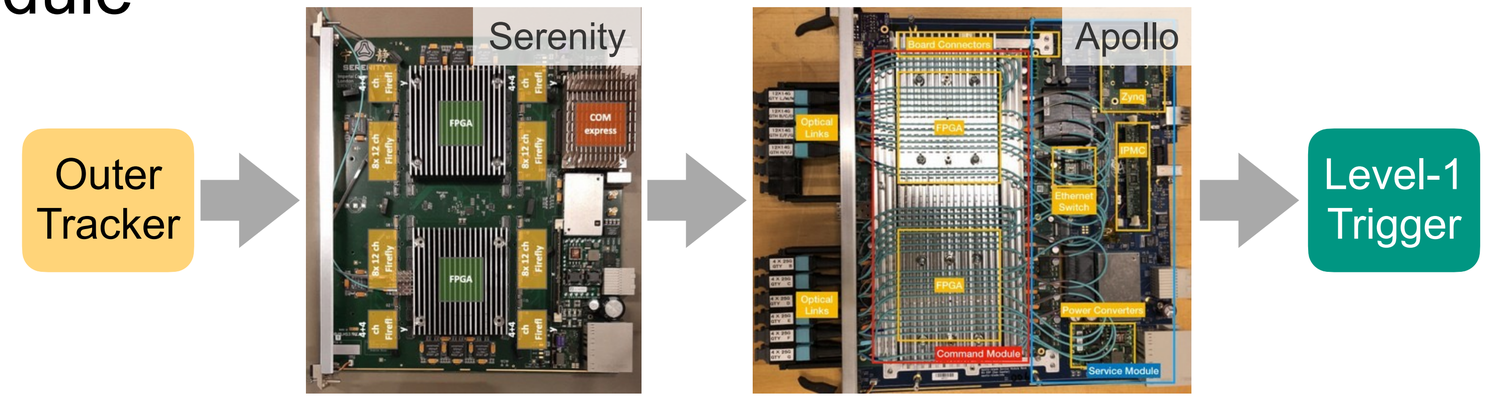


F. Wittig

CMS@HL-LHC: Track Triggering

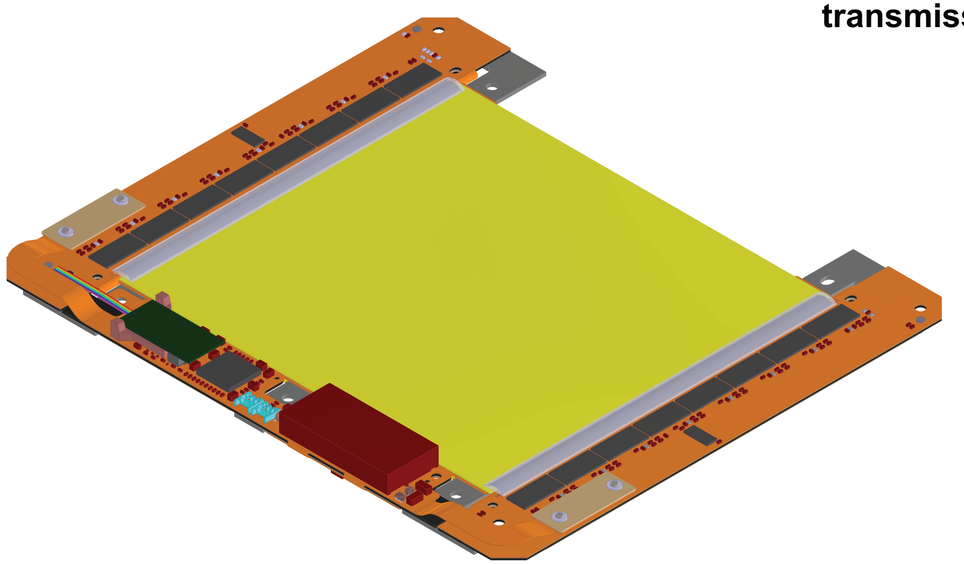
- **HL-LHC** (high-luminosity LHC): data-taking from 2029
- Motivation: keep **trigger rates manageable** without removing interesting physics (Higgs, …)
- Step 1: transverse momentum (p_T) filtering on detector module level → **p_T modules**
- Step 2: FPGA-based **fast electronics** to provide tracks for Level-1 trigger

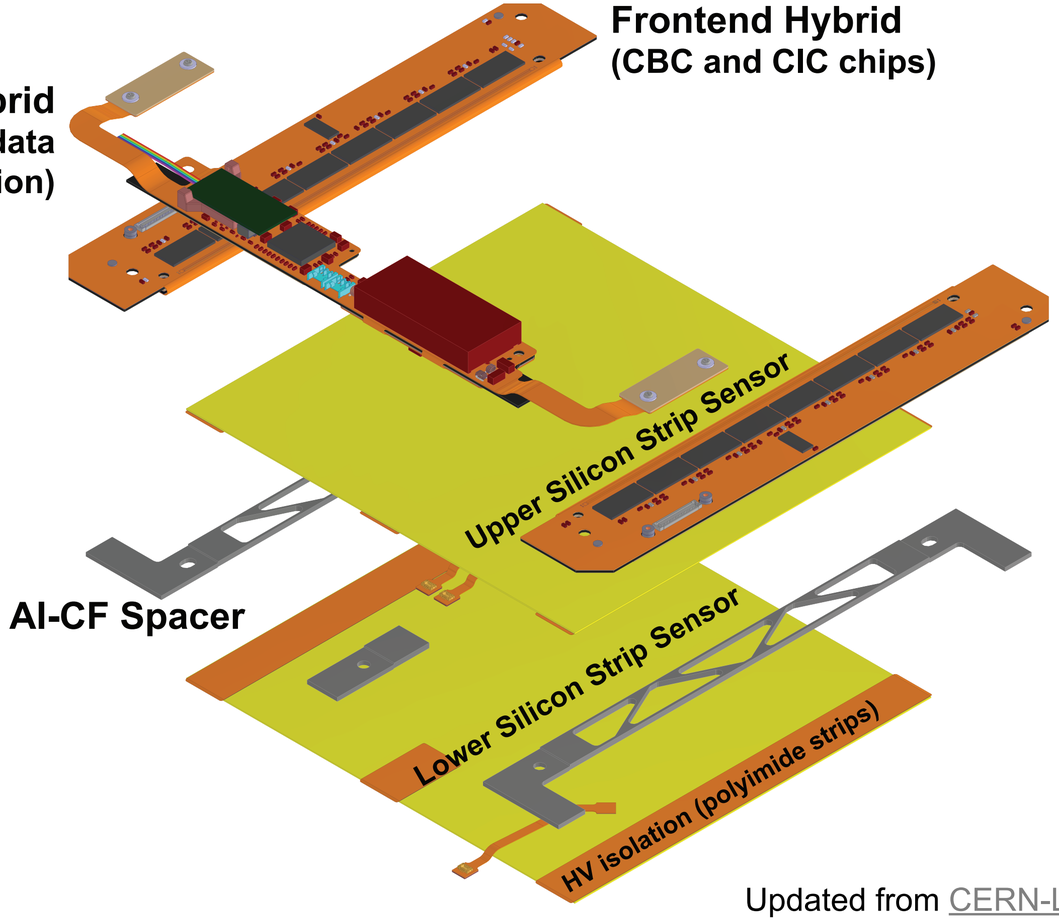




p_T Modules

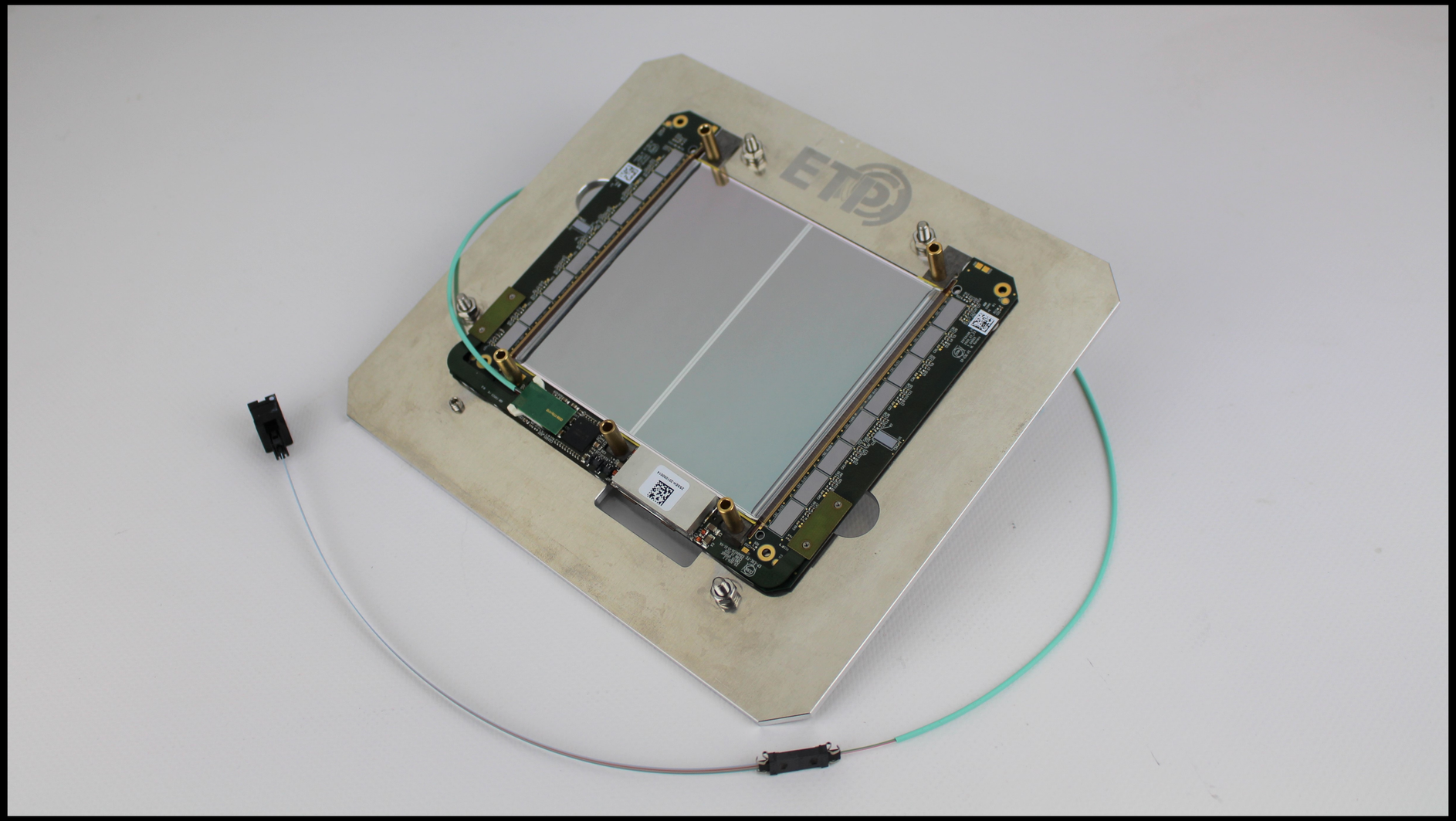
- Outer part of CMS Outer Tracker: **2S modules**
  → two silicon strip sensors





