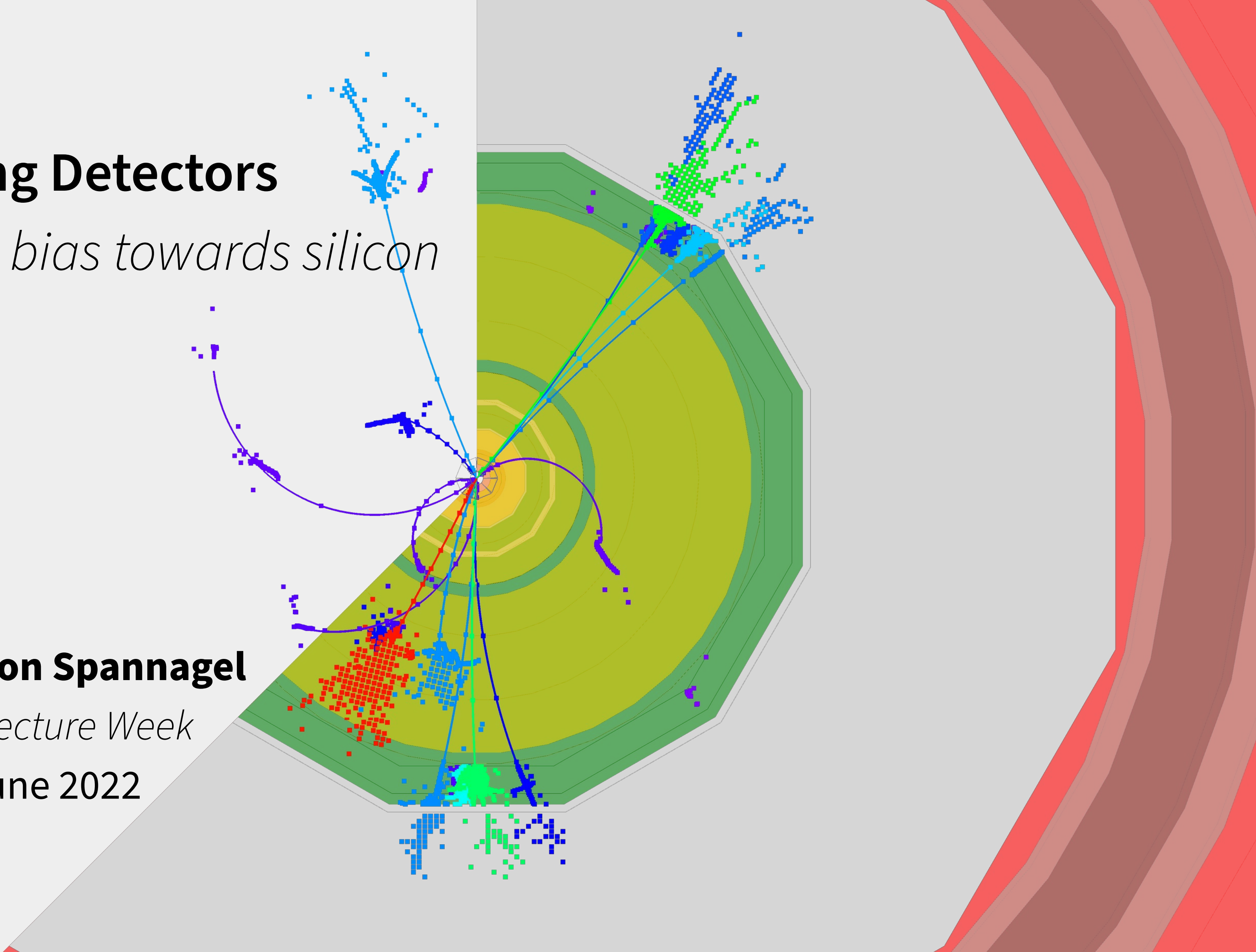
https://www.desy.de/

Modern Tracking Detectors

… with a strong bias towards silicon



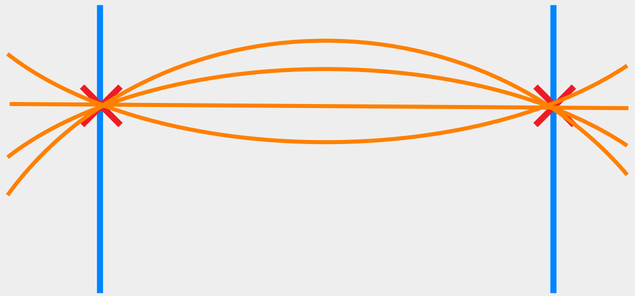
Simon Spannagel

HighRR Lecture Week

29 June 2022

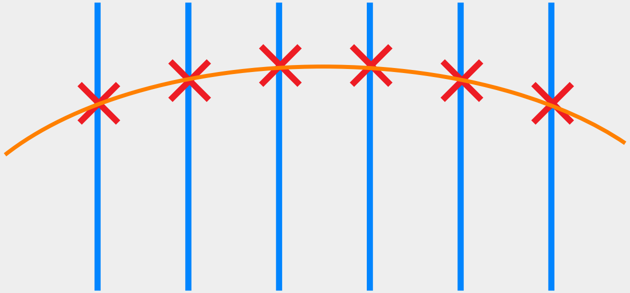
Motivation

- Efficient & precise tracking of relativistic particles always requires several measurement points



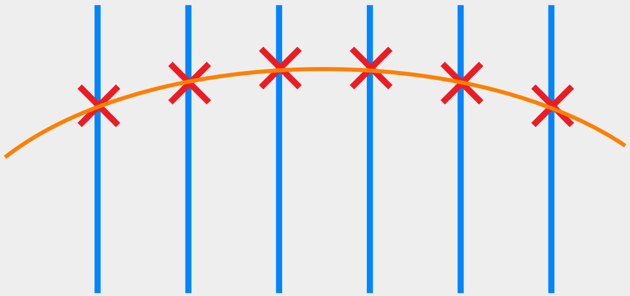
Motivation

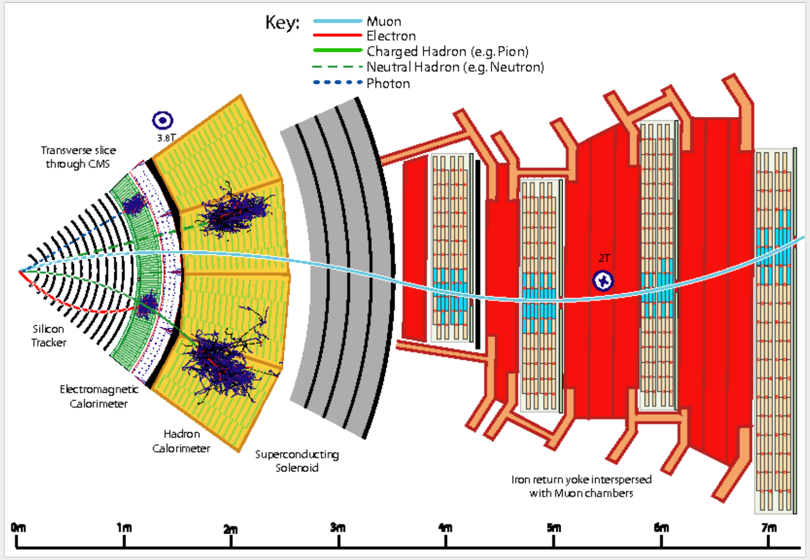
- Efficient & precise tracking of relativistic particles always requires several measurement points



Motivation

- Efficient & precise tracking of relativistic particles always requires several measurement points
  - TPC: one data point per pad
  - Silicon tracker: one data point per layer
- Tracking detector systems:
  - Momentum determination
  - Vertex reconstruction
    - Pile-up mitigation, background suppression
    - Secondary vertices → B-tagging
- Supports identification of particle types





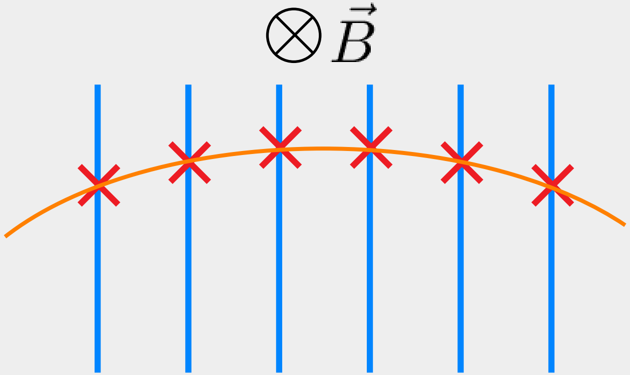
Momentum Reconstruction

Momentum Reconstruction

- Relativistic particles in magnetic field:
  - $\vec{p} \perp \vec{B}$ circular track
  - $\vec{p} \parallel \vec{B}$ straight track
  - Else helical track
- Lorentz force and centripetal force in equilibrium:

$$\begin{aligned} |\vec{F}_L| &= |\vec{F}_Z| \\ |q\vec{v} \times \vec{B}| &= \frac{m\vec{v}^2}{R} \\ p_T &= qBR \end{aligned}$$

- Measurement of the radius of curved tracks yields *transverse momentum* $\mathrm{p_T}$



Simple approximation

$$p_T = 0.3|z|BR$$

$$[p_T] = \mathrm{GeV/c}$$

with

$$[R] = \mathrm{m}$$

$$[B] = \mathrm{T}$$

$$z = q/e$$

Momentum Measurement

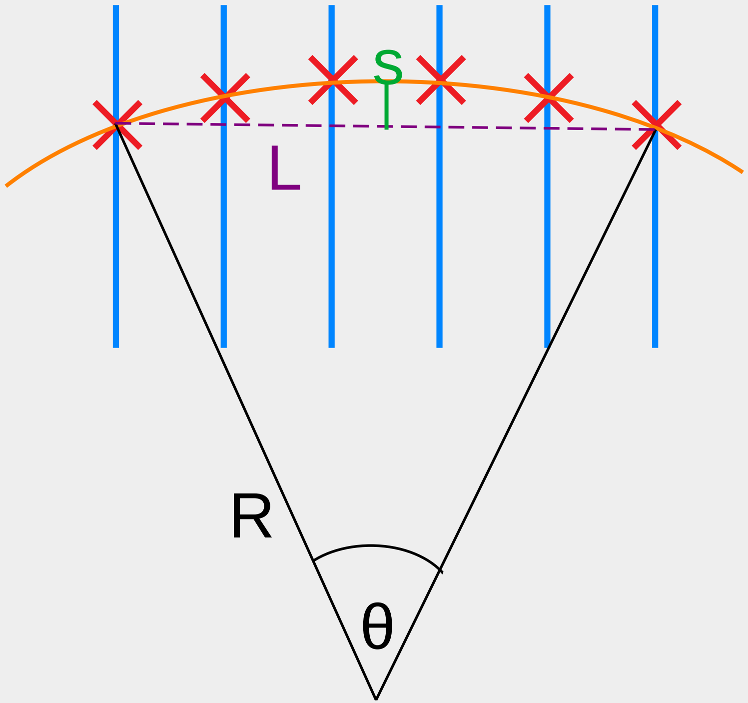
- Radius can be determined by measurement of *sagitta* length s at track length L

$$s \approx \frac{L^2}{8R}$$

- Uncertainty of momentum proportional to uncertainty of sagitta measurement:

$$p = qBR = \frac{8qB}{L^2} s \quad \Rightarrow \quad \sigma_p \propto \sigma_s$$

- Uncertainties of sagitta measurement:
  - Spatial detector resolution
  - Multiple Coulomb scattering



Momentum Measurement – Uncertainty

Contribution from detector resolution

- ✔ Spatial detector resolution σ_m
- ✔ Track length L
- ✔ Magnetic field B
- ✔ Number of measurements N
- ✗ Transverse momentum p_T

Gluckstern formula (for $\mathrm{N} > 10$)

$$\frac{\sigma_{p_T}}{p_T} = \frac{p_T}{0.3|z|} \frac{1}{L^2 B} \sqrt{\frac{720}{N+4}} \sigma_m$$

➔ Large tracking detector inside a strong magnetic field essential!

Momentum Measurement – Uncertainty

Contribution from multiple Coulomb Scattering

- Scattering: $\theta_0 \propto \frac{1}{p}\sqrt{\frac{l}{X_0}}$

✔ Track length L

✔ Magnetic field B

✔ Number of measurements N

✗ Material budget $\varepsilon = l/X_0$

Momentum Uncertainty (Scattering)

$$\frac{\sigma_{p_T}}{p_T} = \frac{p_T}{BL}\frac{\theta_{0,N}}{\sin\theta}\sqrt{C_N}$$

$$\theta = \angle(\vec{p}, \vec{B}) \qquad \theta_{0,N} = \sum_N \theta_{0,i}$$

$$C_N = \frac{2N(2N-1)}{3(N-1)^2}$$

Momentum Measurement – Uncertainty

Contribution from multiple Coulomb Scattering

- Scattering: $\theta_0 \propto \frac{1}{p}\sqrt{\frac{l}{X_0}}$

✔ Track length L

✔ Magnetic field B

✔ Number of measurements N

✗ Material budget $\varepsilon = l/X_0$

$$\frac{\sigma_{p_T}}{p_T}(p_T) \propto p_T \theta_{0,N} = \text{const.}$$

➔ Constant as a function of p_T

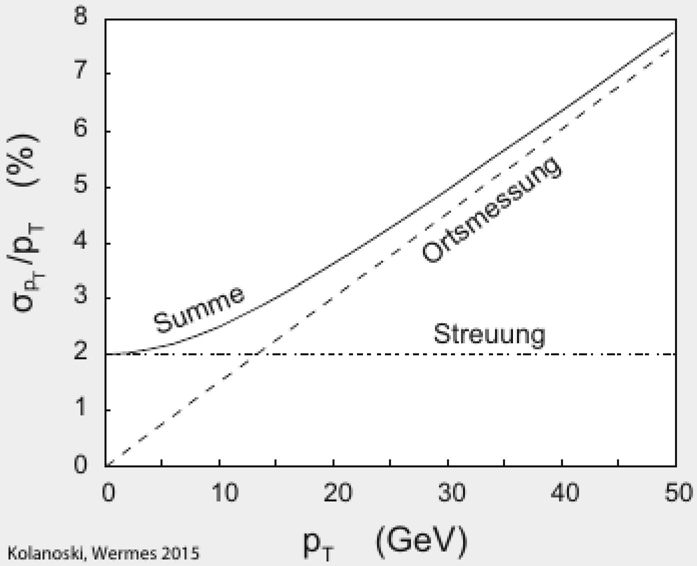
Momentum Uncertainty (Scattering)

$$\frac{\sigma_{p_T}}{p_T} = \frac{p_T}{BL}\frac{\theta_{0,N}}{\sin\theta}\sqrt{C_N}$$

$$\theta = \angle(\vec{p}, \vec{B}) \qquad \theta_{0,N} = \sum_N \theta_{0,i}$$

$$C_N = \frac{2N(2N-1)}{3(N-1)^2}$$

Momentum Measurement – Uncertainty



Kolanoski, Wermes 2015

Total Uncertainty

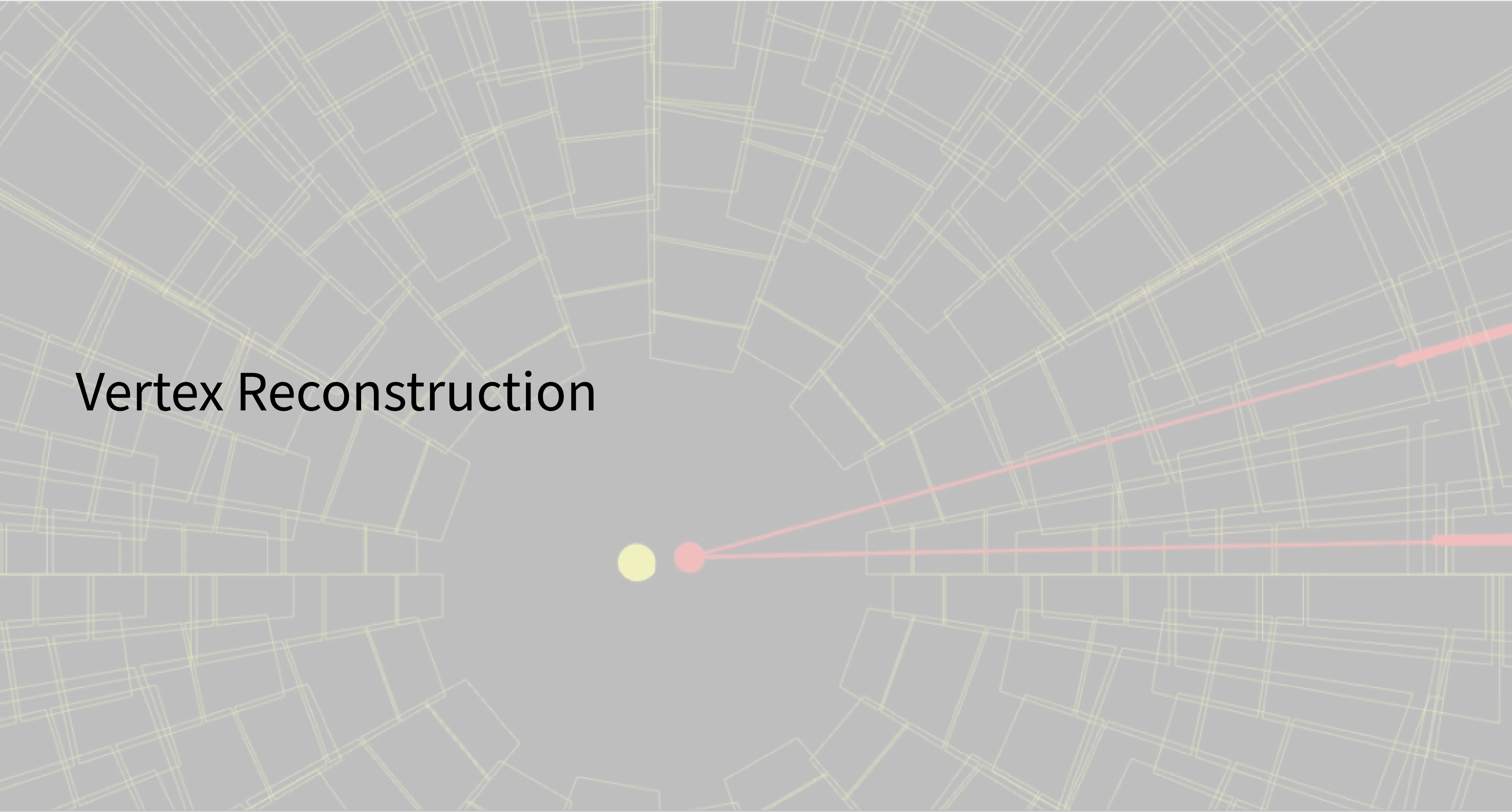
$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\text{meas}} + \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\text{scat}}}$$