Updated from CERN-LHCC-2017-009

2S Prototype Module on Carrier

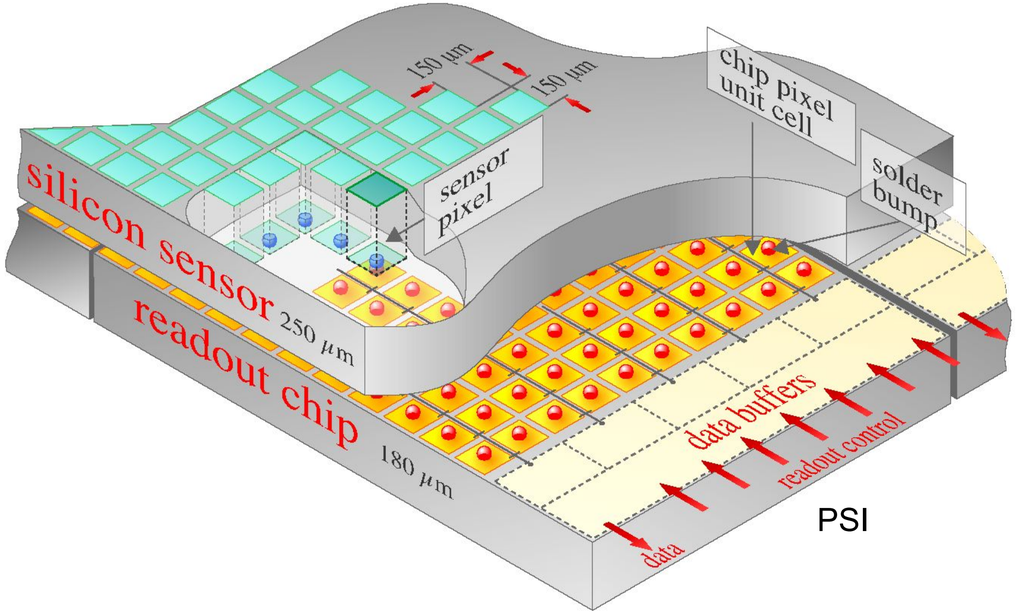


Silicon Pixel Detectors

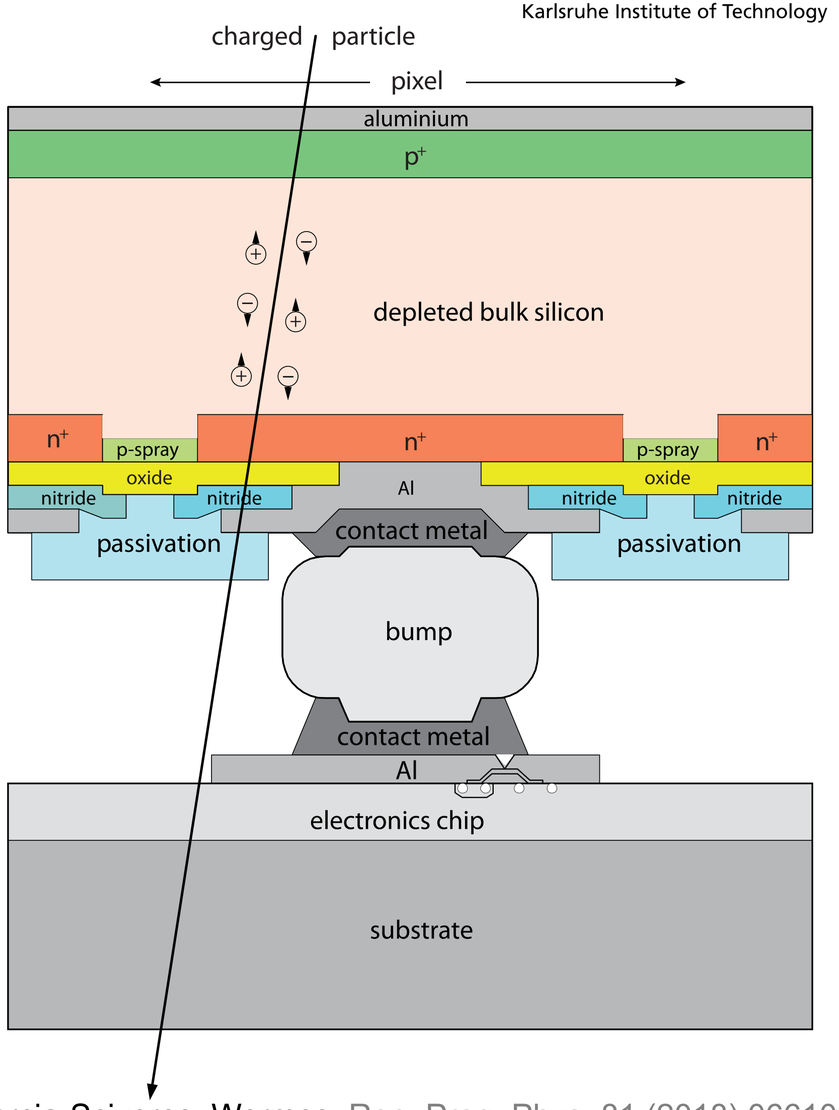
- Semiconductor detectors with **2D segmentation**: pixel detectors
  → real 3D space points, no ambiguities
- Consequences of small pixel size
  - **High granularity**: high resolution, but large number of readout channels (100s of millions → challenge for data volume, power consumption, cost)
  - **Small pixel volume**: low leakage current
  - **Low capacitance**: low noise, high signal-to-noise ratio
- Many pixel detector technologies, two main classes
  - **Hybrid** pixel detectors: sensor and readout chip produced **separately**
  - **Monolithic** pixel detectors: sensor and readout produced **in same process**

Hybrid Pixel Detectors

- **Separate optimization** of sensor and readout chip, high production cost
- **Bump-bonding**: deposit solder bumps on sensor or chip → **flip-chip** assembly

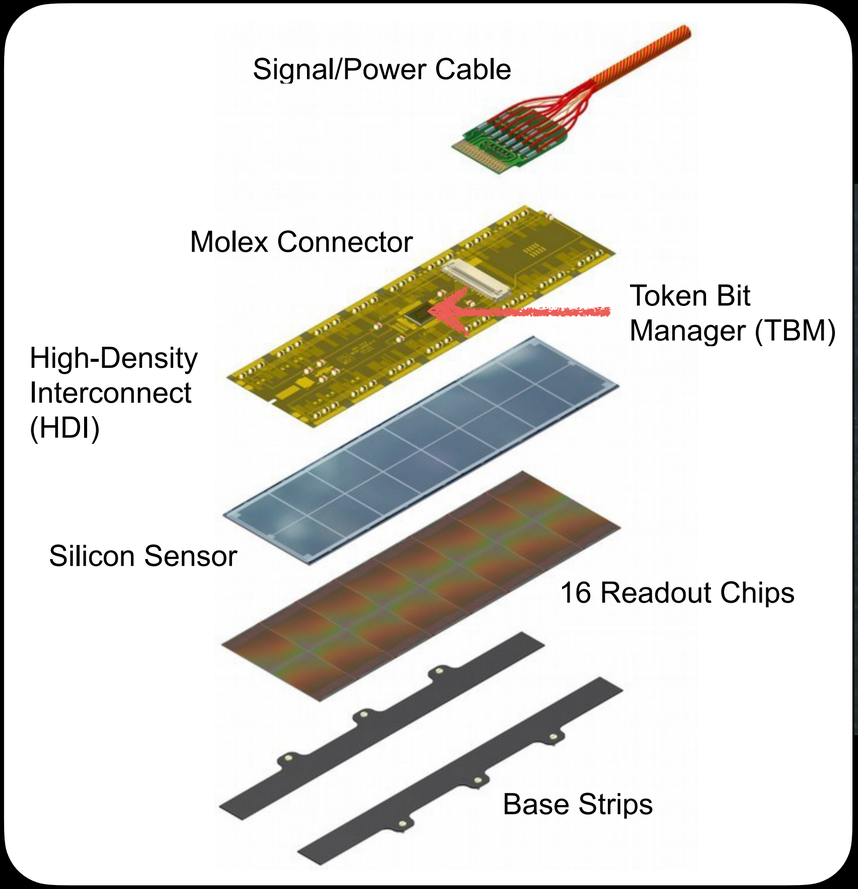


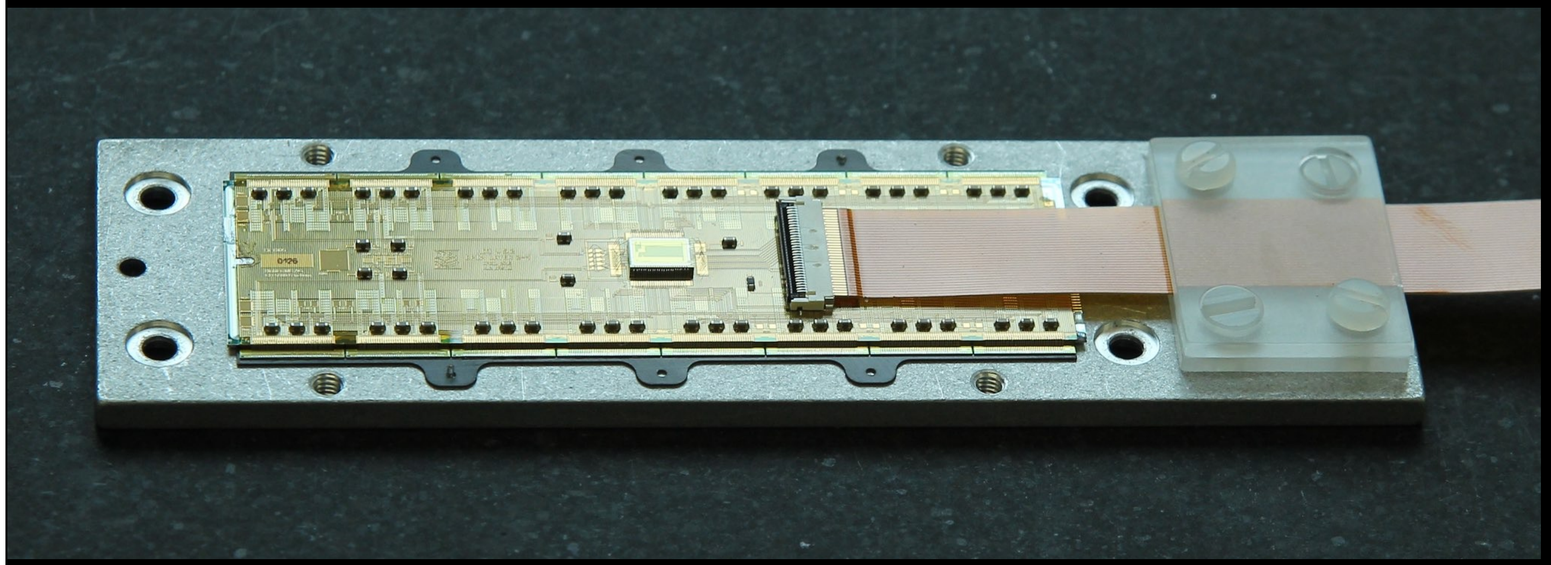
PSI



Garcia-Sciveres, Wermes, Rep. Prog. Phys. 81 (2018) 066101

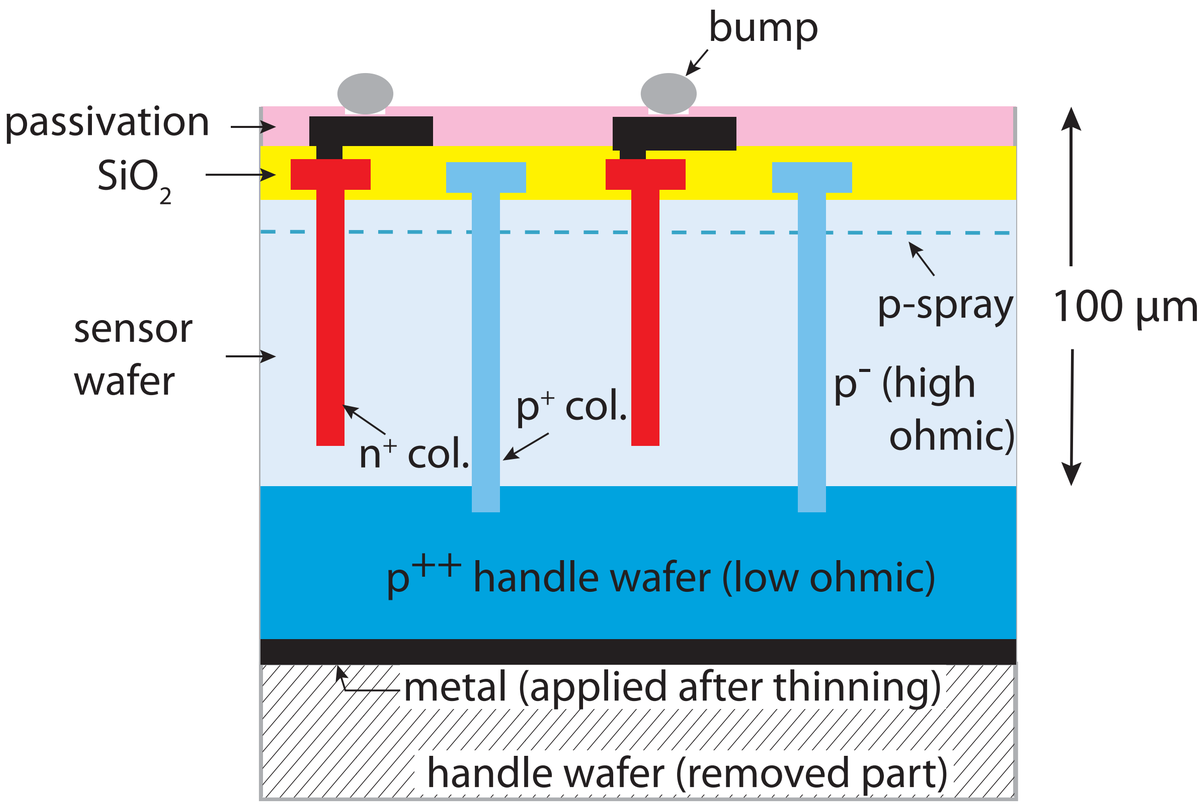
CMS Phase-1 Pixel Module





3D Silicon Sensors

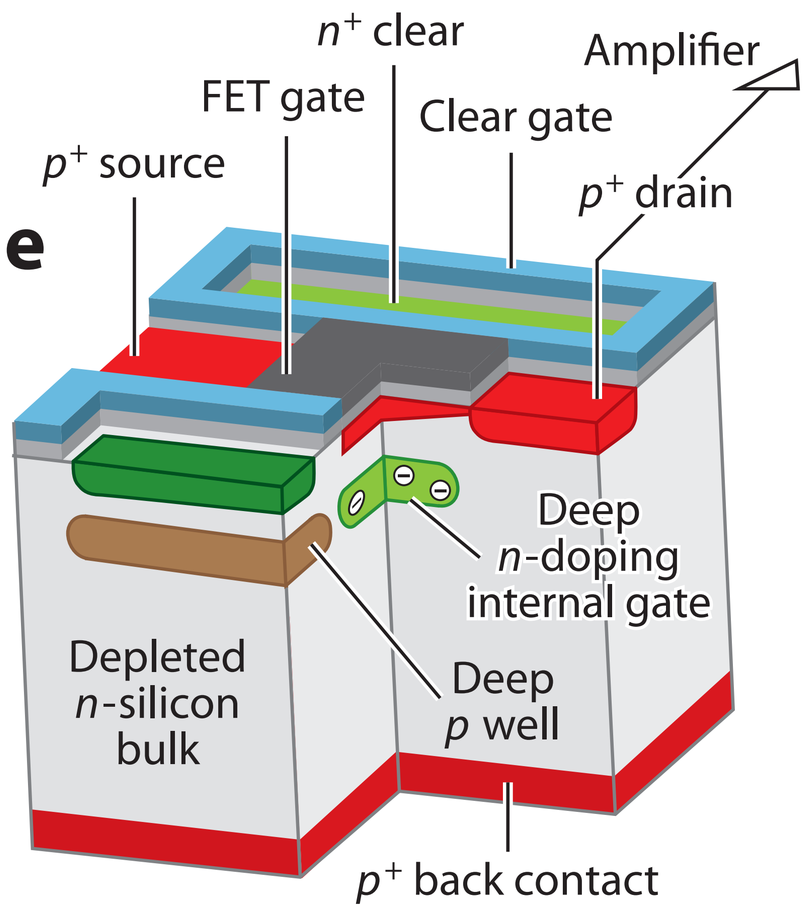
- **Columnar** electrode implants:
  - Decoupling of particle trajectory and drift direction
  - Shorter drift distance to electrodes (<50 µm)
  - High drift fields with moderate bias voltage (10s of volts)
  - More radiation hard (trapping reduced)
- Current HEP application: some modules of ATLAS pixel detector (in Insertable B-Layer, IBL)



Garcia-Sciveres, Wermes, Rep. Prog. Phys. 81 (2018) 066101

Active Pixel Sensors: DEPFET

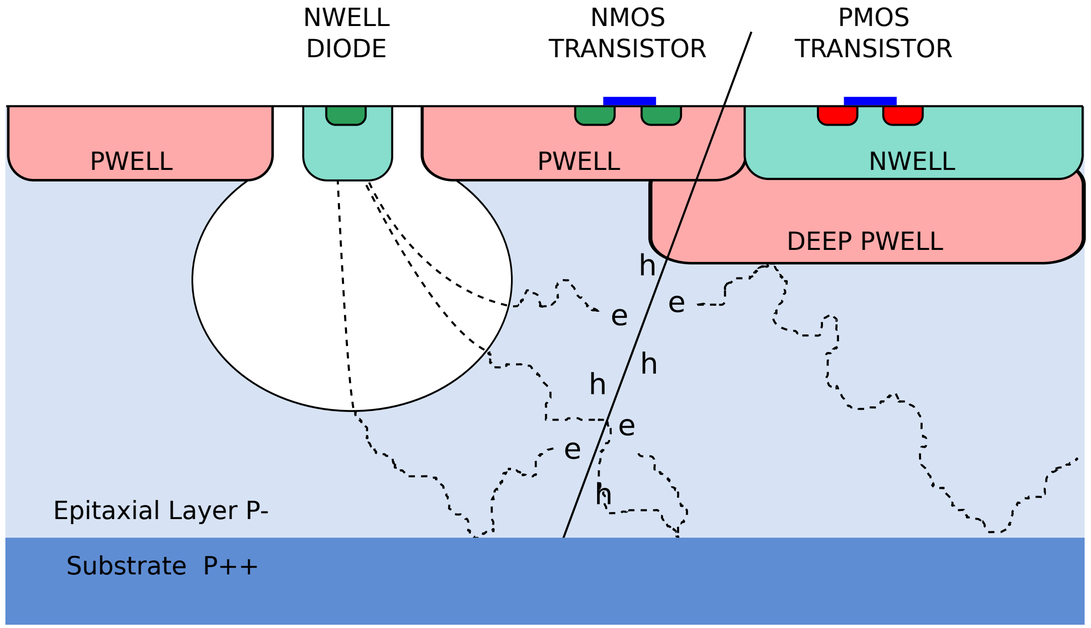
- **DEPFET** (depleted p-channel field-effect transistor; Kemmer, Lutz, 1985)
  - **Depleted** bulk as sensitive volume, PMOS transistor for amplification
  - **Internal gate**: local potential minimum below transistor channel
  - Collected charge → increased **transistor current** (need circuitry to clear internal gate)
  - First HEP application: pixel detector for **Belle II**



Hartmann, Kaminski, Annu. Rev. Nucl. Part. Sci 61 (2011) 197

MAPS: Monolithic Active Pixel Sensors

- Guiding idea: integrate particle **detection** and first **amplification** stage in single device → **monolithic active pixel sensors** (MAPS)
- Most commonly used: **CMOS sensors** (complementary metal-oxide-semiconductor)
  - Microelectronics **standard**, widely available (digital cameras, …)
  - **No/small bias voltage**: particle detection in epitaxial layer (20 µm) → **diffusion** to shallow depletion zone
  - **Small signals** but also **small noise**
  - Example: **ALPIDE** (LHC Run-3 Pixel Detector for ALICE)