- Resolution: linear dependency on $\mathrm{p_T}$
- Scattering: constant as a function of $\mathrm{p_T}$

Comparison

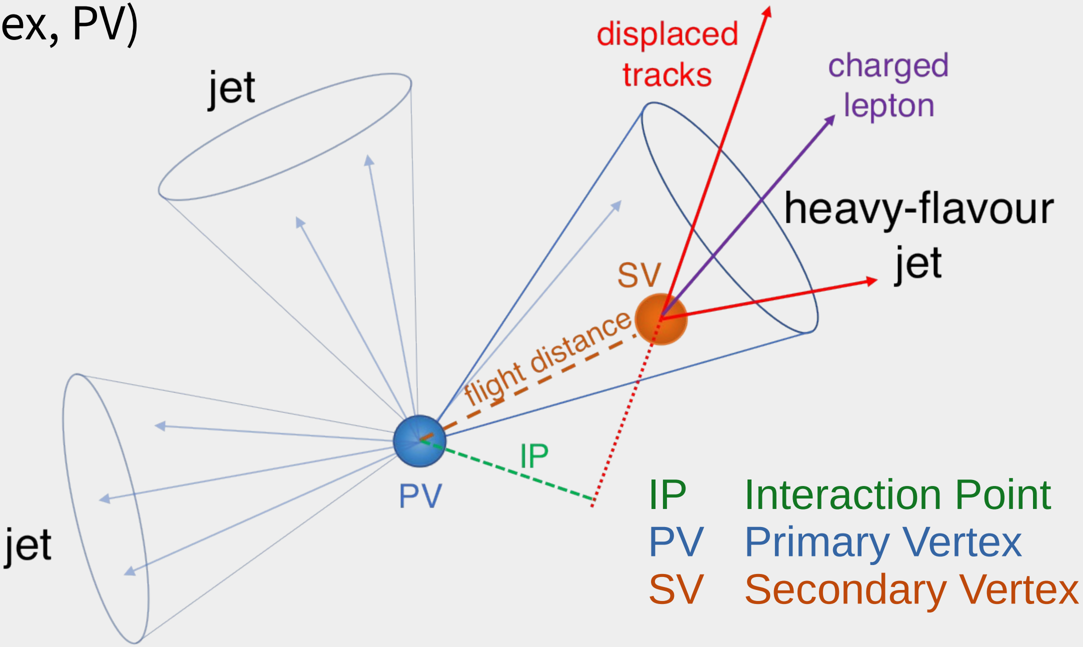
- Calorimeters: $\frac{\sigma_E}{E} \propto 1/\sqrt{E}$
- Tracking: $\frac{\sigma_{p_T}}{p_T} \underset{\sim}{\propto} p_T$

Vertex Reconstruction



Secondary Vertices – b-Tagging

- Not all particles decay immediately – example: **b-quarks**:
  - Produced at collision (primary vertex, PV)
  - Propagation during finite lifetime
  - Decay → secondary vertex (SV)
- Lifetime of b-quarks: $\mathcal{O}(10^{-12}\ \mathrm{s})$
  - Flight distance: $\mathcal{O}(100\ \mu\mathrm{m})$
  - Can be resolved with modern tracking detectors



- Indication of SV hints at b-quarks, used for e.g. b-Tagging

Secondary Vertices – b-Tagging

- Observable for tracking detectors:
  Impact parameter d_0 of individual tracks w.r.t. main jet
- Resolution: $\sigma_{d0} = \sigma_{d0}(\mathrm{meas}) \oplus \sigma_{d0}(\mathrm{scat})$

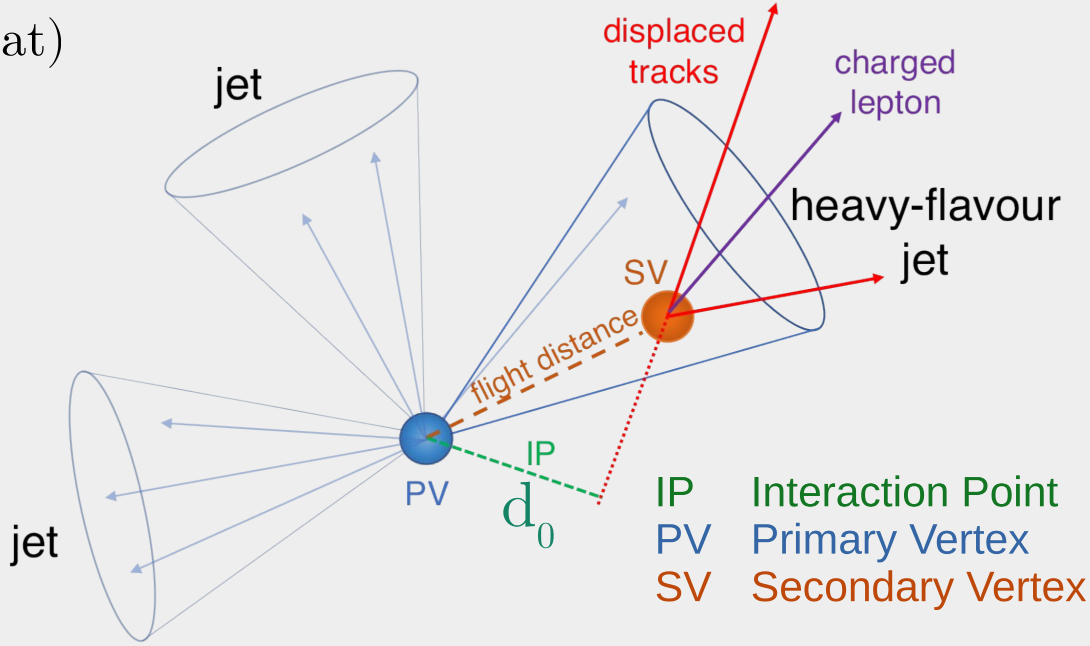
Example: **ATLAS Pixel Detector**

2008: 3 Layers, 10 µm resolution,
Radii: 5.05 cm, 8.85 cm, 12.25 cm.

→ $\sigma_{d0} = 18.1\ \mu\mathrm{m} \oplus 142\ \mu\mathrm{m}/p\ (\mathrm{GeV}/c)$

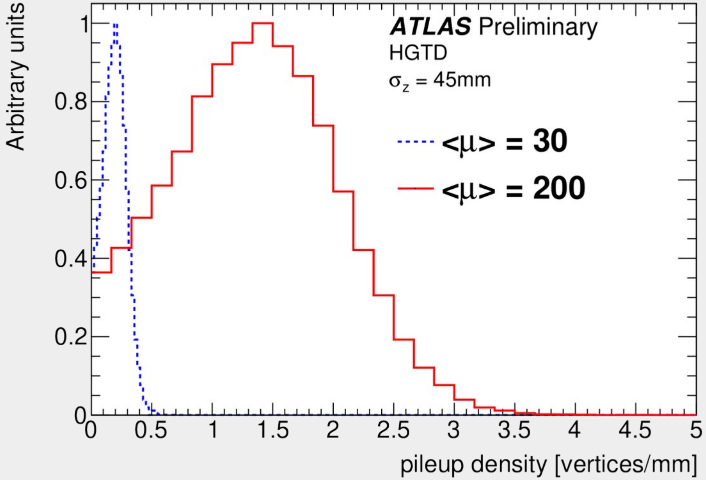
2014: Additional “B-Layer” / IBL @ 3.3 cm

→ $\sigma_{d0} = 12.1\ \mu\mathrm{m} \oplus 93\ \mu\mathrm{m}/p\ (\mathrm{GeV}/c)$

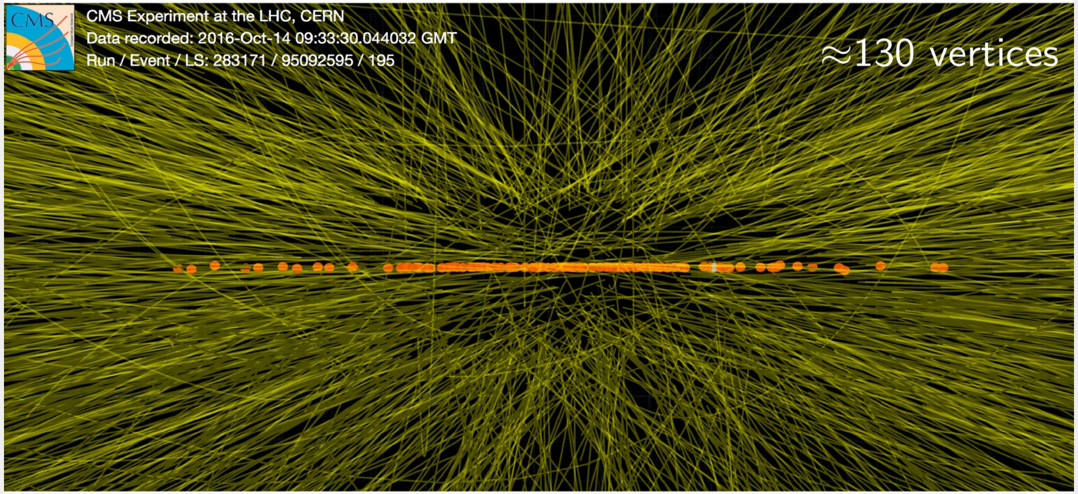


IP	Interaction Point
PV	Primary Vertex
SV	Secondary Vertex

Timing – Background & Pile-Up

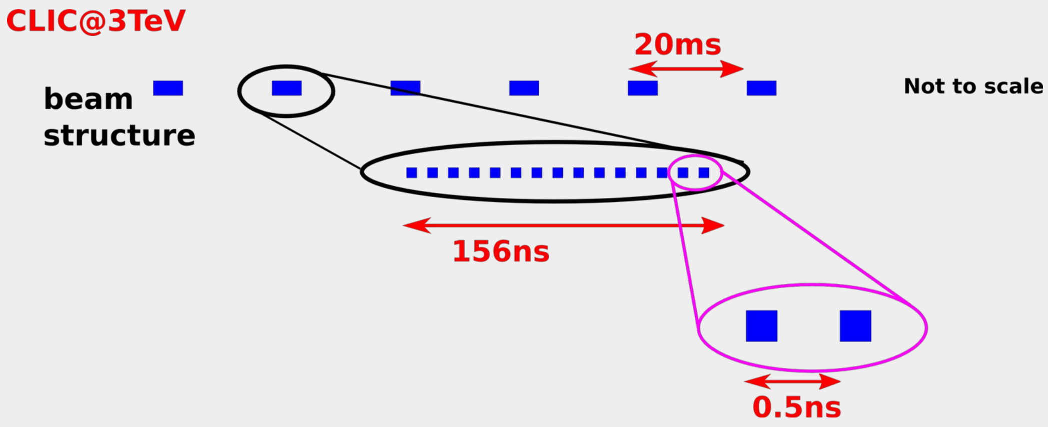


- Collisions become increasingly complex
  - Hadron colliders: Pile-Up
    Multiple hard scattering collisions per bunch crossing
  - Lepton colliders: background
    Often operate in bunch trains, need to separate out hard scattering
- Use time structure of collisions!
- Different approaches
  - Include timing in tracking detect.
  - Dedicated timing detectors



Example – CLIC @ **3 TeV**: Experimental Conditions

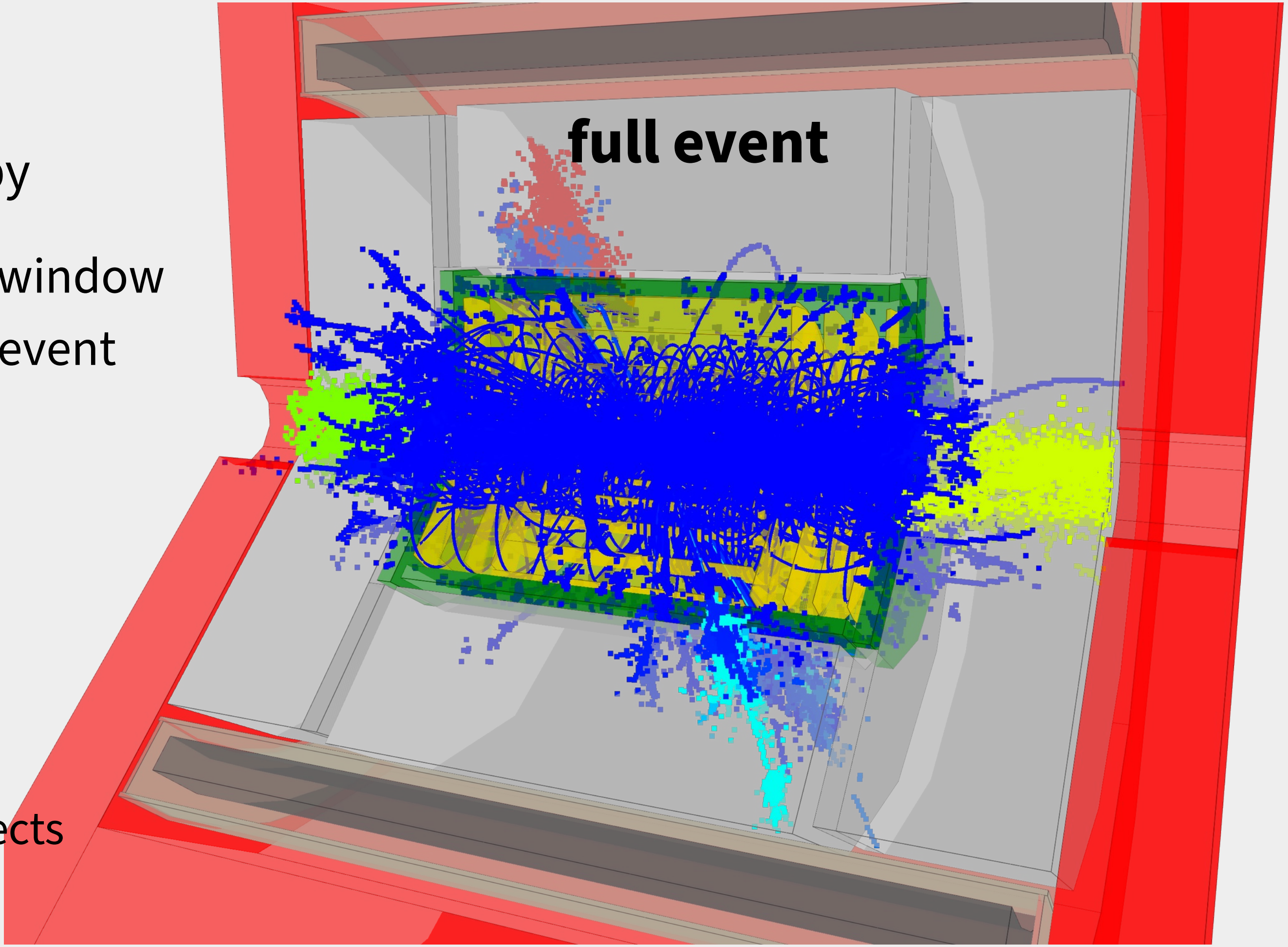
- CLIC operates in bunch trains, repetition rate of 50 Hz
  - 312 bunches within train
  - Bunch separation by 0.5 ns



- Bunch separation & cross-section of background events drive timing requirements for detector
  - 1 ns time resolution for calorimeters
  - 5 ns single-hit resolution for vertex/tracking detectors

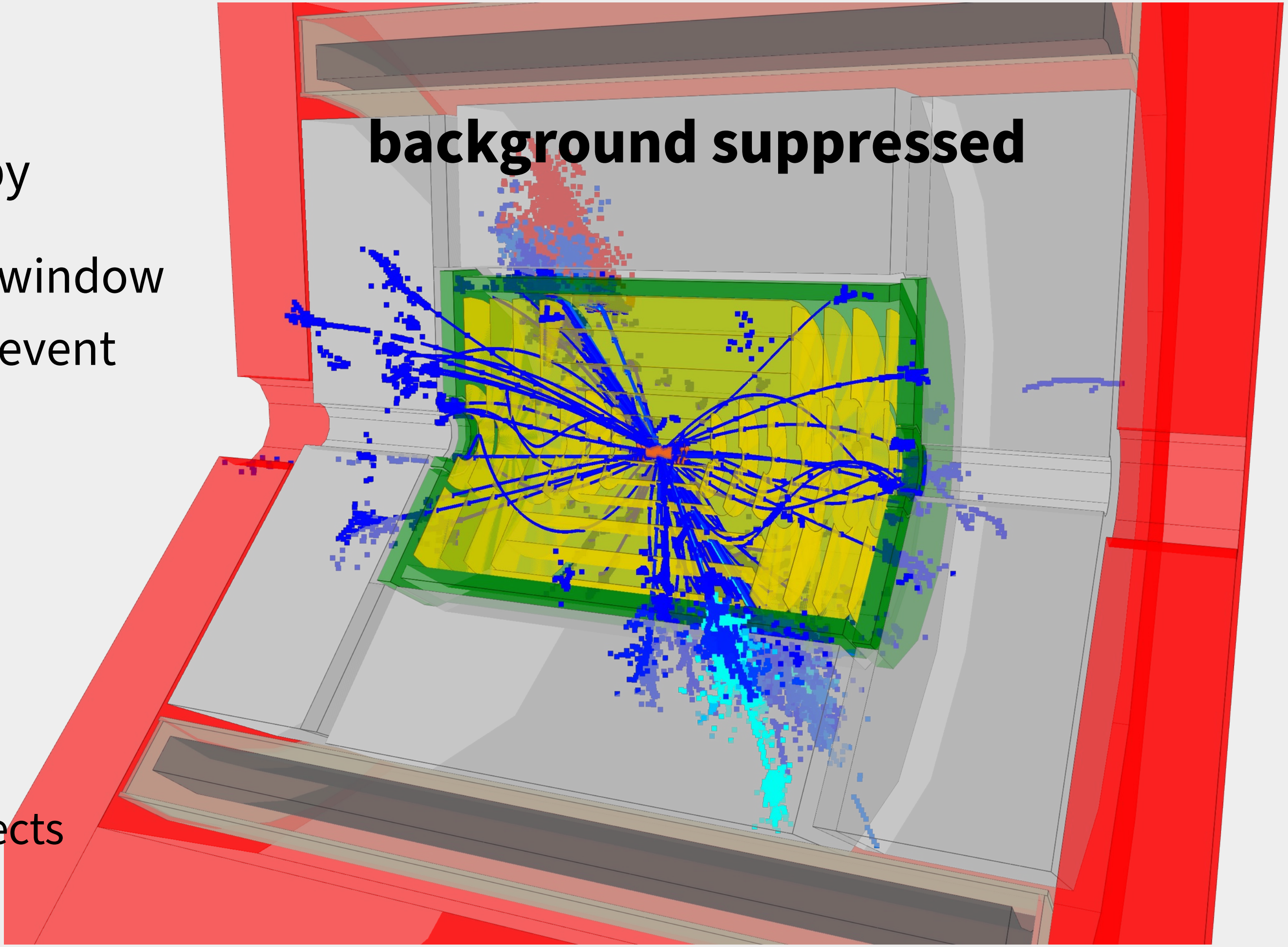
Example – CLIC @ **3 TeV**: Background suppression