Example: TowerJazz 180-nm process, from J. Phys. G41 (2014) 087002

MAPS Example: ALPIDE

LHC Run-3 Pixel Detector for ALICE

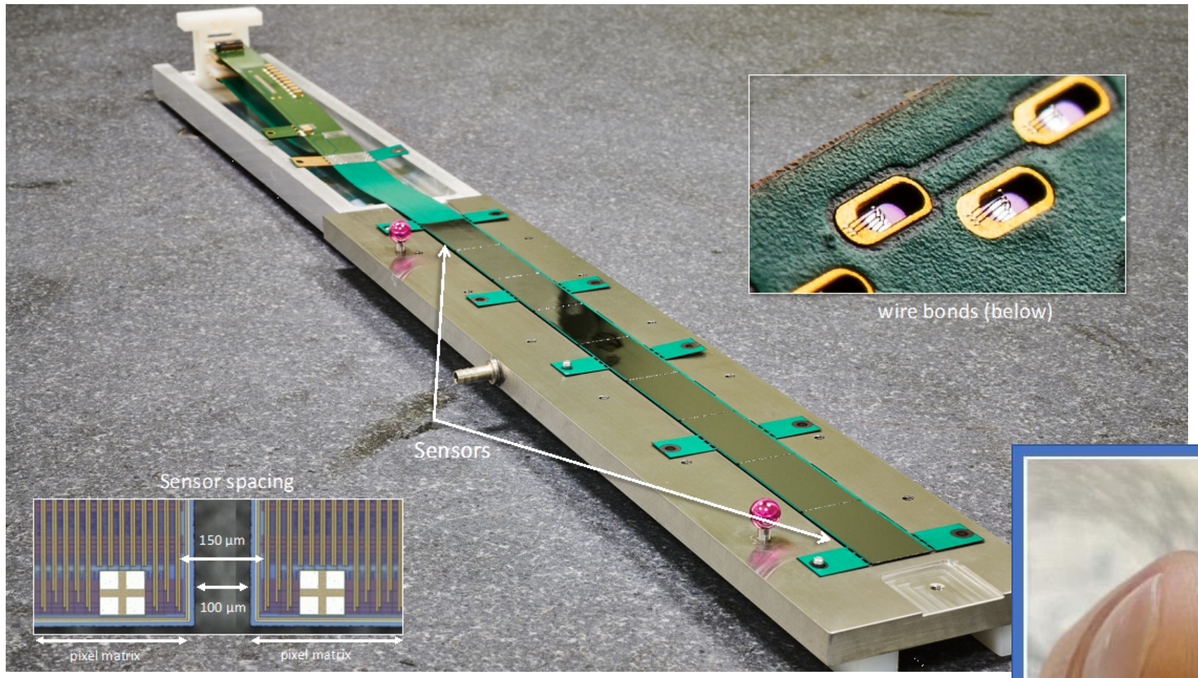
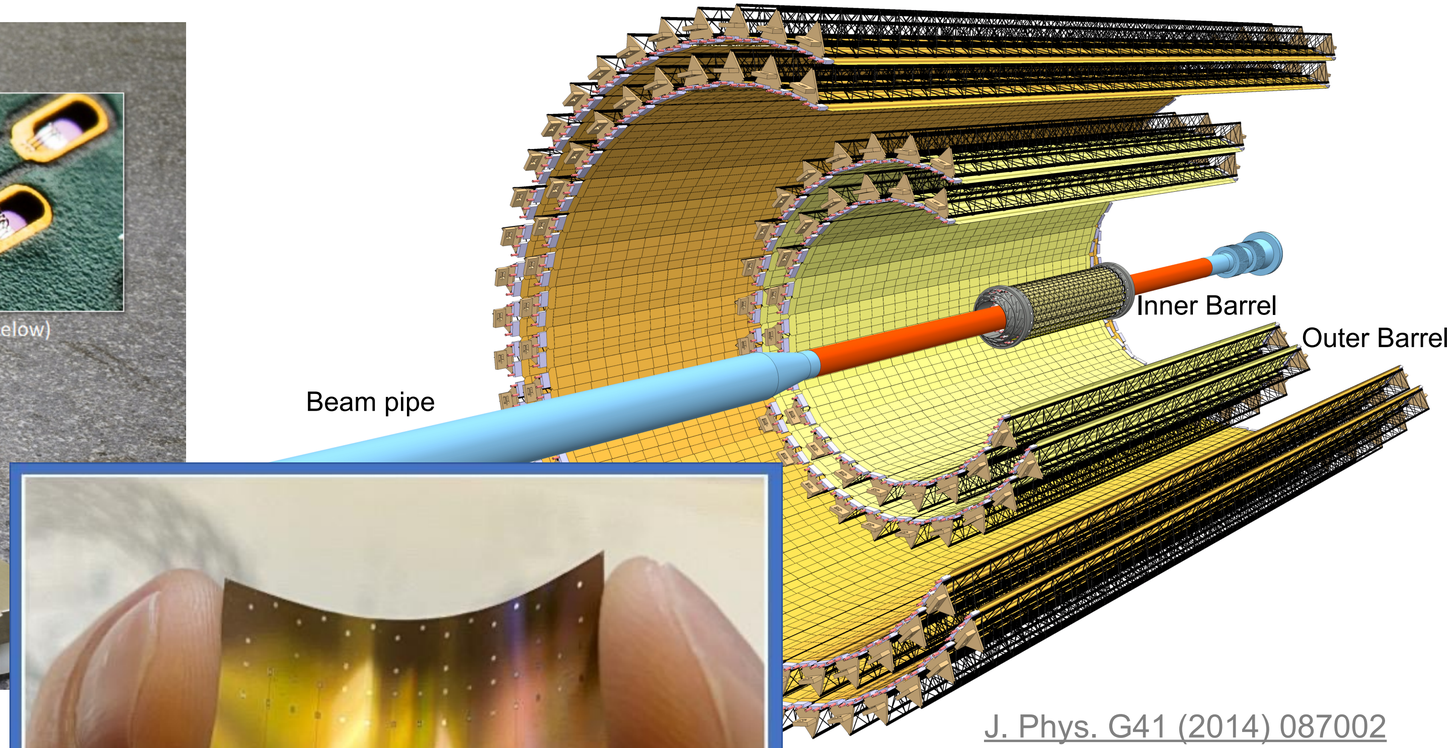