- Fully-hadronic $t\bar{t}$ event
- Background suppression by
  - Defining reconstruction window 10 ns before, 30 ns after event
  - Building physics objects
  - Suppression via
    - Timing requirements
    - Particle type and p_T
    - Retaining high-p_T objects



Example – CLIC @ **3 TeV**: Background suppression

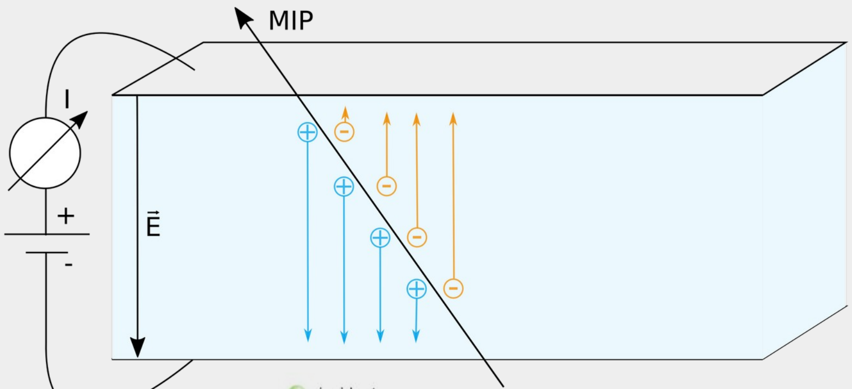
- Fully-hadronic $t\bar{t}$ event
- Background suppression by
  - Defining reconstruction window 10 ns before, 30 ns after event
  - Building physics objects
  - Suppression via
    - Timing requirements
    - Particle type and p_T
    - Retaining high-p_T objects

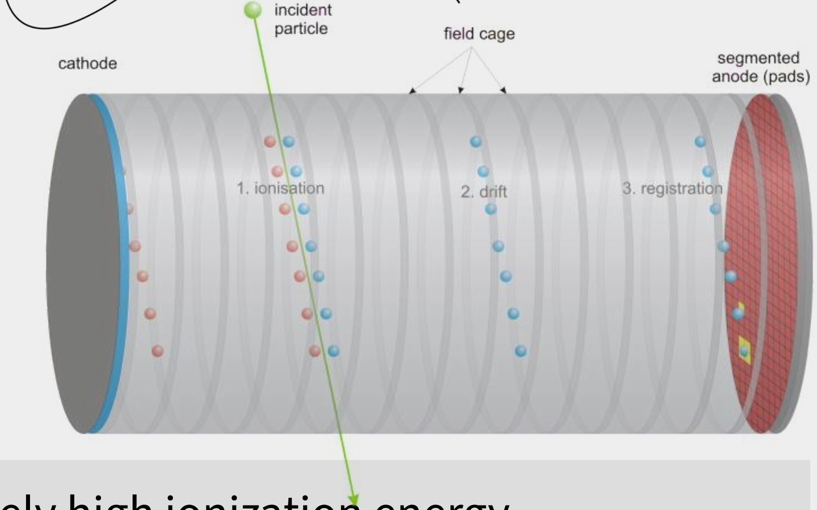


Very Short Recap

Gaseous Detectors vs. Semiconductor Detectors

Gaseous Detectors





Working principle

- Ions & electrons generated via ionization, ~ 30 eV ion. energy
- Electrons and ions drift in an electric field, current is induced by the drift of charge carriers
- Gas amplification for increase of signal

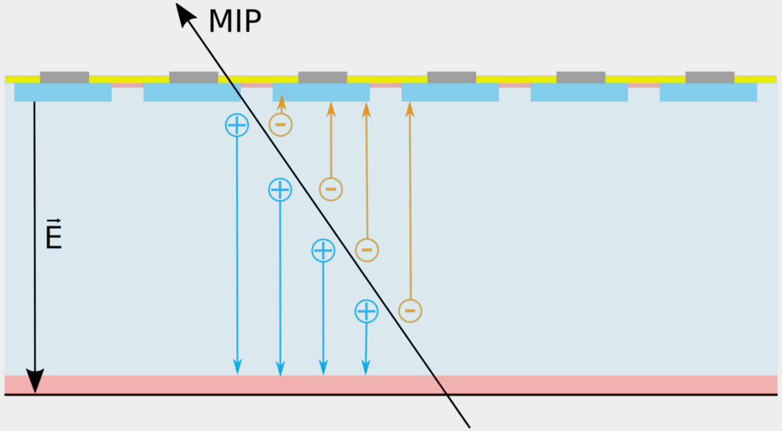
Types (selection)

- Multi-wire proportional chamber
- Micro pattern gas detectors (MicroMegas, *GEM*)
- Drift Chamber, Time Projection Chamber

➕ Very lightweight
Few issues with rad. damage
Large volume instrumentation

➖ Relatively high ionization energy
Limited rate capabilities
Mechanical fragility (for some types)

Semiconductor Detectors



- Oversimplified: ”Semiconductor ionization chamber”
  - Electron-hole pairs created from ionization energy, ~ few eV
  - Electrons/holes propagate in an electric field
  - Current is induced by drift of the charge carriers

! Technically very different from gaseous detectors!
→ Using established IC industry processes for production

➕ Low signal generation energy
Nano-scale structures via lithography
Capable of running in high fluxes

➖ Expensive for large area instrumentation
Solid material placed in particle path
Often complex module / detector setup

Short Recap

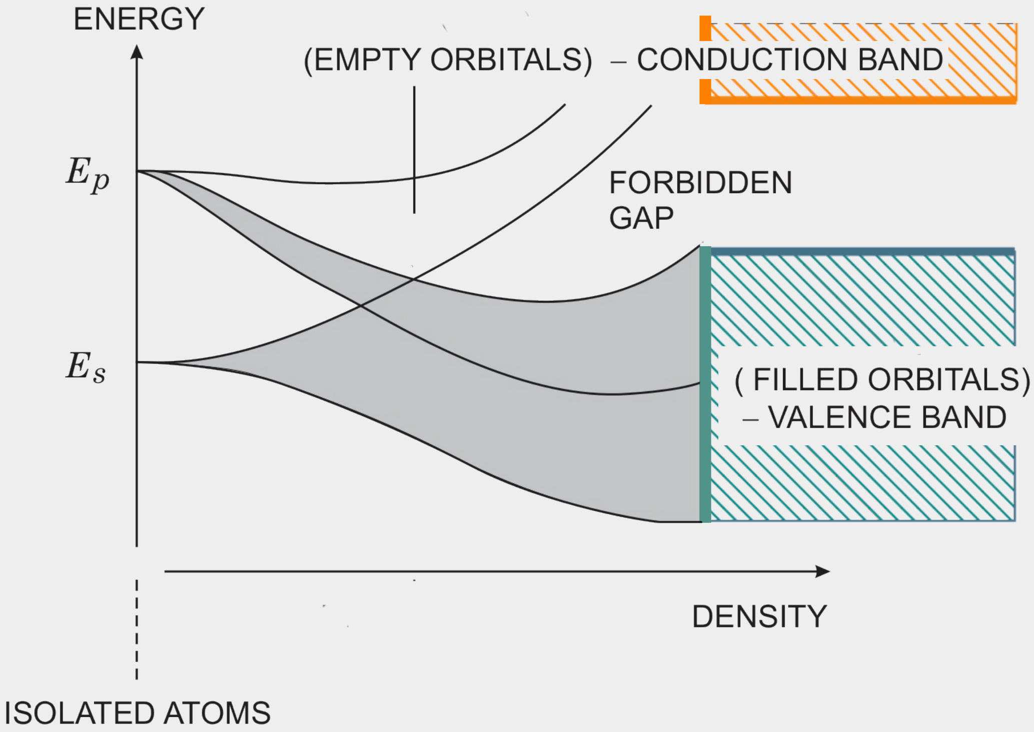
Semiconductors, Bandgap, Doping

The Energy Band Model

- Atom: discreet energy levels, orbitals
- Crystal lattice: levels smear out

- Formation of energy bands
    - Valence band – (last) fully filled
    - Band gap
    - Conduction band

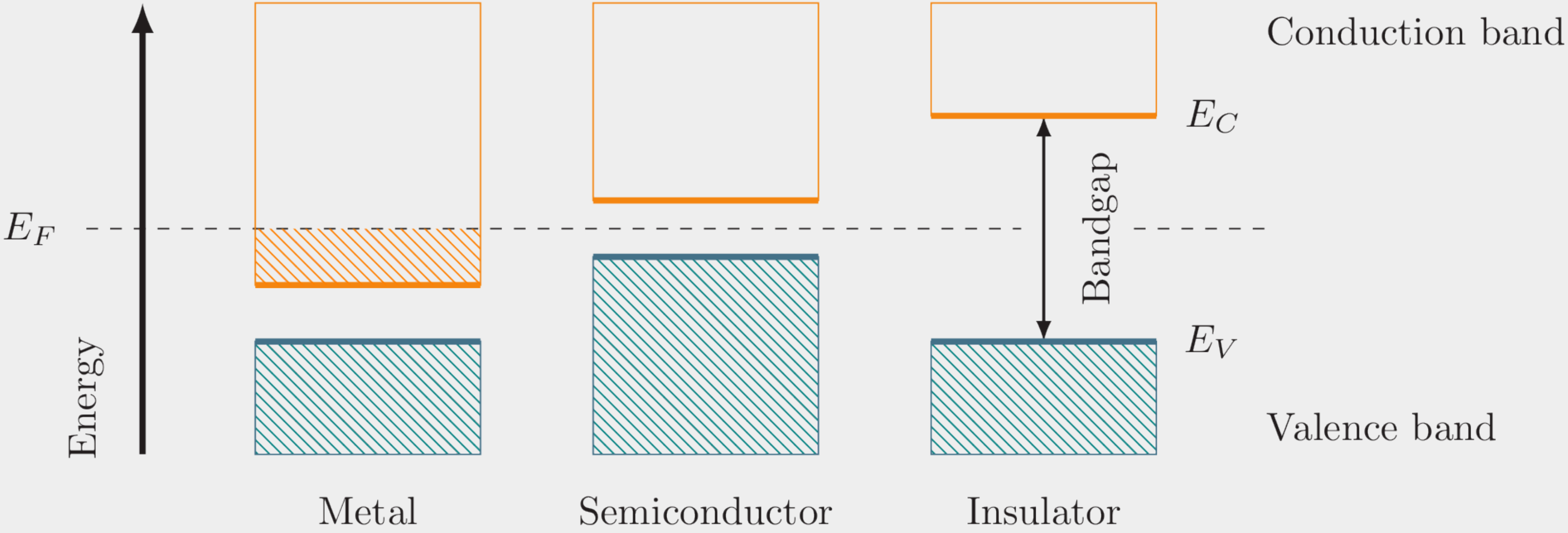
H. Spieler



Metals, Insulators, Semiconductors

bandgap silicon:

$E_G \approx 1.12$ eV (300K)

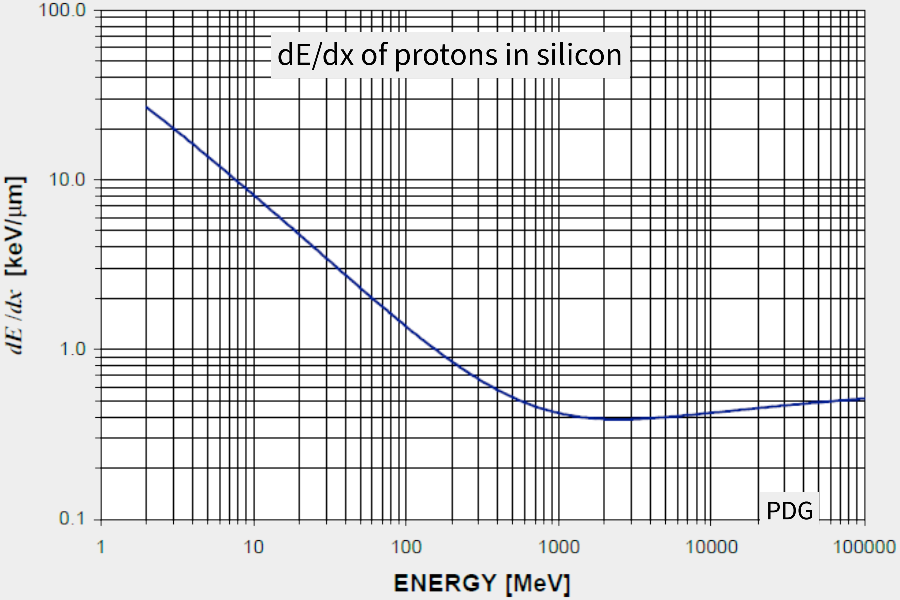


Detecting a Particle with Intrinsic Silicon

- Silicon sensor: *$A = 1\ cm^2$* and *$d = 300\ \mu m$*
- Signal of MIP:
  - Mean ionization: $E_0 = 3.6$ eV (silicon)
  - Mean energy loss: dE/dx = 3.9 MeV/cm

$$\frac{dE}{dx} \cdot \frac{d}{E_0} = 3.9 \cdot 10^6\, eV/cm \cdot 0.03\, cm / 3.6\, eV$$

$$\approx 3 \cdot 10^4\, e/h\ pairs$$

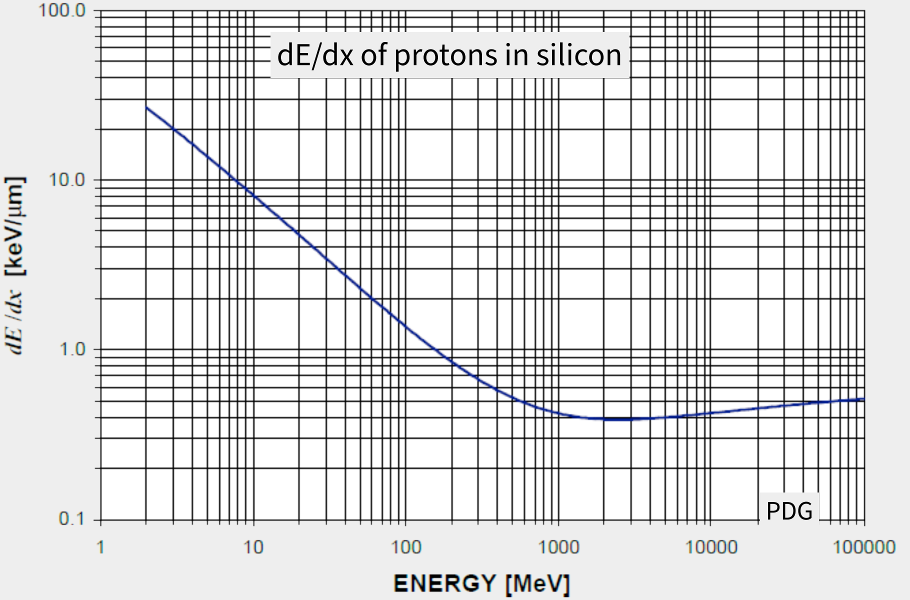


Detecting a Particle with Intrinsic Silicon

- Silicon sensor: $A = 1\ cm^2$ and $d = 300\ \mu m$
- Signal of MIP:
  - Mean ionization: $E_0 = 3.6$ eV (silicon)
  - Mean energy loss: dE/dx = 3.9 MeV/cm

$$\frac{dE}{dx} \cdot \frac{d}{E_0} = 3.9 \cdot 10^6\, eV/cm \cdot 0.03\, cm / 3.6\, eV$$

$$\approx 3 \cdot 10^4\, e/h\ pairs$$



- Thermally excited charge carriers in silicon: $n_i = 1.45 \times 10^{10}\ cm^{-3}$ (at 300K)

$$n_i \cdot d \cdot A = 1.45 \cdot 10^{10}\, cm^{-3} \cdot 0.03\, cm \cdot 1\, cm^2$$

$$\approx 4 \cdot 10^8\, e/h\ pairs$$

density silicon:

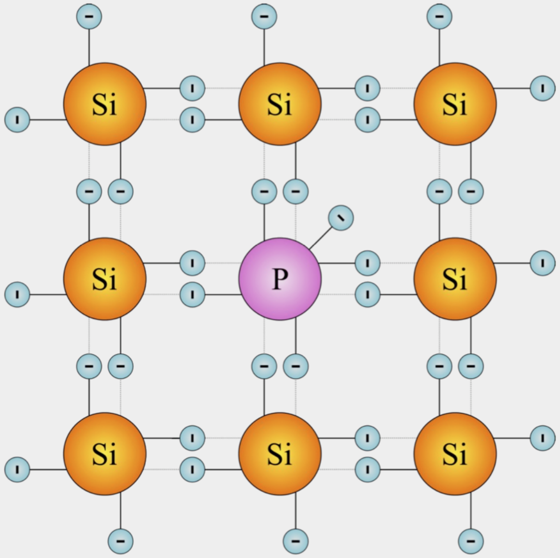
$N \approx 10^{22}$ atoms/cm^3

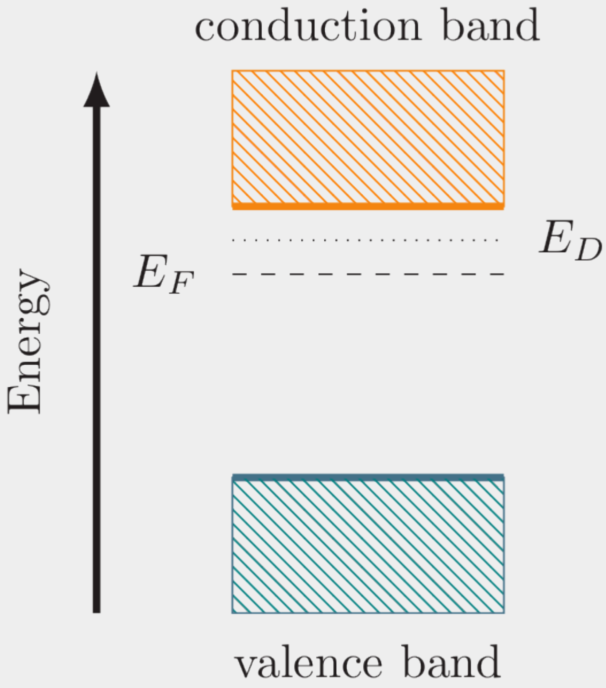
Doping Silicon – *n*-type

typical doping (p-in-n sensor):

$N_D \approx 10^{12}\ \mathrm{cm}^{-3}$

- Adding group-V element (phosphorus)
- Four covalent bonds, one “dangling” e
- Introduces “donor” state
- Negative majority charge carrier: “*n*”



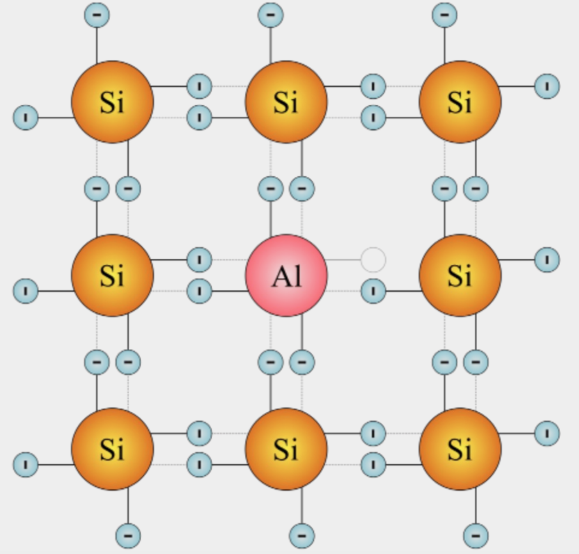


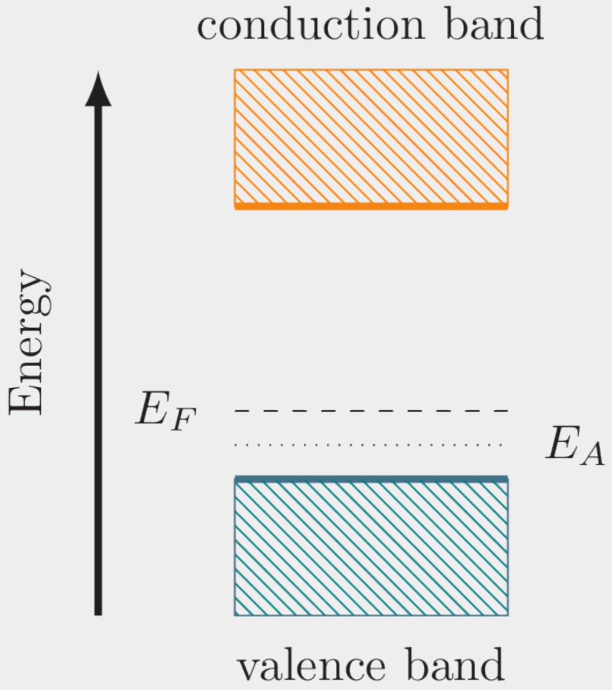
Doping Silicon – *p*-type

typical doping (p-in-n sensor):

$N_A \approx 10^{15}$ cm^{-3}

- Adding group-III element (boron, aluminum)
- Vacancy in covalent bonds – “hole”
- Introduces “acceptor” state
- Positive majority charge carrier: “*p*”

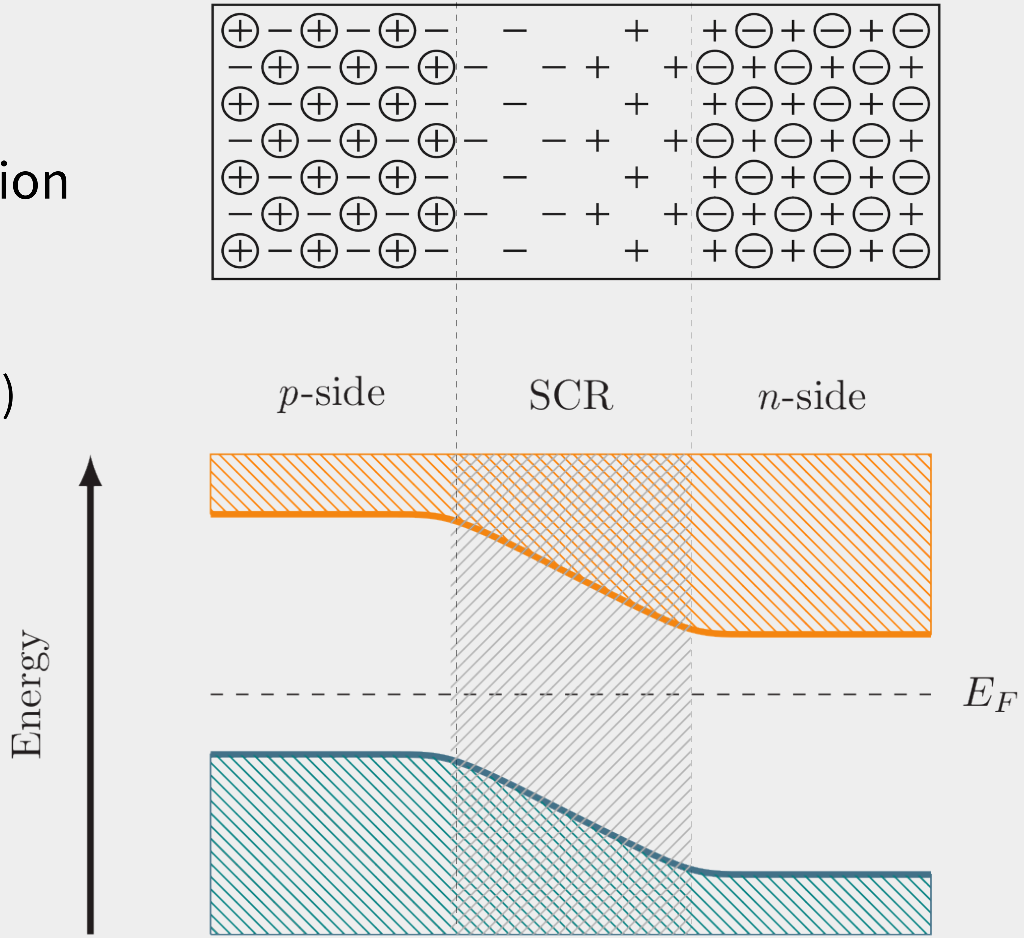




Forming a *pn*-Junction

- Electrons and holes diffuse over junction
- Donor/acceptor atoms remain
  - Depleted / space charge region (SCR)
  - Potential U_{bi} builds up
- Thermal equilibrium:
  Built-in potential balances diffusion
- Constant Fermi level:
  Deformation of energy bands

H. Spieler



Built-in Voltage U_{bi}

silicon p-in-n sensor:

$N_A \approx 10^{15}\ cm^{-3}$

$N_D \approx 10^{12}\ cm^{-3}$

$k_B T \approx 0.026\ V$

$n_i = 1.45 \times 10^{10}\ cm^{-3}$

- Potential across the junction: difference of Fermi energies

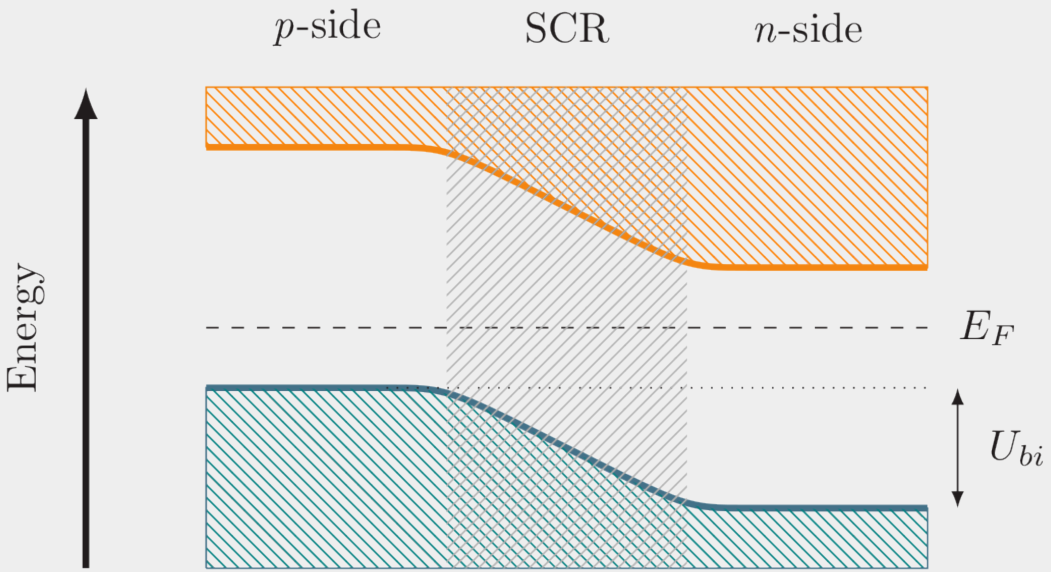
p-in-n sensor: $U_{bi} \approx 0.4\ V$

$$\begin{aligned} U_{bi} &= E_{Fn} - E_{Fp} \\ &= k_B T \ln\left(\frac{N_A N_D}{n_i^2}\right) \end{aligned}$$

- Thickness of built-in SCR:

$$d(U_{bi}) = \sqrt{\frac{2\,\epsilon_r\,\epsilon_0}{|N_D - N_A|} \cdot U_{bi}}$$

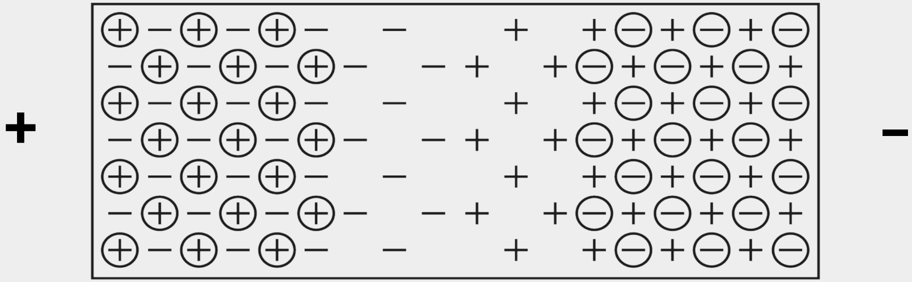
p-in-n sensor: $d \approx 20\ \mu m$

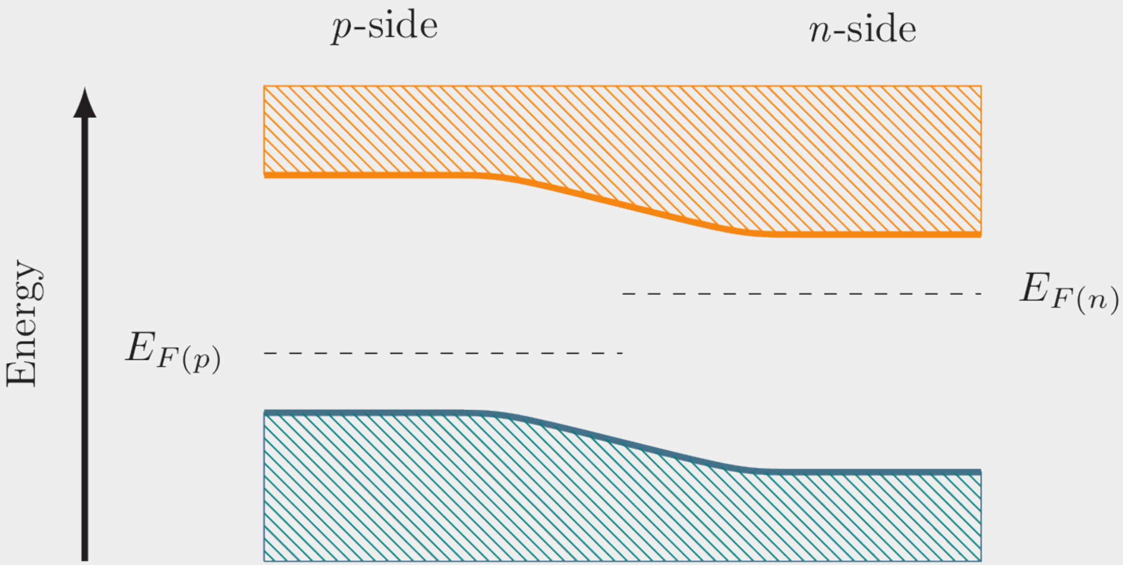


pn-Junction in Forward Bias

H. Spieler

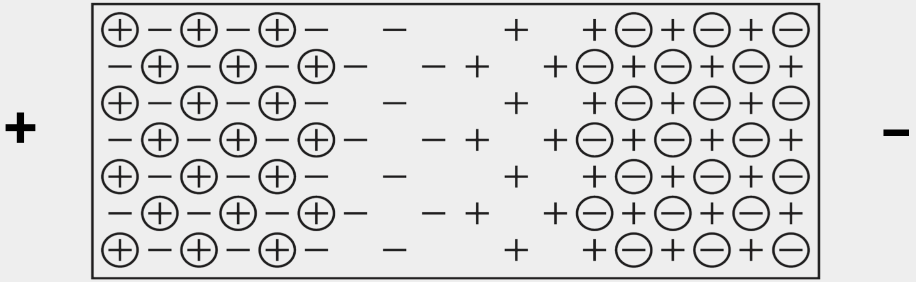
- Lowering potential difference
- Increases flow of electrons & holes



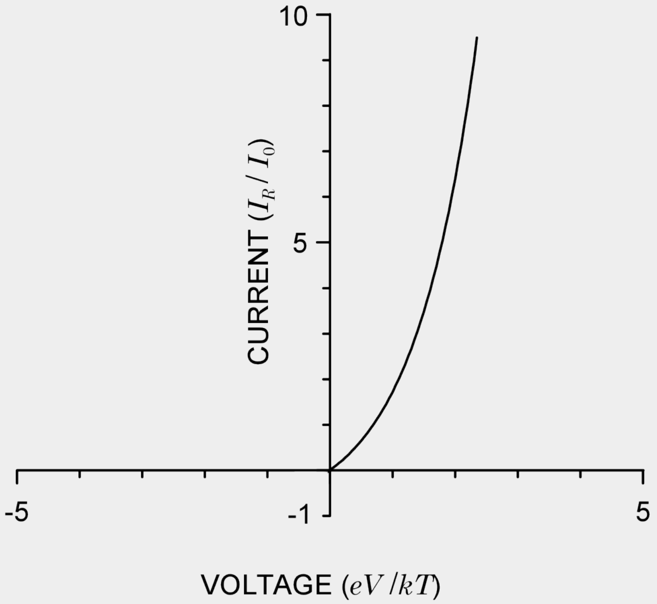


pn-Junction in Forward Bias

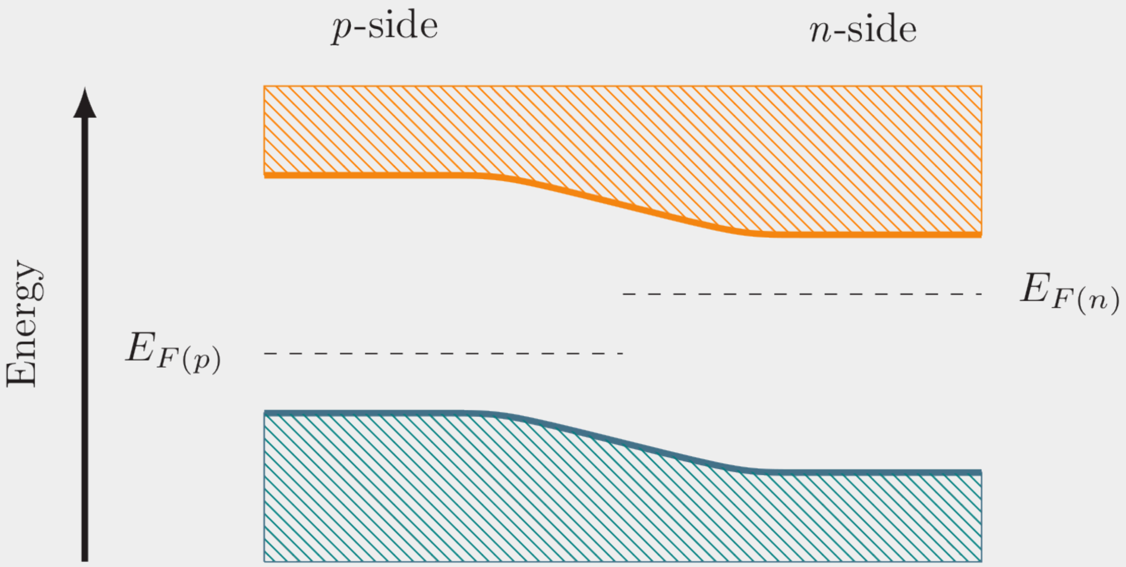
H. Spieler



- Lowering potential difference
- Increases flow of electrons & holes
- Shockley eq. $I = I_0\left(e^{eU/k_B T} - 1\right)$