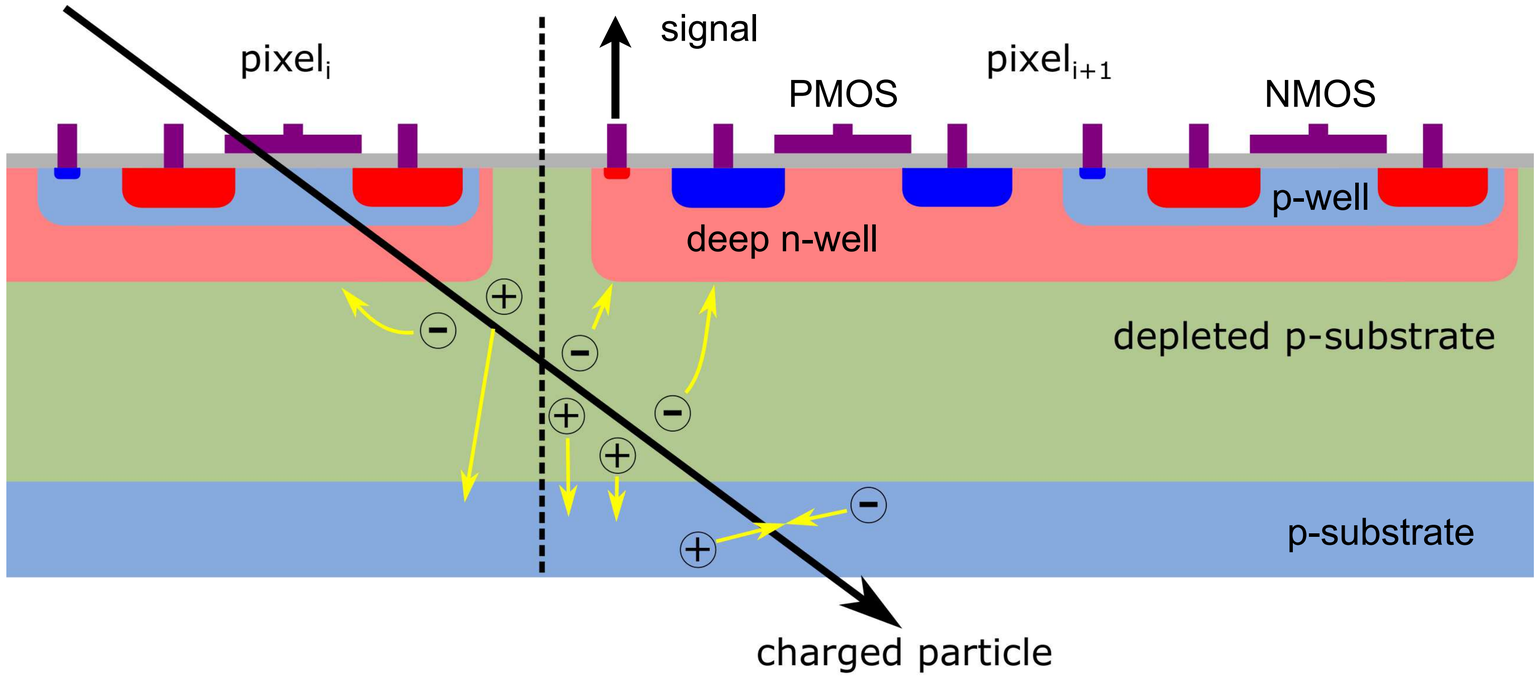
Image credit: ALICE collaboration



J. Phys. G41 (2014) 087002

Depleted MAPS: HV-CMOS

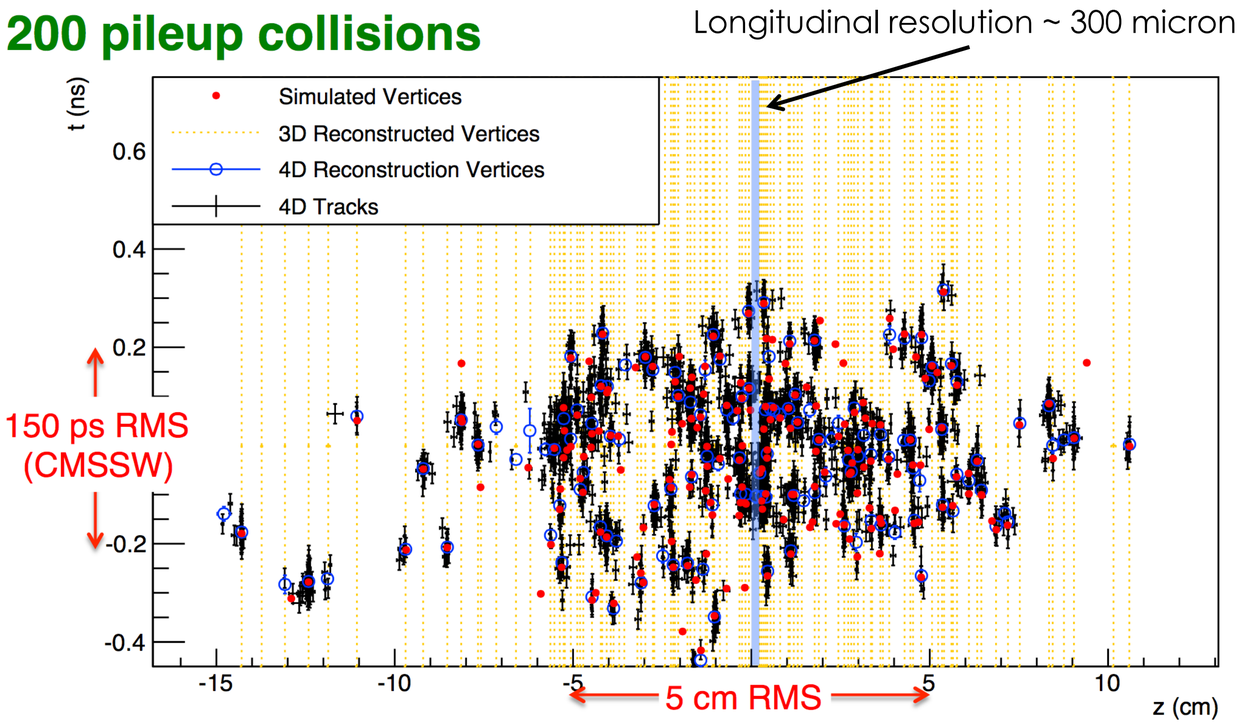
- Key idea: **decouple** CMOS structures for digital logic from **depleted** sensor substrate (protected by deep n-well)
- Charged particles or photons absorbed in depleted region → **drift** in electric field (faster than diffusion)
- Advantages: “cheap”, low material budget (down to 50 µm)
- Applications: Mu3e (MuPix), baseline for LHCb pixel detector upgrade (MightyPix),



After F. Ehrler, Dissertation, KIT 2021

Application II: Fast Timing

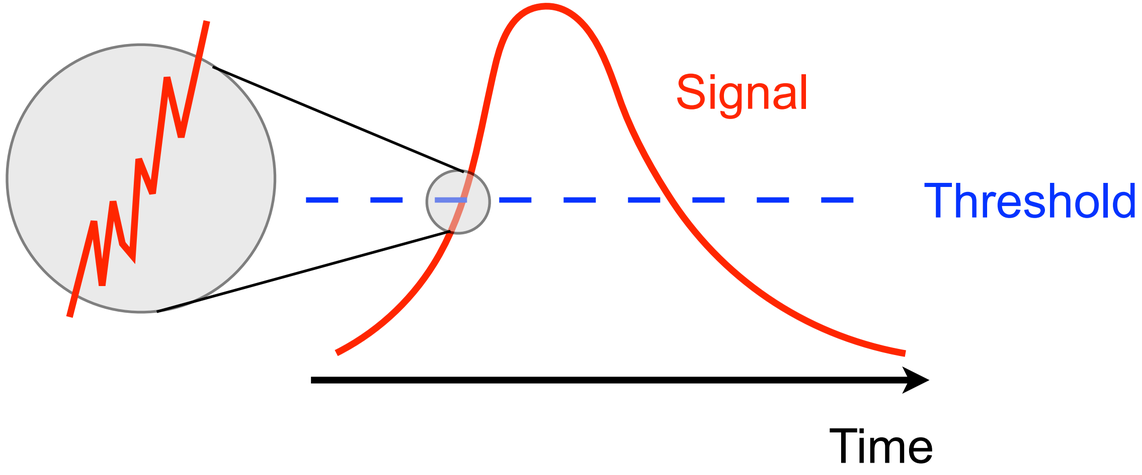
- Vision: add **timing** information as
  - **Fourth dimension** in particle **tracking** (“4D tracking”)
  - **Fifth dimension** in imaging **calorimetry** (“5D calorimetry”)
- Additional time information helps with many aspects of tracking and calorimetry, e.g. **time-of-flight discrimination** in multiple pp collisions at the LHC (“pileup”)



N. Cartiglia

Fast Timing: Basic Requirements

- Important for timing applications: **well defined starting time** of signal
  - Determination of starting time: signal exceeding comparator **threshold** (e.g. constant fraction discriminator)
  - High precision requires very reproducible **signal transit times** (low “jitter”)
  - Helpful for low jitter: large signals, large signal slope d*V*/d*t* (“slew rate”), low signal fluctuations (noise) → interplay of sensor and electronics

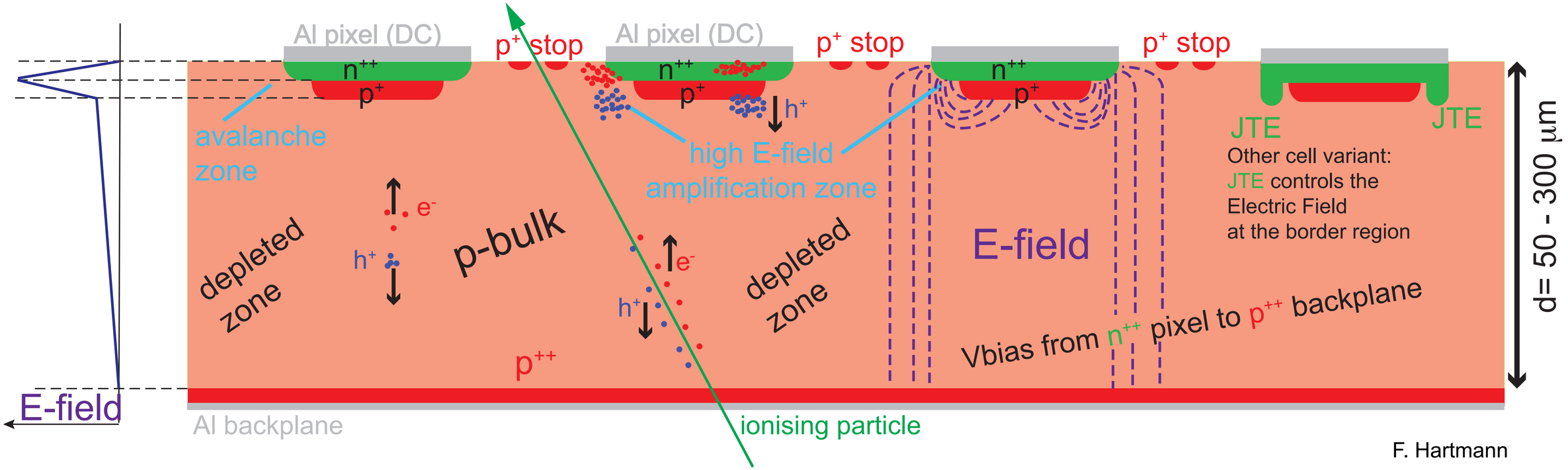


Fast Timing: Solutions

- Very **thin sensors** (50 µm): large slew rate and low fluctuations in deposited charge (“Landau noise”)
- **High resistivity** silicon and careful cell design: uniform electric (weighting) fields → smaller fluctuations
- **Small structure size** (pixels): small capacitance and leakage current → small noise
- **In-silicon amplification:**
  - Local high electric field → charge multiplication through impact ionization
  - However: high gain eventually amplifies noise more than signal
  - Sweet spot: **gain factor of 10–20** (“low gain”)

LGAD: Low-Gain Avalanche Diode

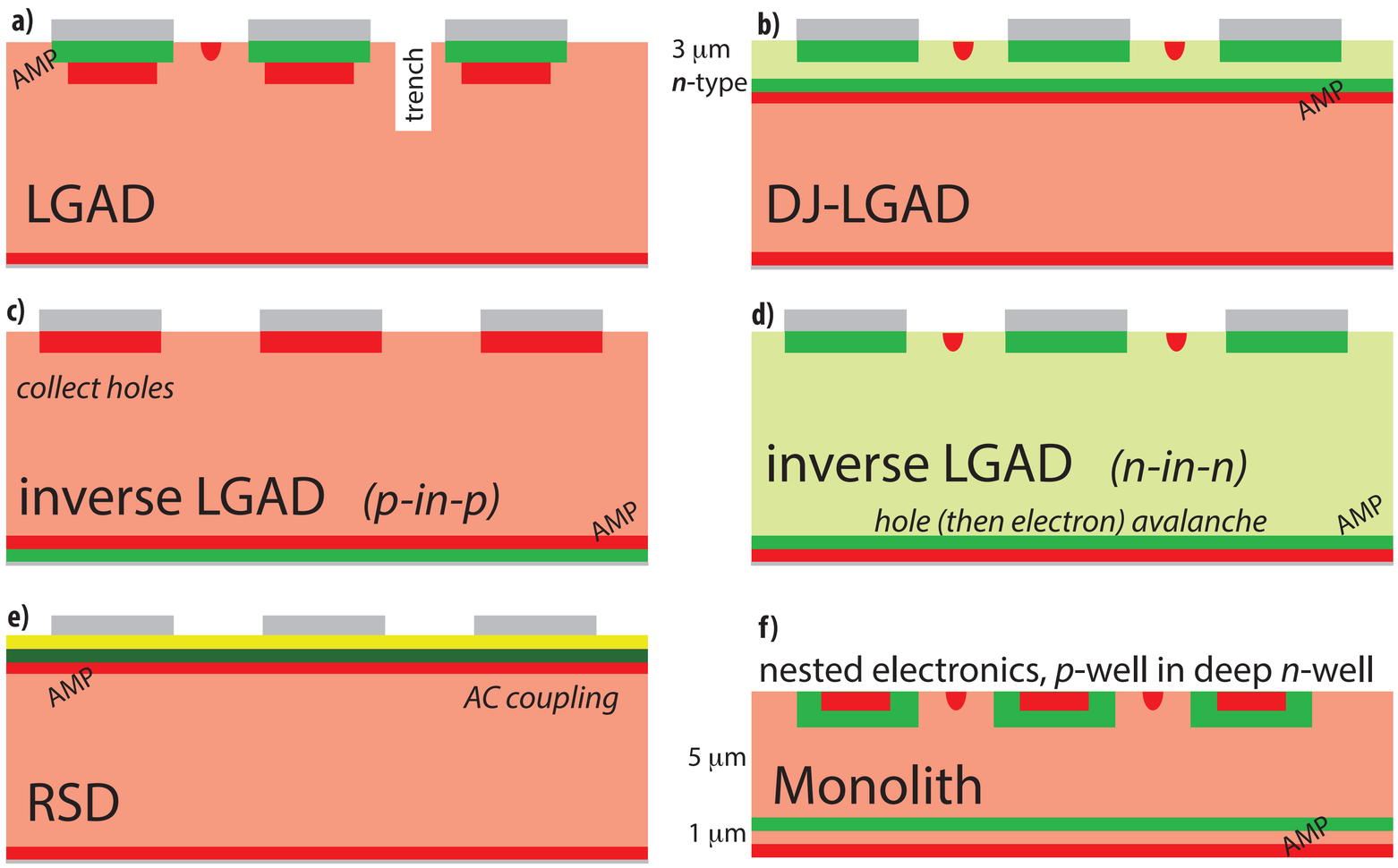
- New type of silicon detector: **LGAD** (Cartiglia, Sadrozinski, Seiden)
  - Fully depleted p-doped bulk, p+ stops to isolate cells
  - **Amplification layer** between deep p+ implant and n++ electrode