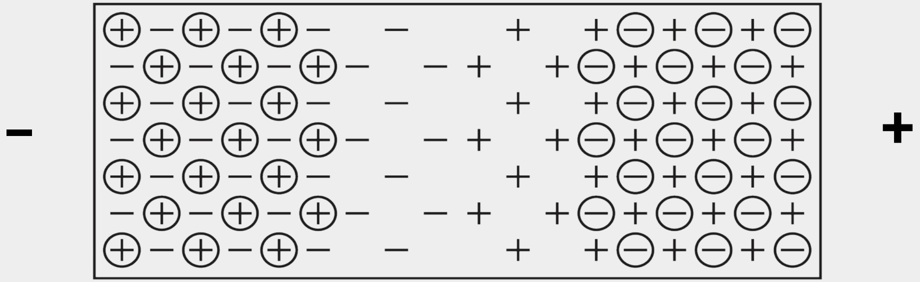


H. Spieler

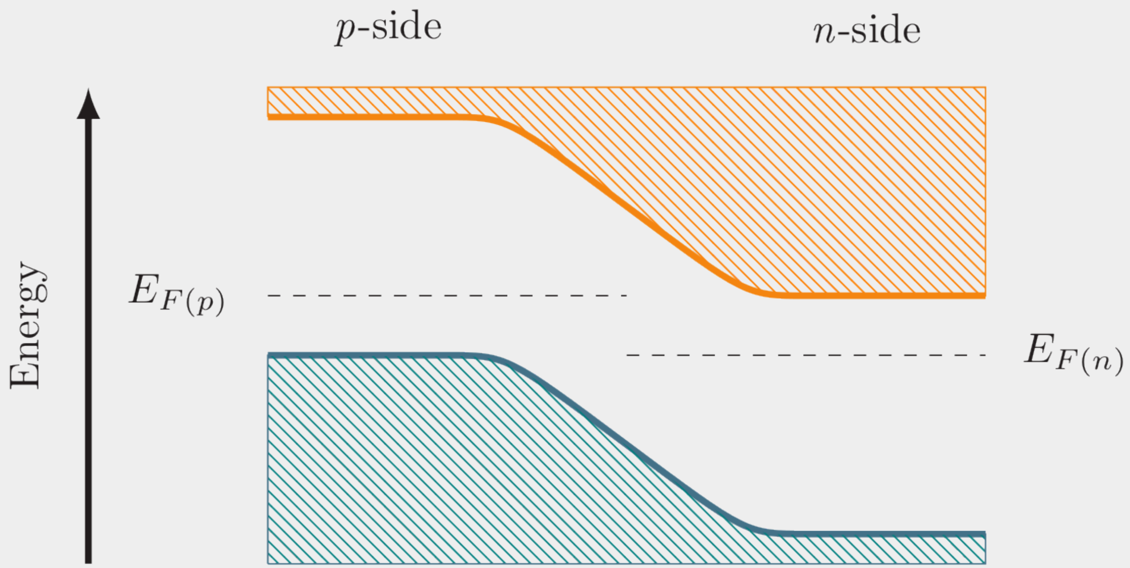


pn-Junction in Reverse Bias

- Raising potential difference
- Widens depletion region

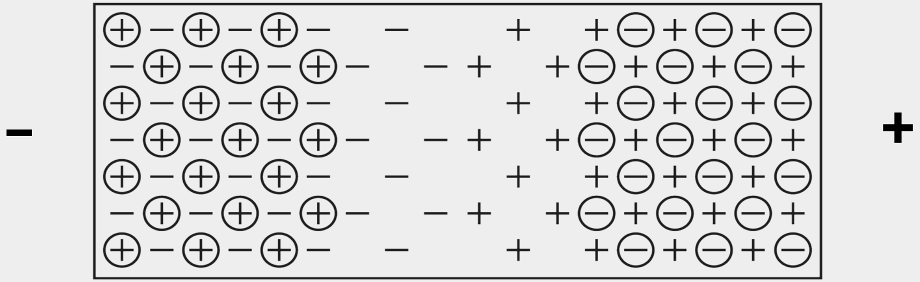


H. Spieler

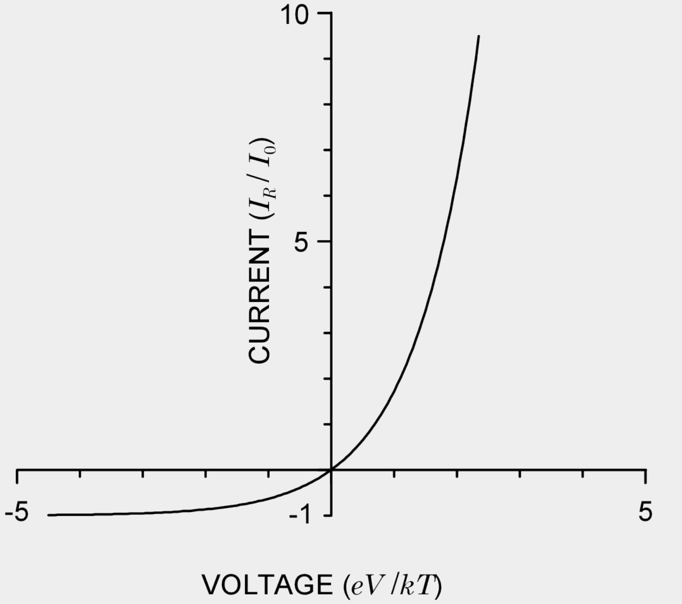


pn-Junction in Reverse Bias

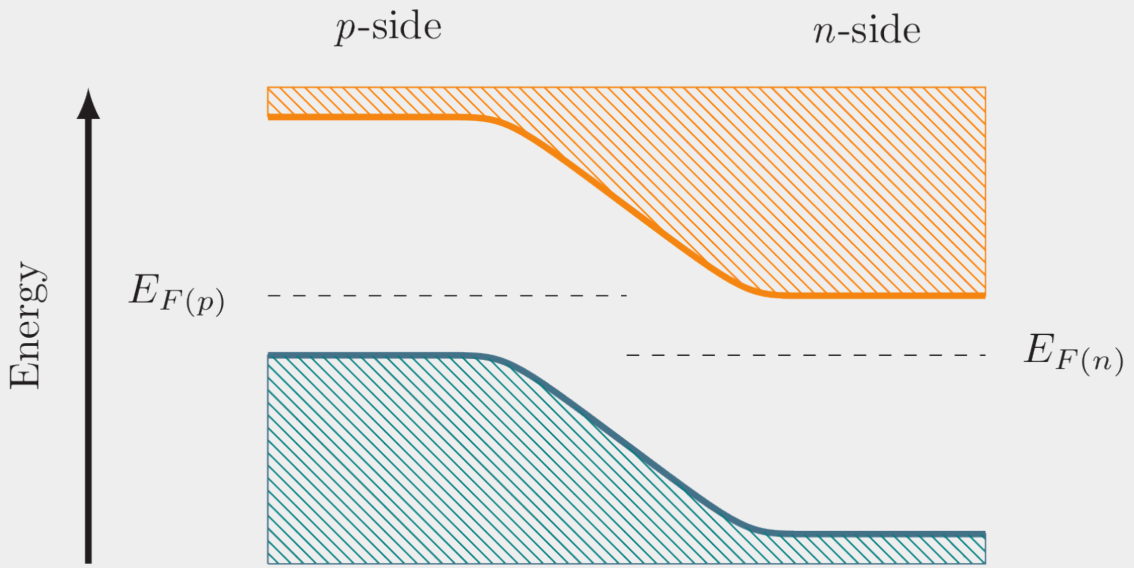
H. Spieler



- Raising potential difference
- Widens depletion region
- Shockley eq. $I = I_0\left(e^{eU/k_B T} - 1\right)$



H. Spieler



pn-Junction in a Sensor

typical doping (p-in-n sensor):

$N_A \approx 10^{15}$ cm^{-3}

$N_D \approx 10^{12}$ cm^{-3}

- Asymmetric pn-junctions, here: *p*-in-*n*
- Lightly doped *n* bulk sensor material
- Thin, highly-doped *p* implant
- Depletion voltage:

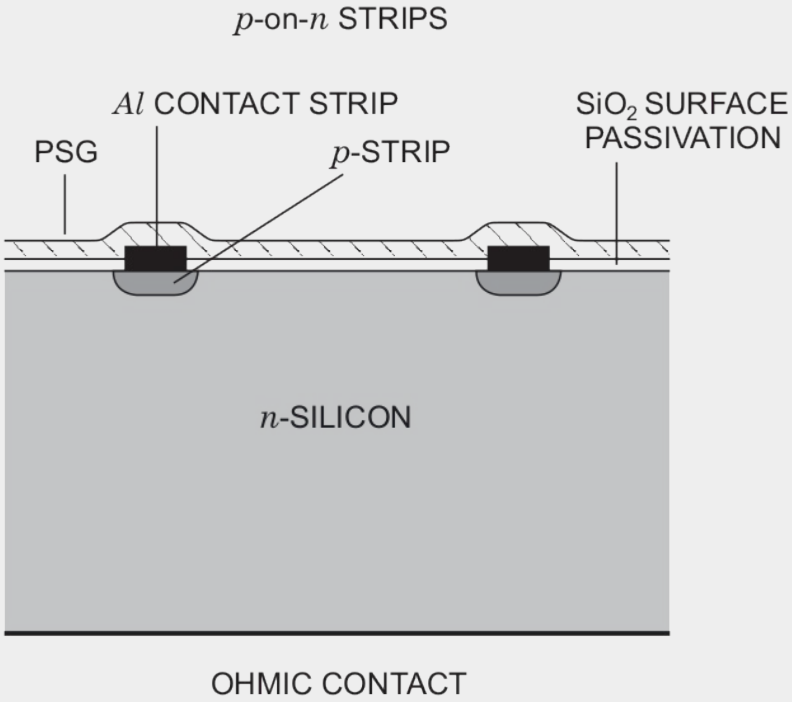
$$V_d = \frac{Ned^2}{2\epsilon_r\epsilon_0}$$

$$\mathrm{e} = 1.6 \times 10^{-19}\ \mathrm{As}$$

$$\epsilon_0 = 8.8 \times 10^{-12}\ \mathrm{As/V/m}$$

$$\epsilon_r(\mathrm{Si}) = 11.7$$

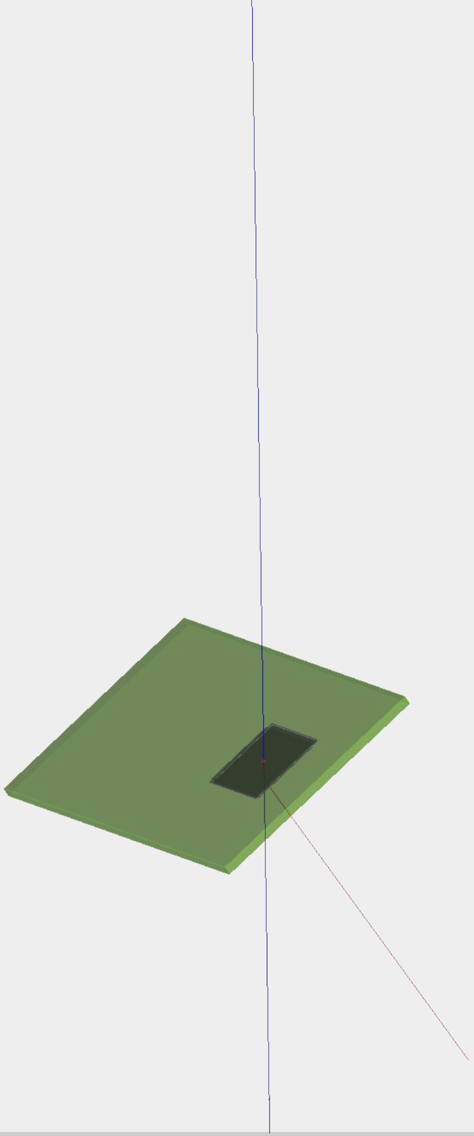
- Segmentation of implant: separate channels
- Backside: layer of highly doped *n^+* as ohmic contact



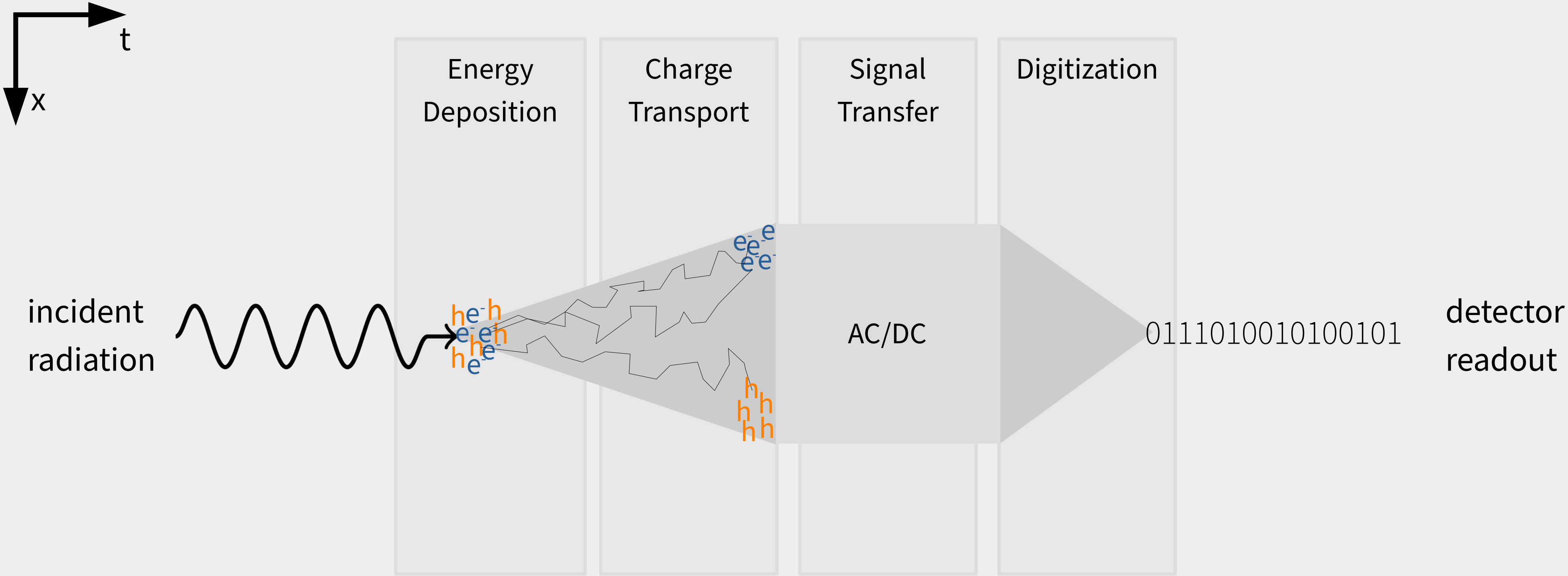
H. Spieler

Particle Detection

With Semiconductor Detectors



Particle Detection with Semiconductor Detectors



Energy Deposition – Energy Loss

- (heavy) charged particles:

  Mean energy loss described by **Bethe** formula

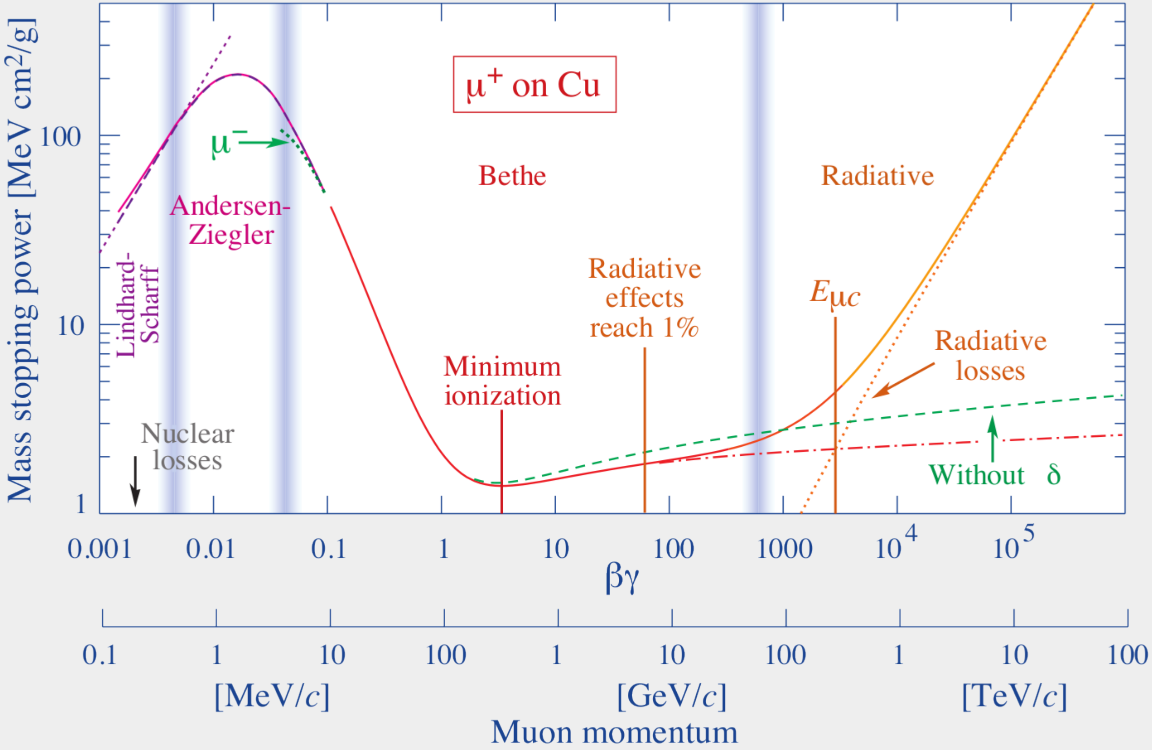
  (sparing you the formula…)

- Definition of MIP:

  Minimum Ionizing Particle

  $\beta\gamma \approx 3$

Phys. Rev. D 98, 030001
doi:10.1103/PhysRevD.98.030001

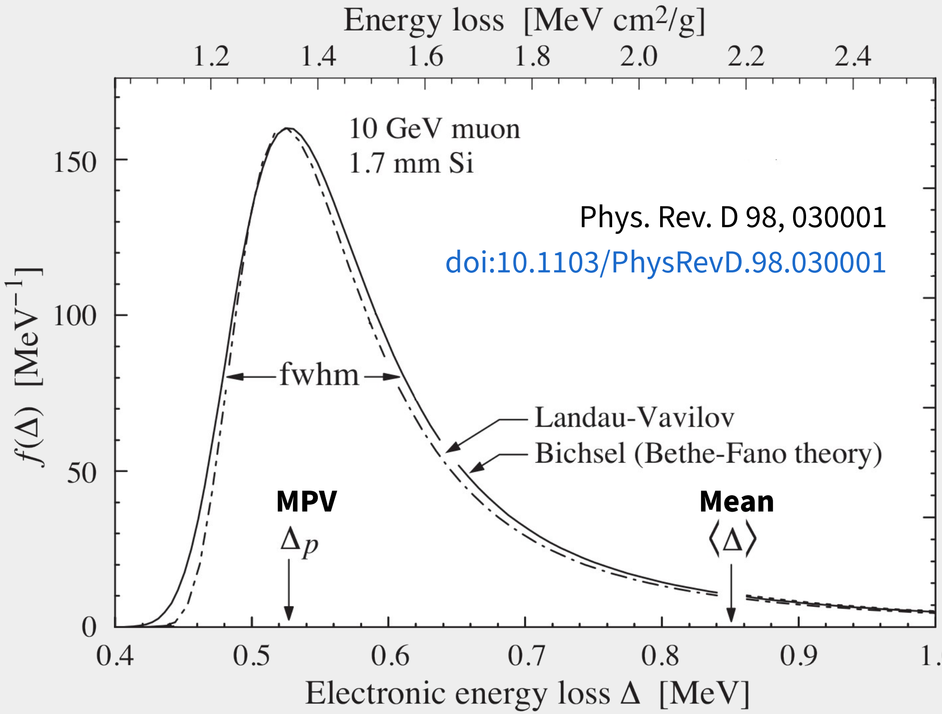


Energy Deposition – Fluctuations

- Strong fluctuations of energy loss: **Landau-Vavilov** distribution / **Bichsel** model
  - Varying number interactions, energy transfer
  - Secondary particles (e.g. delta rays)
  - Most probable value (MPV) < Mean

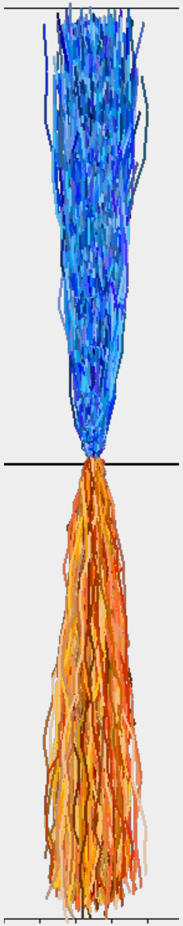
- Photons: Photo effect, Compton effect, pair production

- Creation of e/h pairs: 3.64 eV / pair
  Fluctuations: **Fano** Factor $\sigma_{e/h} = \sqrt{N_{e/h}}\sqrt{F}$



Phys. Rev. D 98, 030001
doi:10.1103/PhysRevD.98.030001

Signal Formation



- Sensor operated as diode in reverse bias → depleted volume
- Signal formed by motion of e/h pairs in electric field

- Contribution to motion:
  - **Diffusion – Temperature-driven random motion**, mean free path ~ 0.1 µm, mean 0
  - **Drift – Directed motion**, depending on electric field and charge carrier mobility, different parametrizations for mobility available, depending on temperature, silicon, …

- Motion stops when…
  - Charge carriers reach readout electrode (conductor)
  - Charge carriers recombine/get trapped (depends on purity, doping, lattice defects, …)

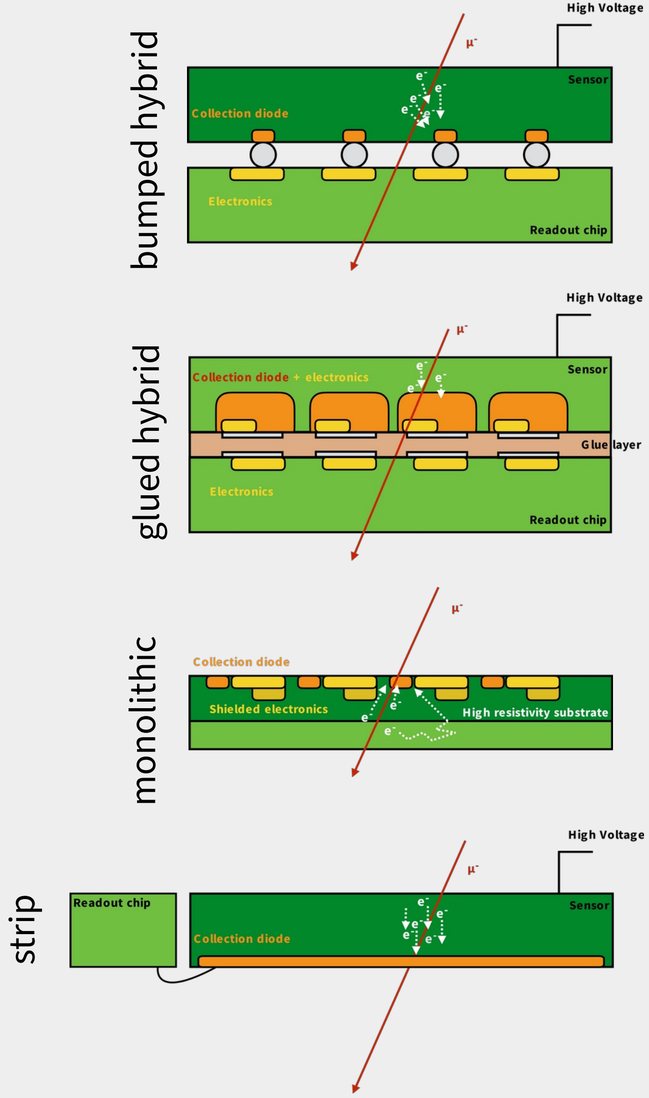
Signal Transfer

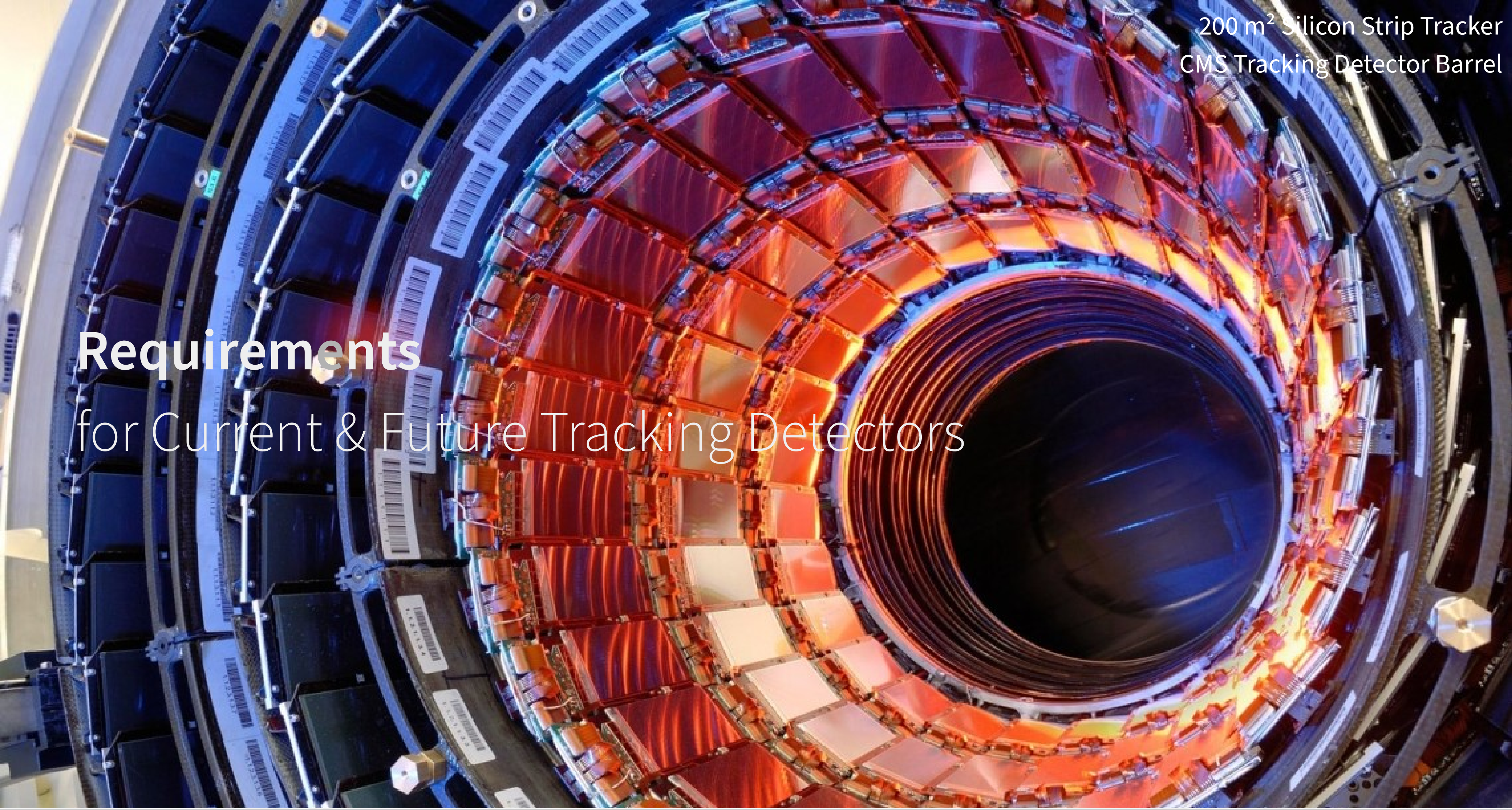
Coupling between sensor & front-end can be

- DC: bump bonds (hybrid pixel), direct (monolithic pixel), …
- AC: glue layers (hybrid pixel), SiO_2 (strip detectors), …

Digitization

- Signal is amplified, shaped, zero-suppression (discriminator)
- Digitization of the signal via
  - Full ADC
  - Time-over -threshold
  - Threshold crossing (binary hit information)
- Buffering, encoding, data transmission...





200 m^2 Silicon Strip Tracker
CMS Tracking Detector Barrel

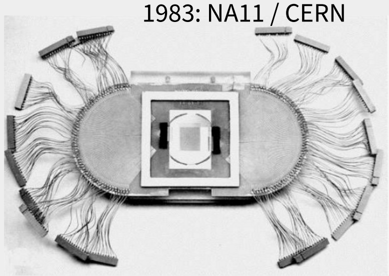
Requirements

for Current & Future Tracking Detectors

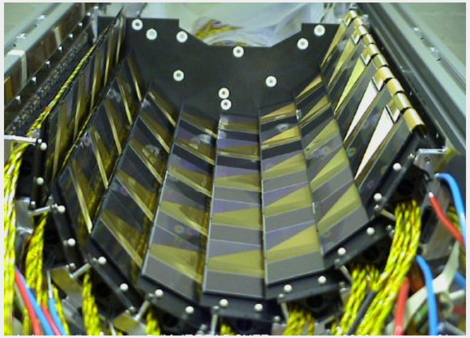
Silicon Tracking Detectors in Particle Physics

- Silicon tracking detectors have long history in particle physics
- Instrumental in discovery of Higgs boson at LHC
- Larges detectors installed in ATLAS & CMS
  - Tracking detectors: strips, 200 m^2 silicon, 70M channels
  - Vertex detectors: pixels, 1 m^2 silicon, 140M channels
- Detector upgrades for HL-LHC in preparation
  - More resilient against radiation-induced damage
  - Additional capabilities (e.g. triggering)

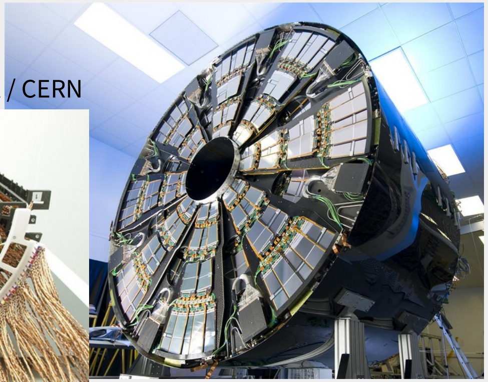
1983: NA11 / CERN



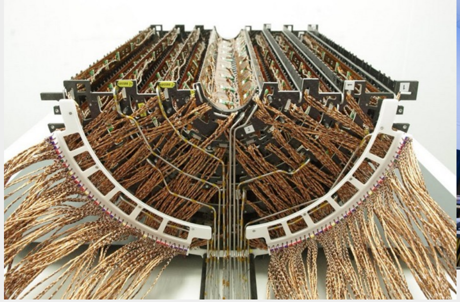
2000: ZEUS MVD / DESY



2007: CMS Tracker / CERN



2017: CMS Phase 1 Pixel / CERN

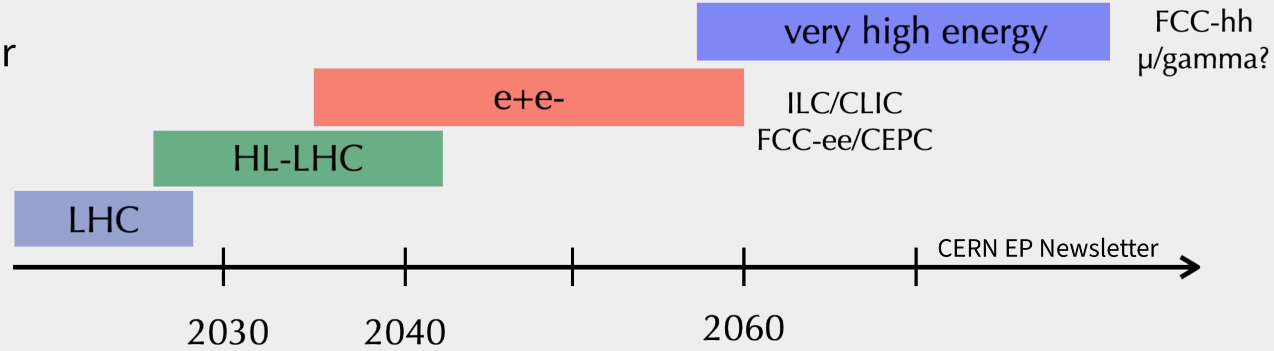


The Future of Particle Physics

- European Strategy Update: possible directions for particle physics
  - Importance of fundamental detector R&D specifically highlighted

- Higgs boson plays unique role in extending knowledge
  - Address questions within SM, provide sensitivity to new physics
  - Yukawa couplings, self-couplings, branching ratios
  - Precision measurements required

- Highest priority: future lepton collider
  - Different initial states
  - New opportunities
    & challenges



CERN EP Newsletter

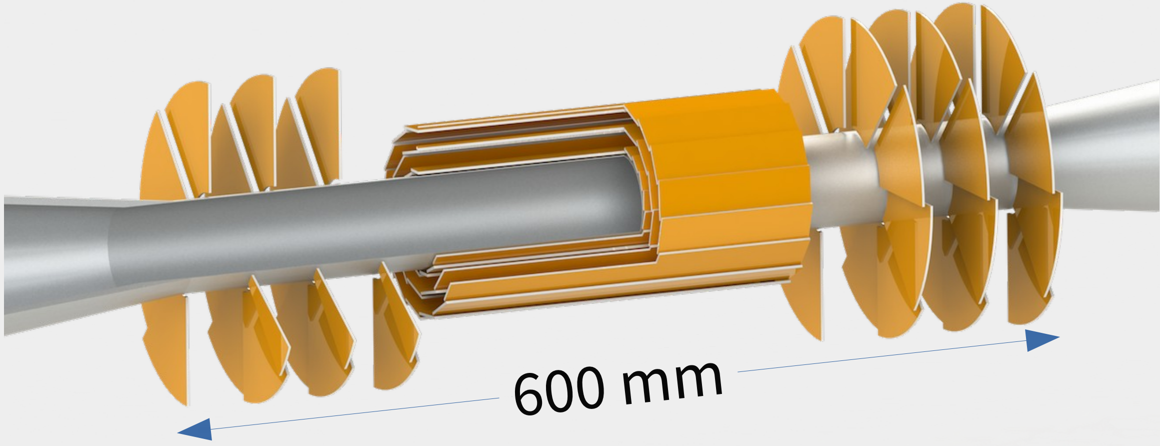
Silicon Detector Requirements at a Lepton Collider

- Precision measurements especially demanding on vertex & tracking detectors
  - Momentum resolution – large lever arm, minimum scattering
  - Impact parameter resolution – high resolution, minimum scattering
  - Time resolution – fast sensor response, large S/N

- Physics studies for lepton colliders provide guidelines:

	Lepton Colliders	**(HL-) LHC (ATLAS/CMS)**
Material budget	< 1% X_0	10% X_0
Single-point resolution	≤ 3 μm	~ 15μm
Time resolution	~ ps – ns	25ns
Granularity	≤ 25 μm x 25 μm	50μm x 50μm
Radiation tolerance	< 10^{11} n_{eq} / cm^2	**O(10^{16} n_{eq} / cm^2)**

CLICdet Vertex Detector



Design driven by flavor tagging

- Minimal scattering
- High-resolution

Requirements

- **Low mass**
  0.2% X_0 per layer
- **Low power consumption**
  < 50 mW/cm^{-2} for air-flow cooling
- **High single-point resolution**
  σ_{SP} ~ 3 µm
- **Precise time stamping** ~ 5 ns

Current design:

- Double layer sensors
- 100 µm of silicon, 25 µm pixel pitch
- Surface area of ~ 1 m^2
- Three barrel double-layers,
  2x three spiral double-disks