F. Hartmann

LGADs Today

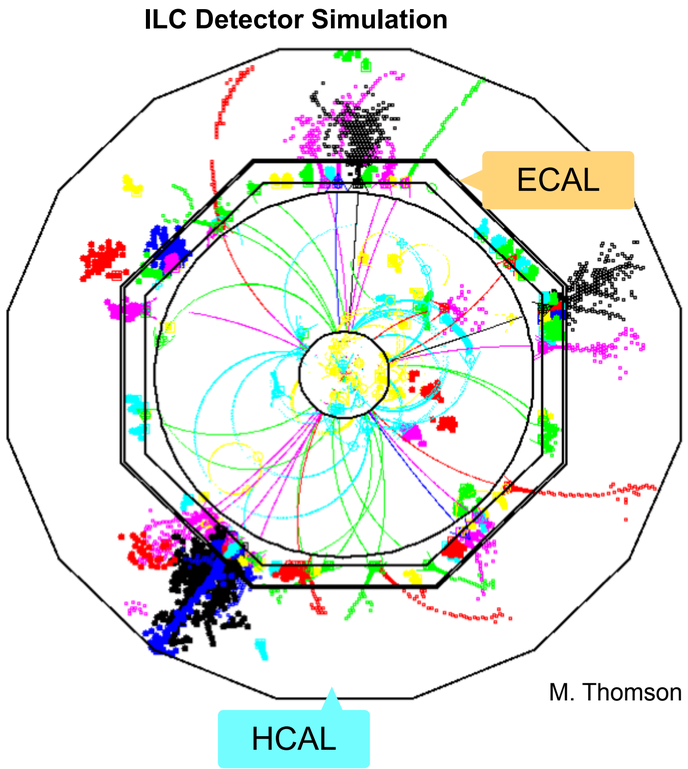
- Ongoing R&D effort: several LGAD variants being conceived
- HEP applications: **fast timing layers** in ATLAS (HGTD) and CMS (MTD) for high-luminosity LHC



F. Hartmann

Application III: Calorimetry

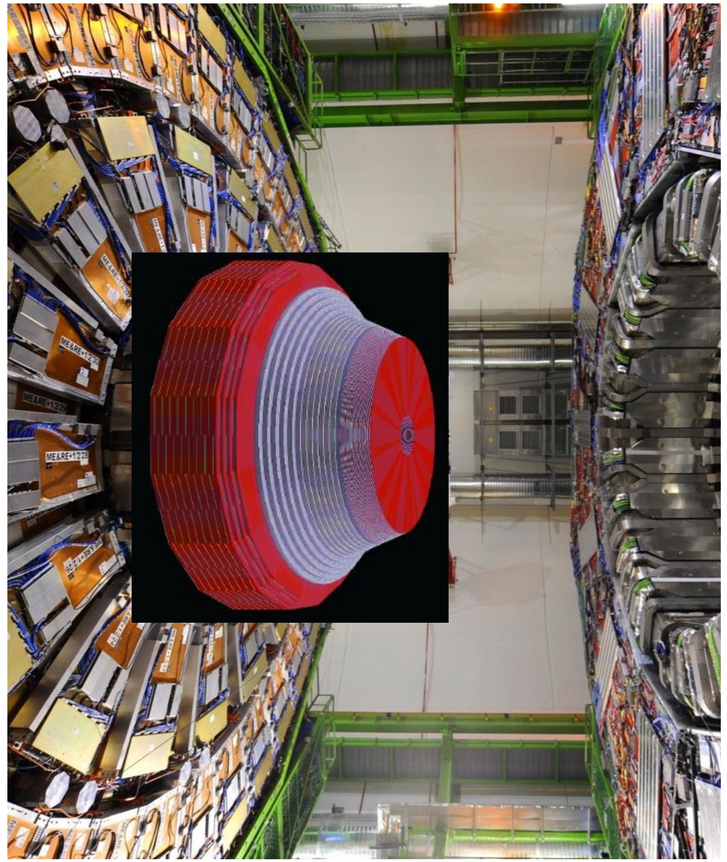
- **Imaging calorimeters**:
  - **Particle flow** paradigm: most precise measurement of each particle in a jet → rely on calorimetry **only for neutral hadrons**
  - Problem: wrong assignment of energy deposits to particles → **reduced resolution** due to **confusion**
  - Keep confusion small: very high (longitudinal and lateral) **granularity** (at least) as important as high energy resolution



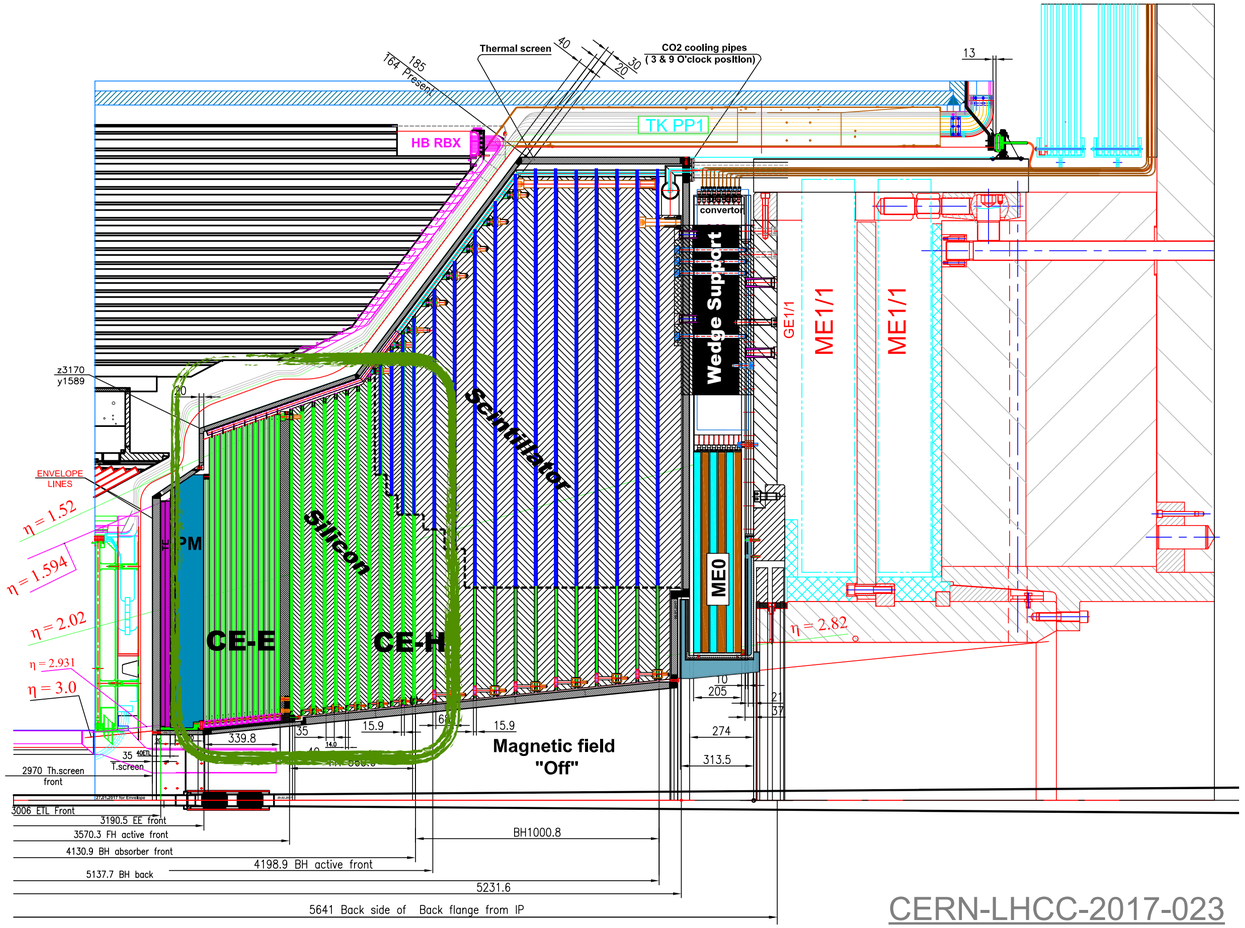
- Calorimetry at the HL-LHC:
  - **Physics with forward jets** still interesting, e.g. vector-boson fusion
  - **Too high radiation levels** for scintillator-based sampling calorimeters in forward (endcap) detector regions → active layers made from **silicon**

CMS HGCAL

- CMS approach: **high-granularity calorimeter** (HGCAL) for endcaps



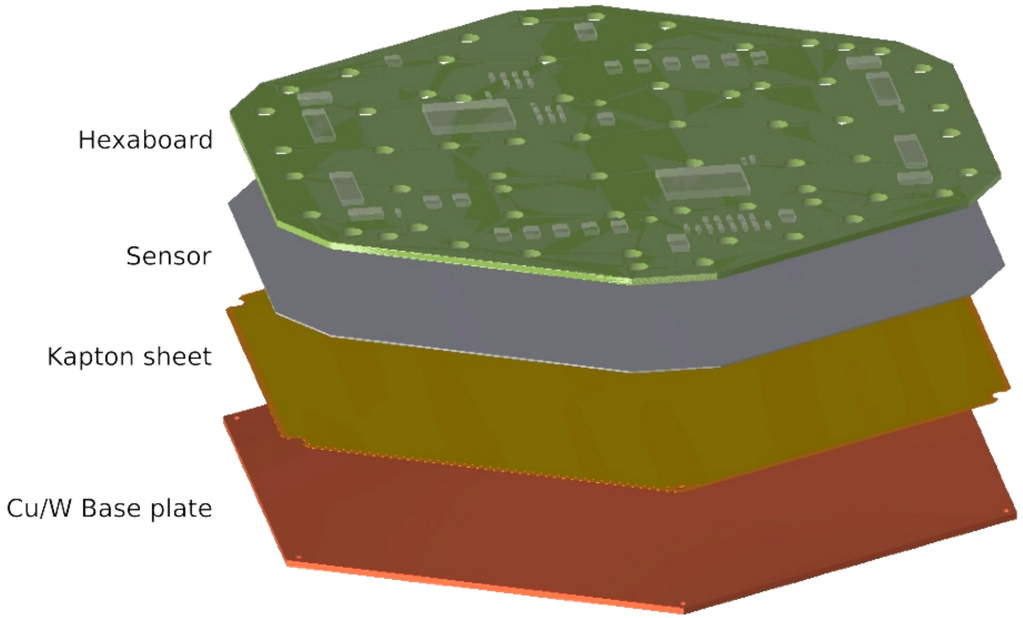
R. Rusack

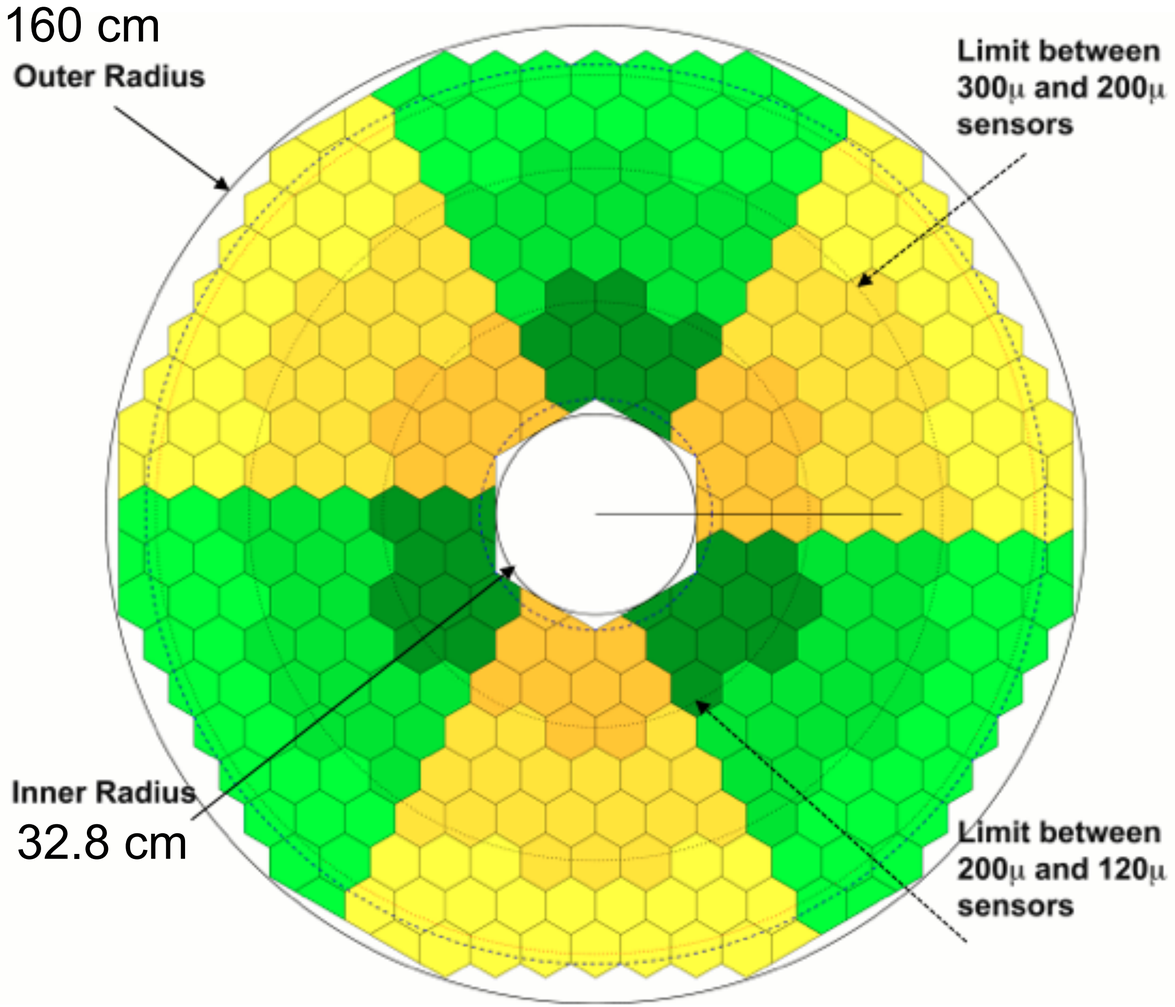


CERN-LHCC-2017-023

CMS HGCAL: Silicon Modules

- Active medium in inner parts: **Cu/W + silicon pad** modules
  - 5.8M readout channels, 600 m²
  - Ultra-fast timing (<100 ps)





CERN-LHCC-2017-023

Summary & Conclusions

- Silicon: key technology in particle physics
- Applications: tracking, timing, calorimeter
- This lecture: few selected examples (but there's so much more…)

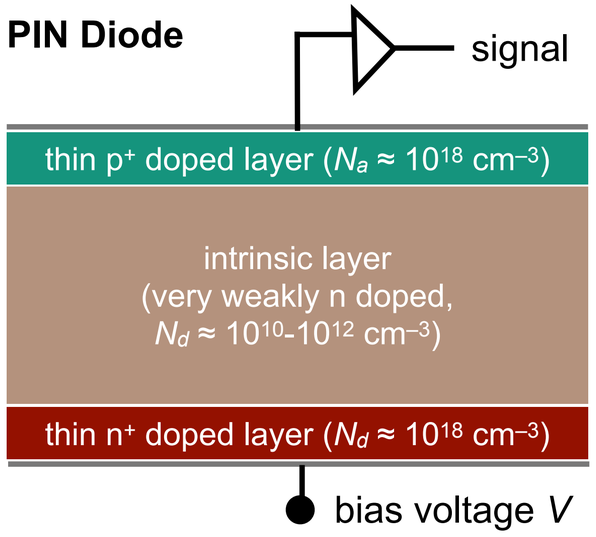
F. Wittig

Optional Topics

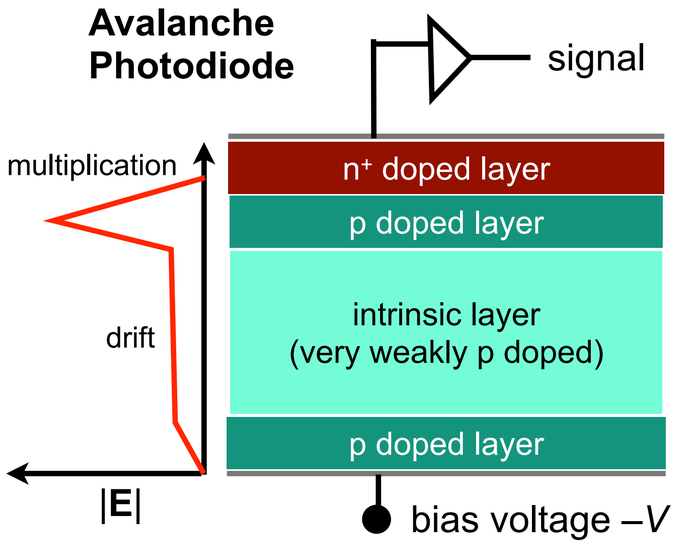
Semiconductor Photon Detectors

- **PIN diode**: positive–intrinsic–negative
  - Forward bias: RF switch, rectifier
  - Reverse bias: **photodiode** → wide depletion zone

$$w \approx x_n = \sqrt{\frac{2\epsilon(-V)}{e}\frac{1}{N_d}}$$

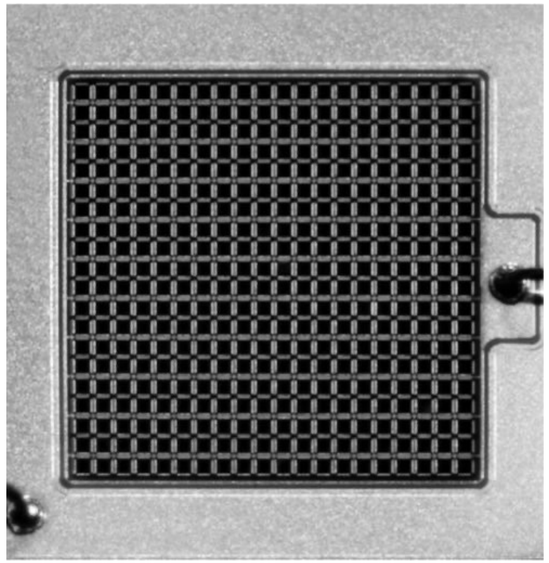


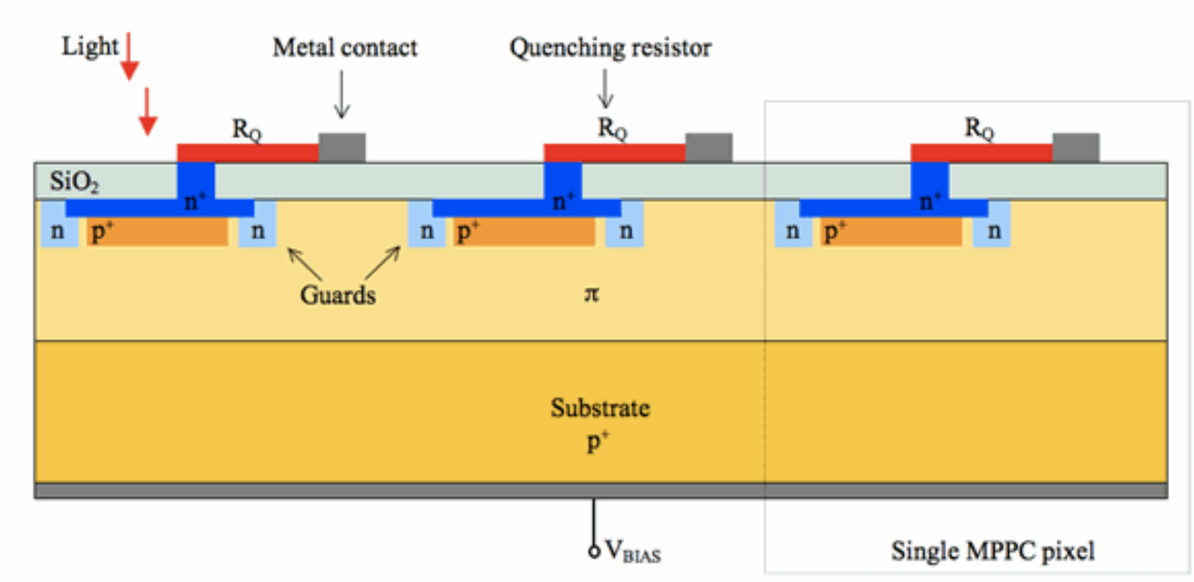
- **Avalanche photodiode** (APD):
  - Photon absorption in intrinsic layer
    → electron drift into multiplication zone
  - Amplification by **impact ionization**,
    typical gains: 100–1000
  - Example: photon detection in CMS ECAL