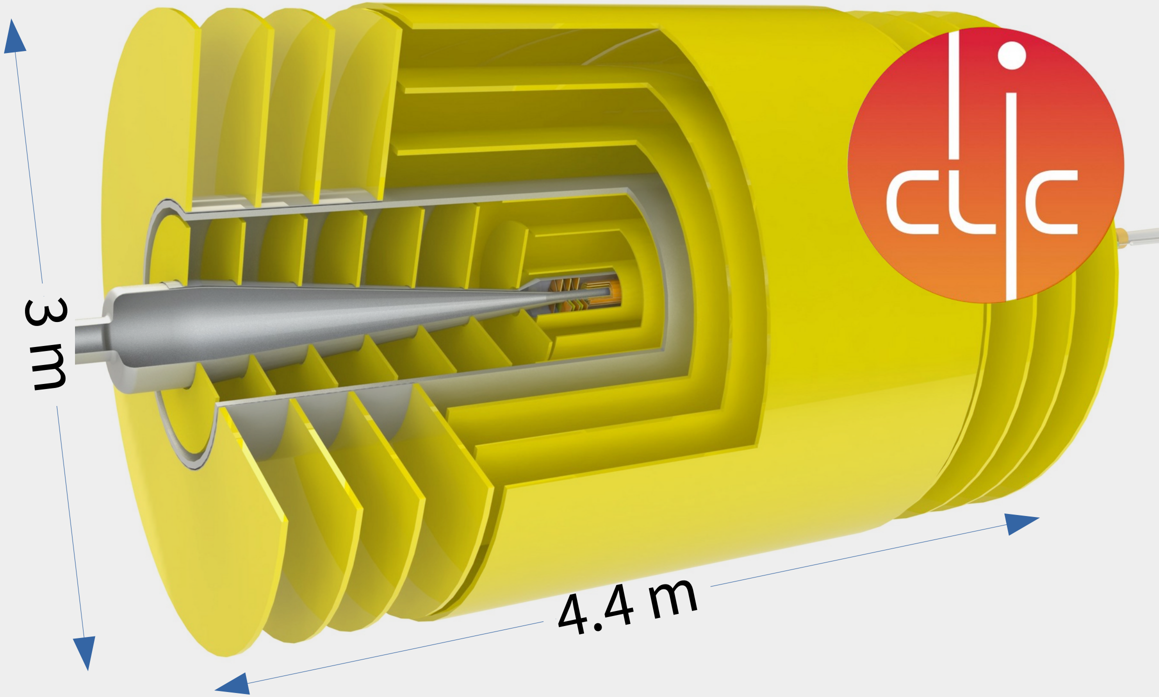
CLICdet Tracking Detector

Design driven by
efficiency & momentum resolution

- Many layers, large lever arm

Requirements

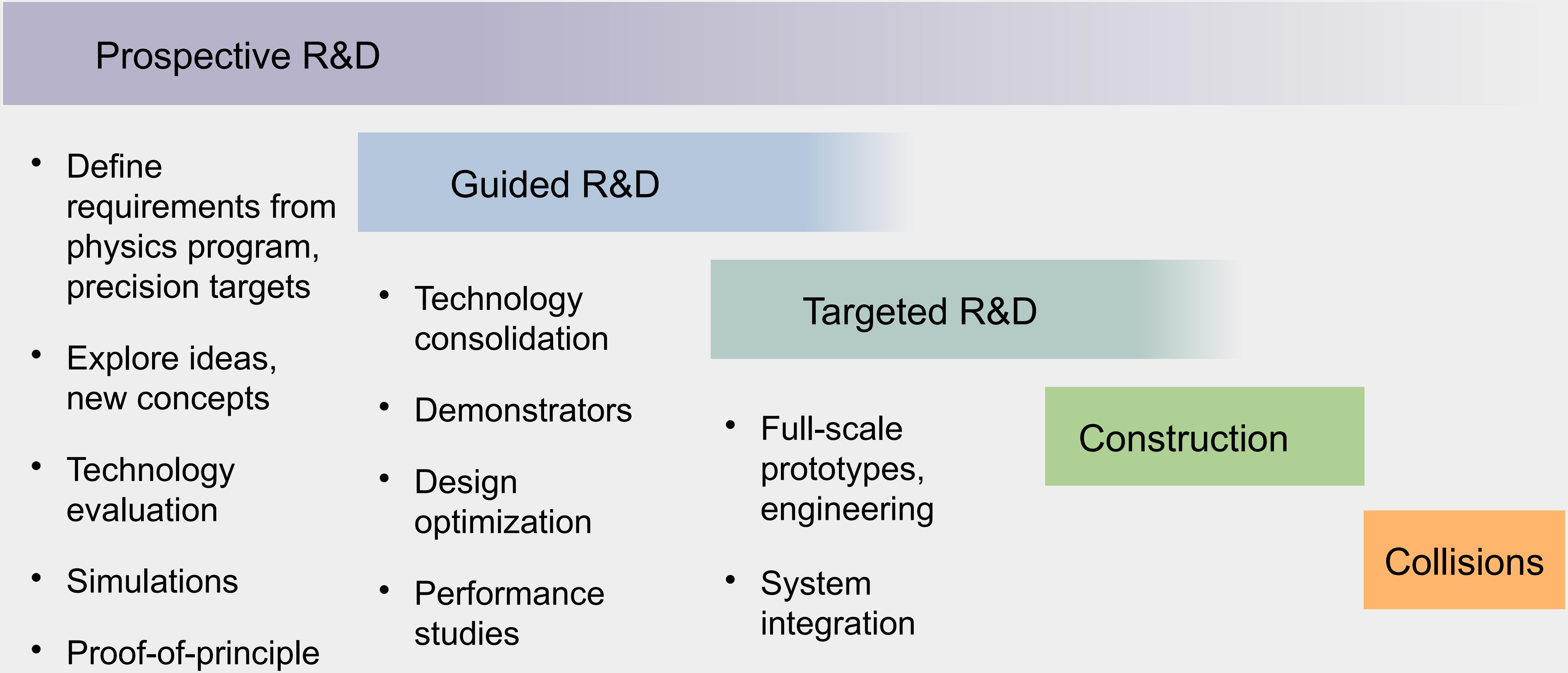
- **Low mass, high rigidity**
  1 – 2% X_0 per layer
- **Good single-point resolution**
  σ_{SP} ~ 7 µm (transverse plane)
- **High granularity**
  few % occupancy from backgrounds
- **Precise time stamping** ~ 5 ns



Current design:

- Detector with (elongated) pixels
- Max. 200 µm sensor, including electronics
- Surface area of approx. 140 m^2
- Leakless water cooling

Towards Next-Generation Tracking Detectors



Prospective R&D

- Define requirements from physics program, precision targets
- Explore ideas, new concepts
- Technology evaluation
- Simulations
- Proof-of-principle

Guided R&D

- Technology consolidation
- Demonstrators
- Design optimization
- Performance studies

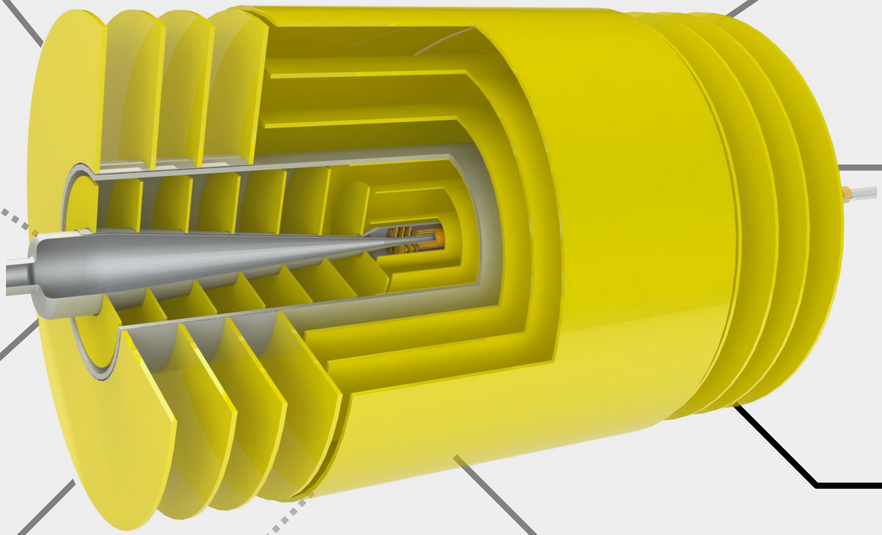
Targeted R&D

- Full-scale prototypes, engineering
- System integration

Construction

Collisions

Next-Generation Vertex & Tracking Detectors



CLICdp

Powering

Machine interface

Cooling

Front-end electronics

Magnet

Mechanical support

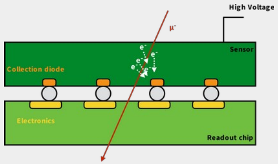
Data transmission

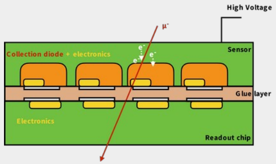
Sensors

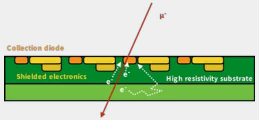
Module design

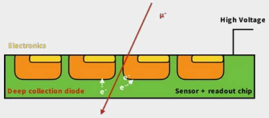
(Some) Sensor Technologies

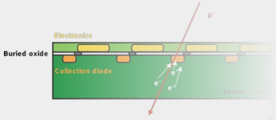
for Future Tracking Detectors







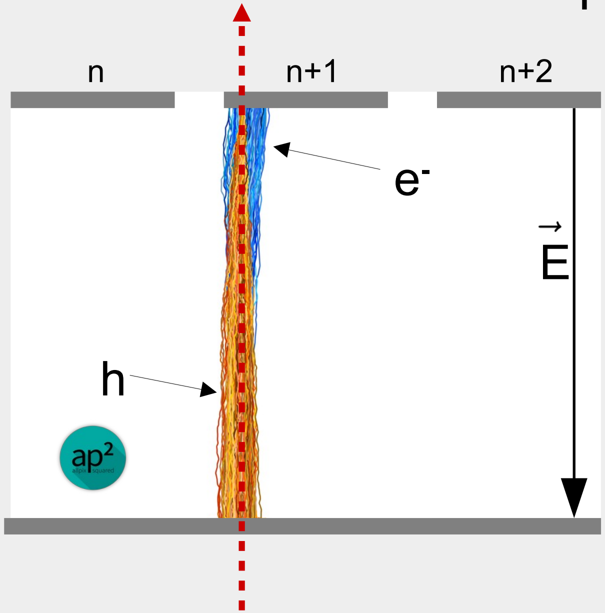


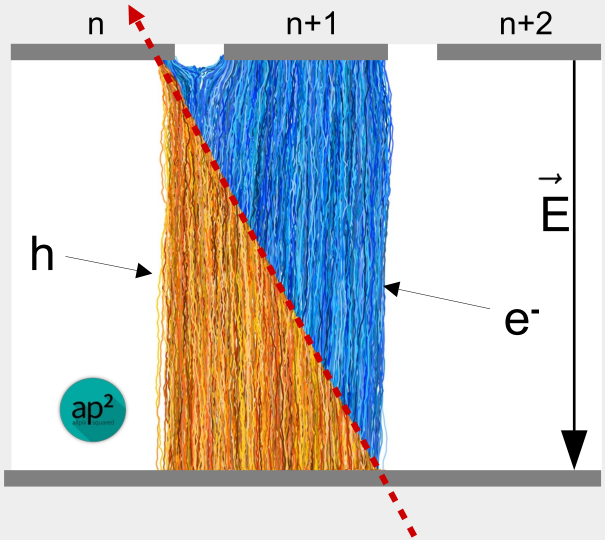


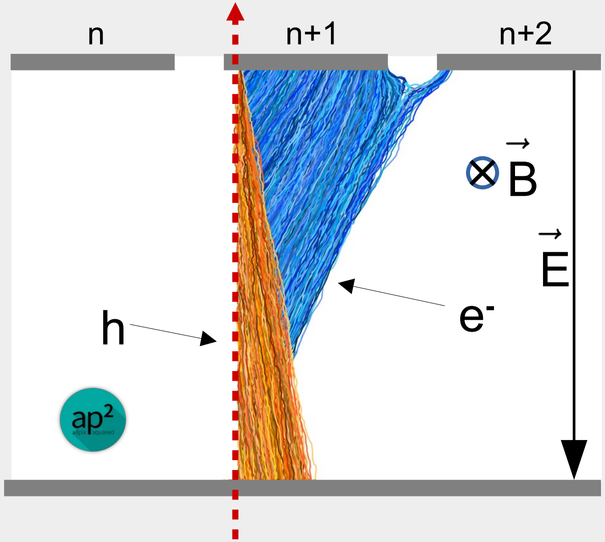
• • •

Charge Sharing – Inclined Tracks & Lorentz Drift

- Charge sharing: distribution of charge carriers / signal over several strips (pixels)
- Can significantly improve the spatial resolution
- Often used: Inclined particle incidence along x & Lorentz drift along y







Position Resolution

- Precision of particle incidence prediction

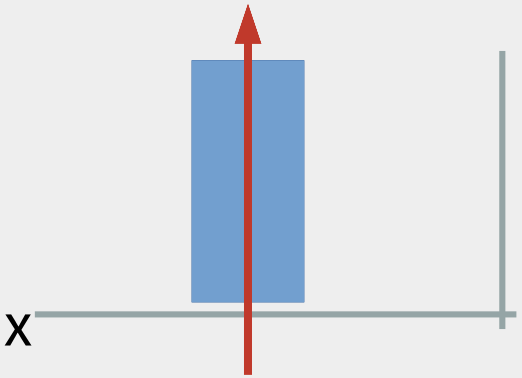
  Just a single pixel struck:
  precision limited to variance of uniform distribution

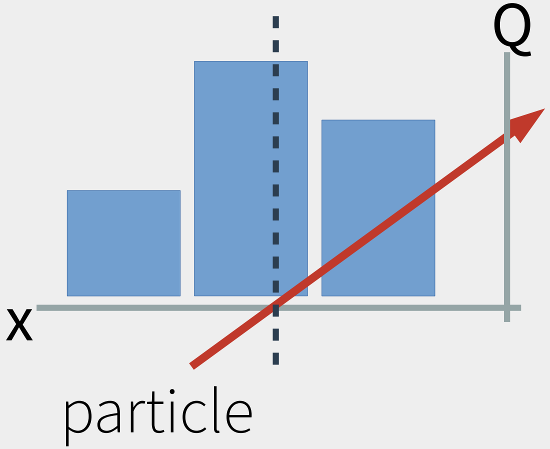
$$\sigma = p/\sqrt{12}$$

- Multiple pixel struck (charge sharing):
  interpolation using relative energy / charge distribution

$$\sigma = \frac{\sum_i Q_i x_i}{\sum_j Q_j}$$

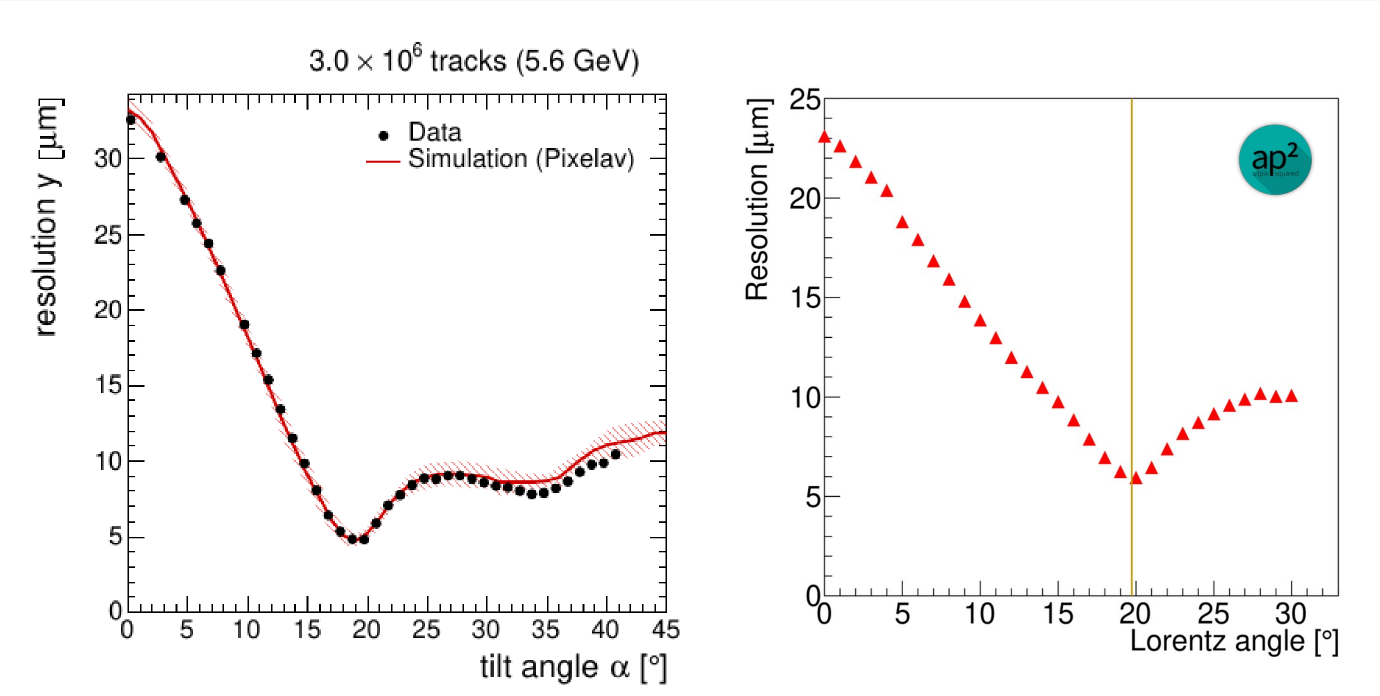
- Thinner sensors: less charge sharing…





Position Resolution

- Charge sharing improves resolution in case of per-pixel charge information
- Similar effects from incidence angle and Lorentz drift