Semiconductor Photon Detectors

- **Silicon photomultiplier** (SiPM, also: multi-pixel photon counter, MPPC):
  - 2D array of APDs operated in **Geiger mode** (voltage above breakdown voltage → discharge independent of light input) with quenching resistor
  - Single pixel: **binary** device, energy = sum of photons detected in all pixels
  - In many fields: modern replacement for traditional photomultiplier tubes



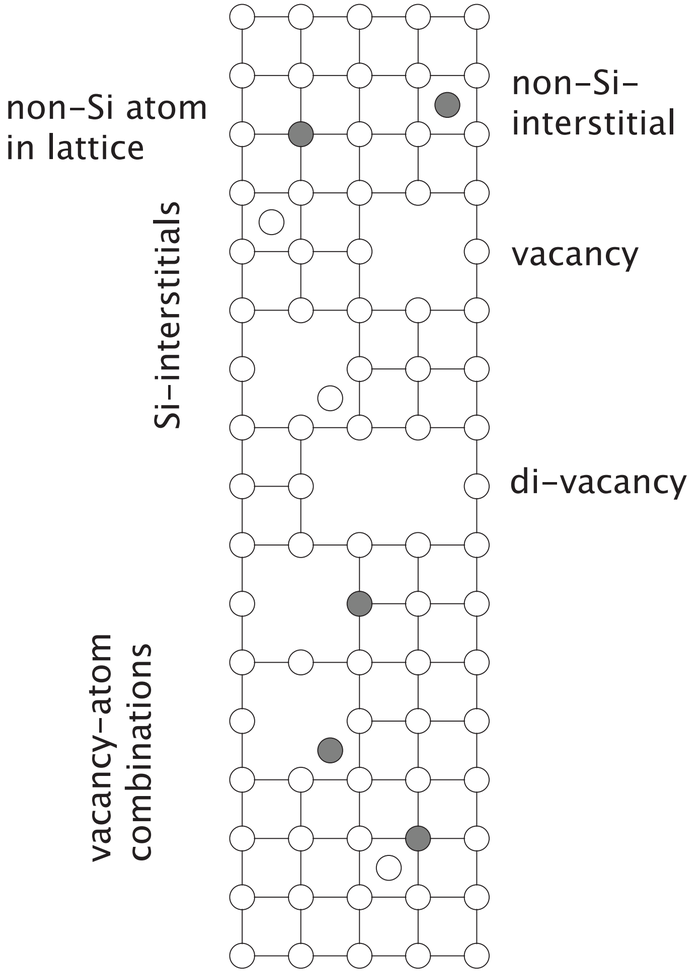


www.hamamatsu.com

Radiation Damage

- Effects of radiation on semiconductor detectors (relevant e.g. for LHC experiments):
  - Ionization: fully **reversible** in detector **bulk**, but **surface** damage
  - **Non-ionizing** energy loss (NIEL): **crystal lattice damage** in detector bulk → point defects and clusters
- **Fluence** = integrated flux of particles
- **NIEL hypothesis**: all damage scales with NIEL fluence (independent of particle type and energy) → normalize to fluence of 1-MeV neutrons Φ_{eq}

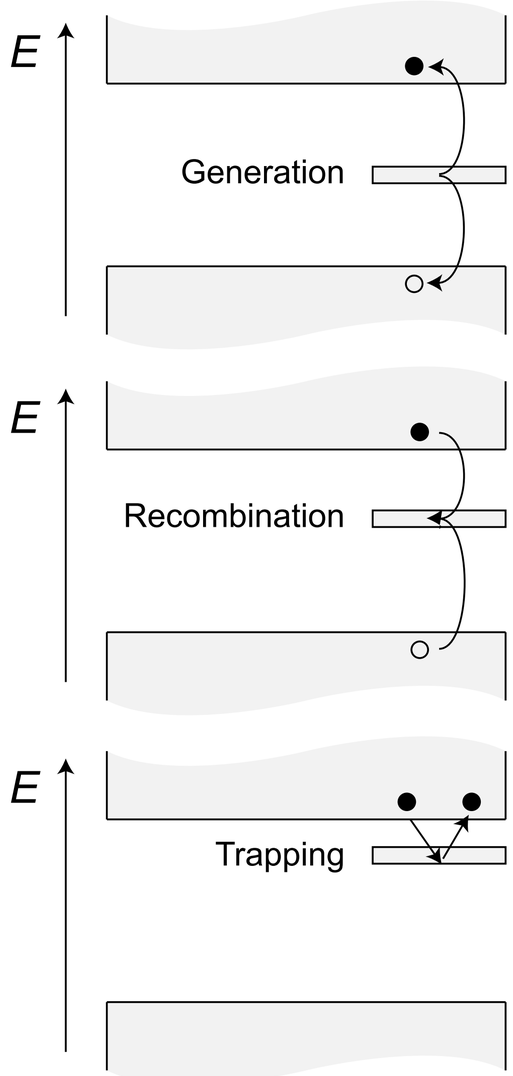
Point Defects in a Silicon Lattice



J. Große-Knetter, Habilitation Thesis, U Bonn (2008), after R. Wunstorf

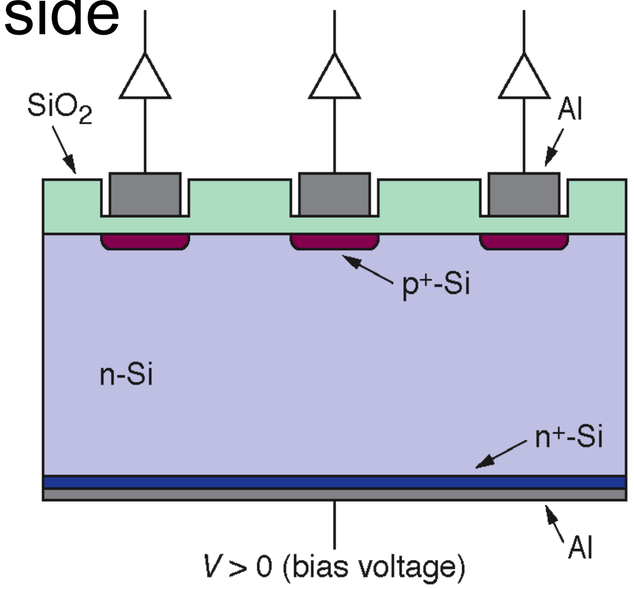
Radiation Damage

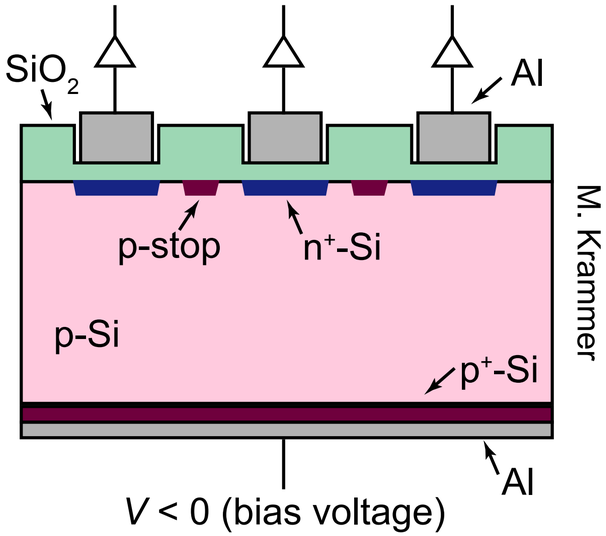
- Microscopic effects and macroscopic consequences:
  - Defects can be **stable** or **mobile** depending on **temperature** → beneficial or reverse **annealing** of defects by recombination
  - Band model: **additional energy levels** in band gap
  - Change of **effective doping concentration** from n to p (“type inversion”) → increased **depletion voltage** (technical limitation: **discharges**)
  - Deep defects (center of band gap): drastic **increase of leakage current** by charge generation and recombination → increased **noise** and **heat**
  - Shallow defects (close to valence or conduction band): **reduced charge collection** by temporary trapping of charges → smaller **signals**



p-in-n vs. n-in-p Sensors

- Alternative to traditional p-in-n detectors: **n-in-p detectors** with p-doped bulk, n^+-doped implants ("p bulk")
  - **Electron** collection (p-in-n: holes) → faster, but larger Lorentz angle
  - Electron accumulation: **isolate n^+ implants** by p-stop or p spray
  - **More radiation-hard** (e.g. no type inversion) → pn junction always on readout side





M. Krammer

n-in-p sensors: baseline for **HL-LHC upgrades** of ATLAS and CMS

Momentum Resolution

- Parametrization of **momentum resolution** for tracking detectors:

$$\frac{\sigma_{p_T}}{p_T} = \frac{a}{BL^2}\, p_T \oplus \frac{b}{\sqrt{LX_0}\, B}$$

B: magnetic flux density
L: track length
X_0: radiation length of material

  - p_T-dependent term: a proportional to **single-hit resolution σ_x**
  - Contributions to σ_x: **intrinsic resolution** of position-sensitive detector and detector **alignment** (precise knowledge of detector positions, not shown)

$$\sigma_x = \sigma_{\text{intrinsic}} \oplus \sigma_{\text{align}}$$

- **Intrinsic resolution** of position-sensitive detectors → pitch p
  - Binary readout: resolution given by standard deviation of uniform distribution $\sigma_x = \frac{p}{\sqrt{12}}$
  - Improving resolution, e.g. via charge sharing among detector channels
  - Typical values: <10 µm (silicon pixel detectors) to 10 mm (resistive plate chambers)