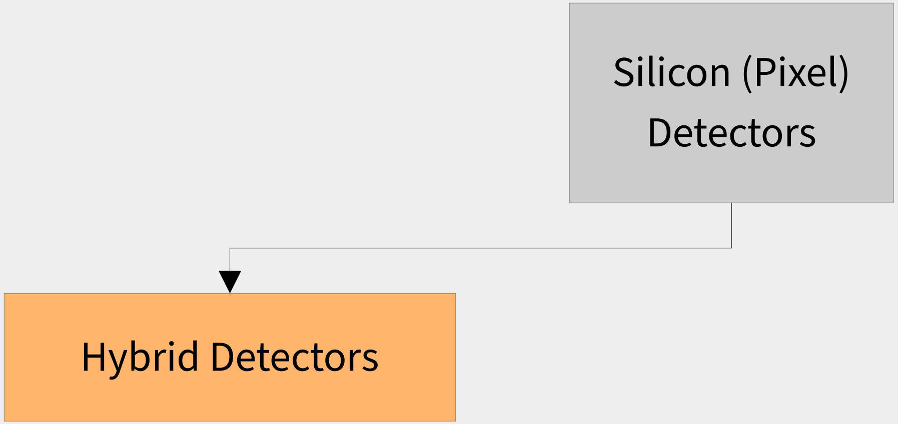


- Typical pixel pitches:

  20 – 400 µm

- Typical resolutions:

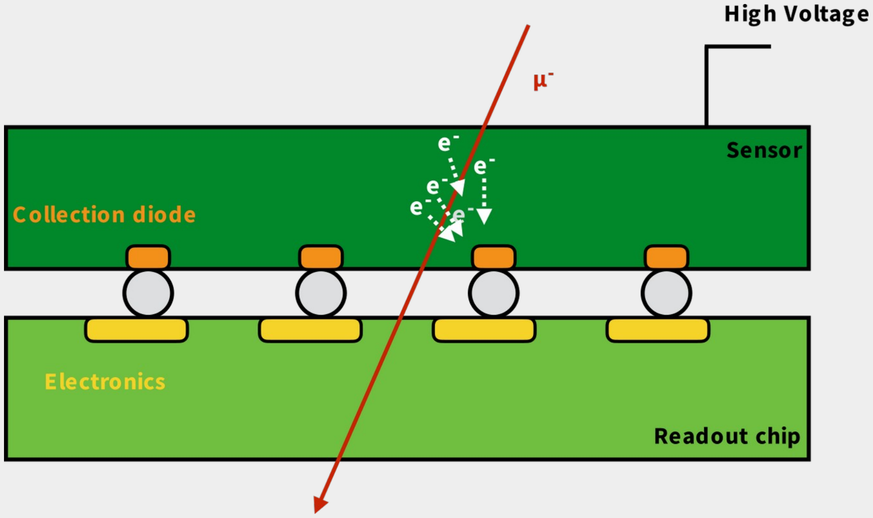
  5 – 15 µm



Silicon (Pixel) Detectors

Hybrid Detectors

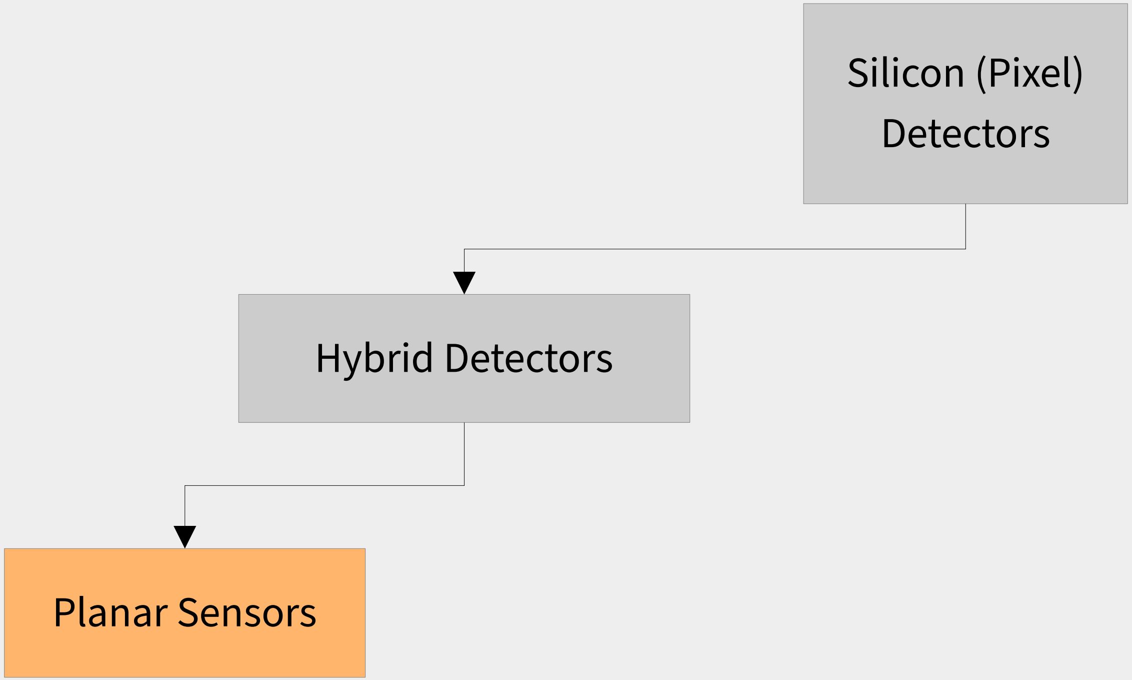
Hybrid Silicon Pixel Detectors



- Traditional design of HEP silicon pixel consist of sensor and separate readout chip
  - Sensor: pn-junction
  - Readout chip: front-end
  - Connection: small solder spheres – bump bonding
- Small pixel cell sizes achieved, ~ 25 μm – limited by interconnects

+ Established mixed-mode CMOS
Complex circuits possible
Small technology nodes available

− Relatively high material budget
Interconnects: cost-driver,
limits pixel pitch & thickness (stability)



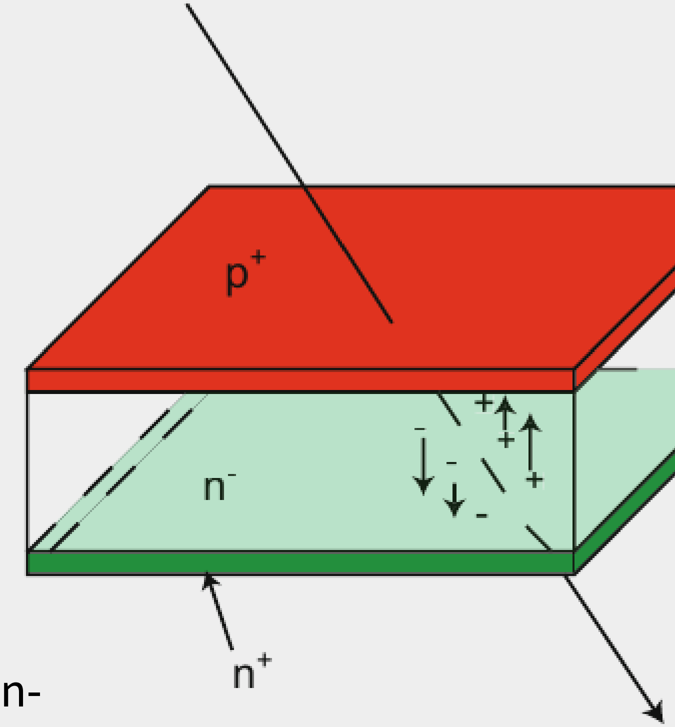
Silicon (Pixel) Detectors

Hybrid Detectors

Planar Sensors

Planar Silicon Sensors – The Diode

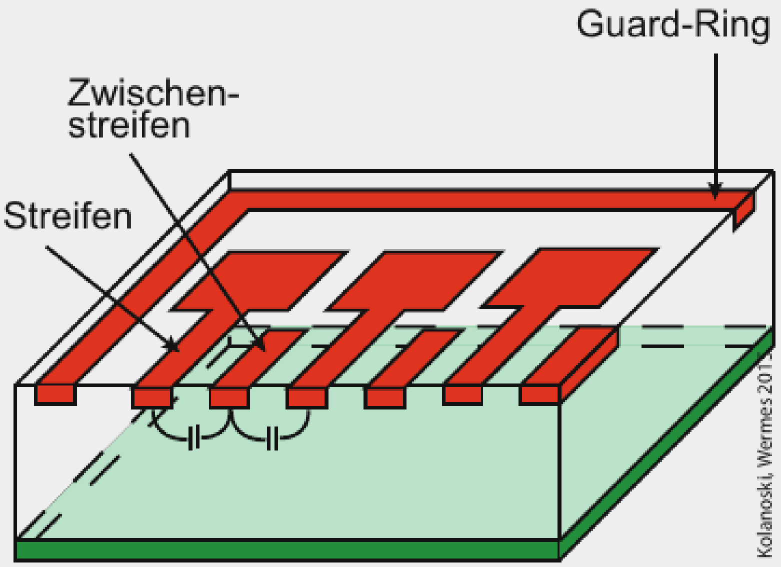
- Simplest semiconductor detector geometry
- Readout of a full area detector pad
- No spatial information
- Number of channels: 1



- Here:
  - Strong p^+ and weak n^- doping create asymmetric pn-junction at the sensor surface
  - Strong doping (n^+) at the backside for Ohmic contact to backside metalisation

Planar Silicon Sensors – Strip Detector

- Segmentation of sensor surface
- Implementation of strips
- Typical pitches: 50 – 100 µm

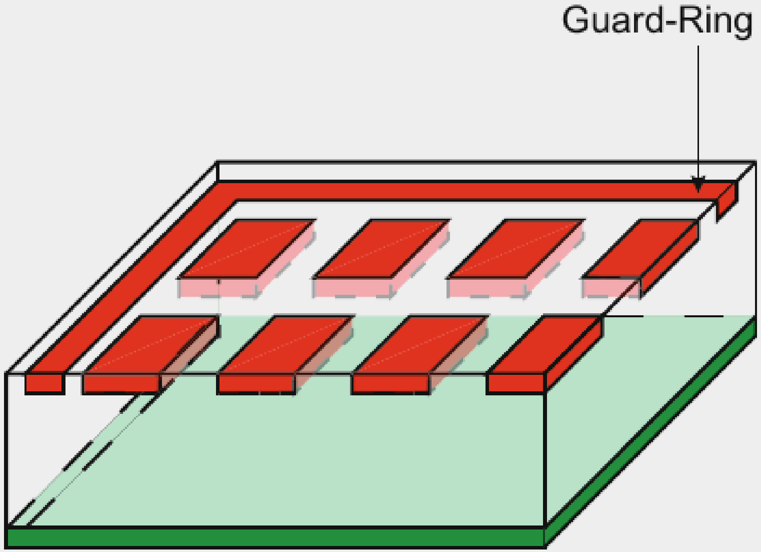


Kolanoski, Wermes 201

- Number of channels: N
- Charge carriers propagate towards one or few strips
  - ➔ 1D spatial information on particle traversal
  - ➔ Add second layer for 2D information

Planar Silicon Sensors – Pixel Detector

- Segmentation of sensor surface
- Implementation of pixels or pads
- Typical pitches: 50 – 400 µm

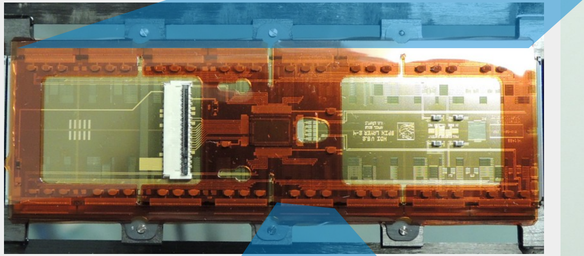


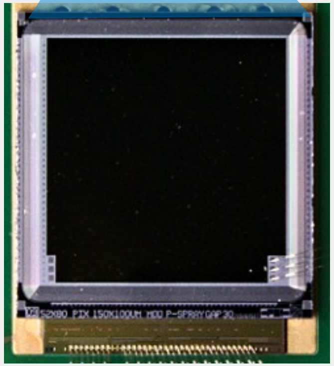
- Number of channels: N^2
- Charge carriers propagate towards one or few pixels

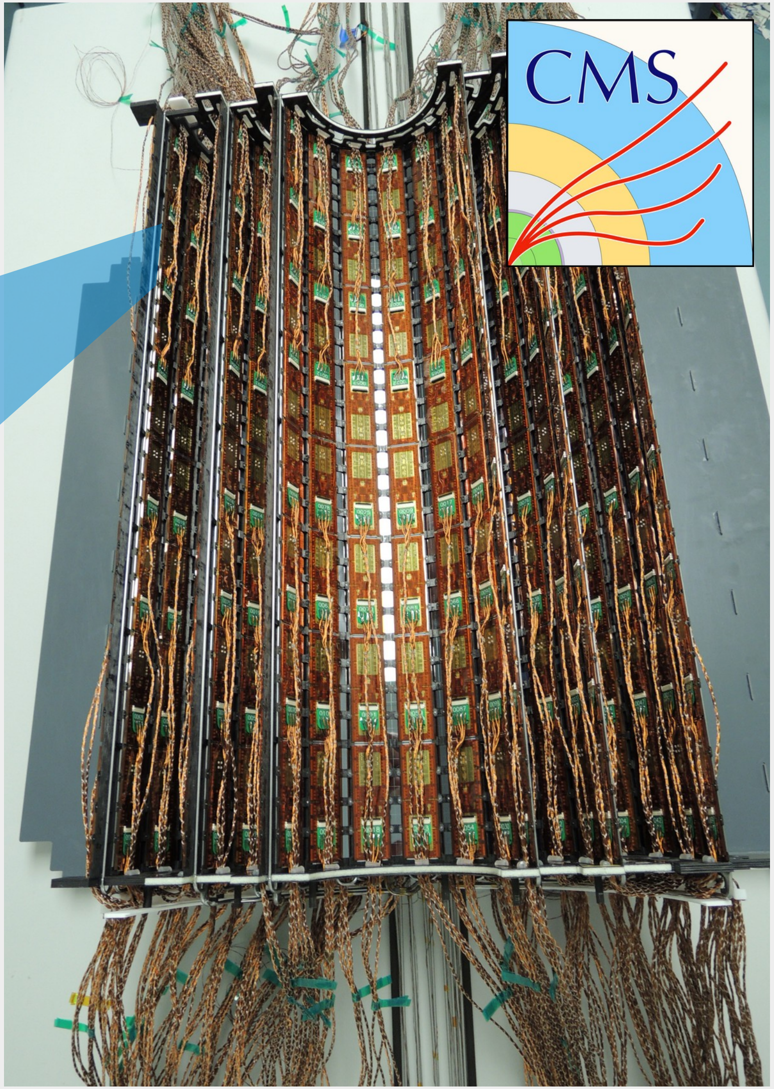
➔ 2D spatial information on particle traversal

Example: CMS Phase I Pixel Detector

- Hybrid pixel detector with planar sensors
  - 4 barrel layers (30 – 160mm radius)
    2x 3 end-cap disks
- ~1900 detector modules
  ~120M channels
- 150 µm x 100 µm pixels
  8 µm (z) / 5 µm (rϕ) resolution
- Material budget:
  ~ 0.3% X_0 per module



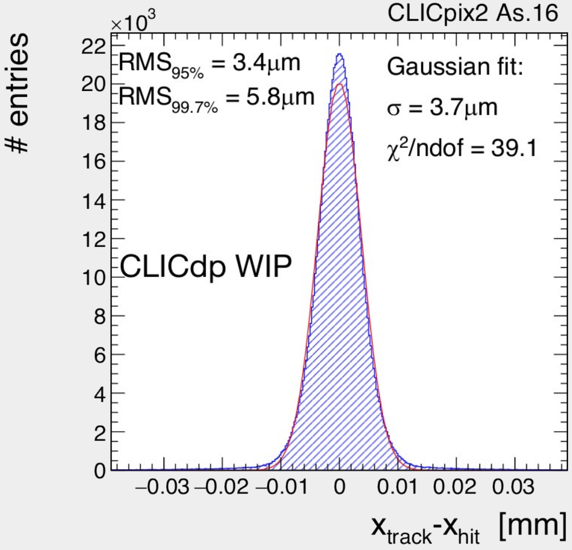


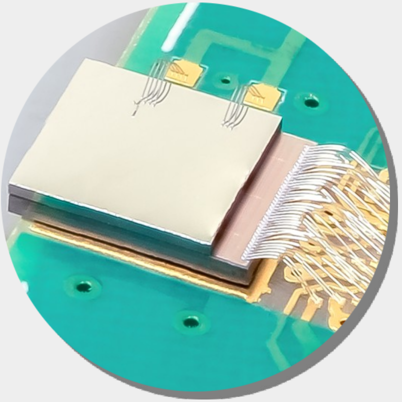


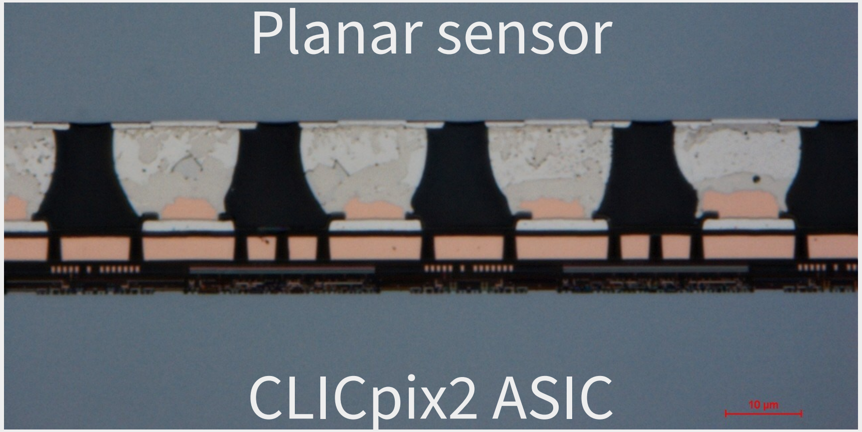
The CLICpix2 Hybrid Prototype

- Readout ASIC designed for CLIC vertex detector
  - Designed in 65nm CMOS process (same as **RD53 for ATLAS/CMS**)
  - Matrix of 128 x 128 pixels of 25 x 25 µm

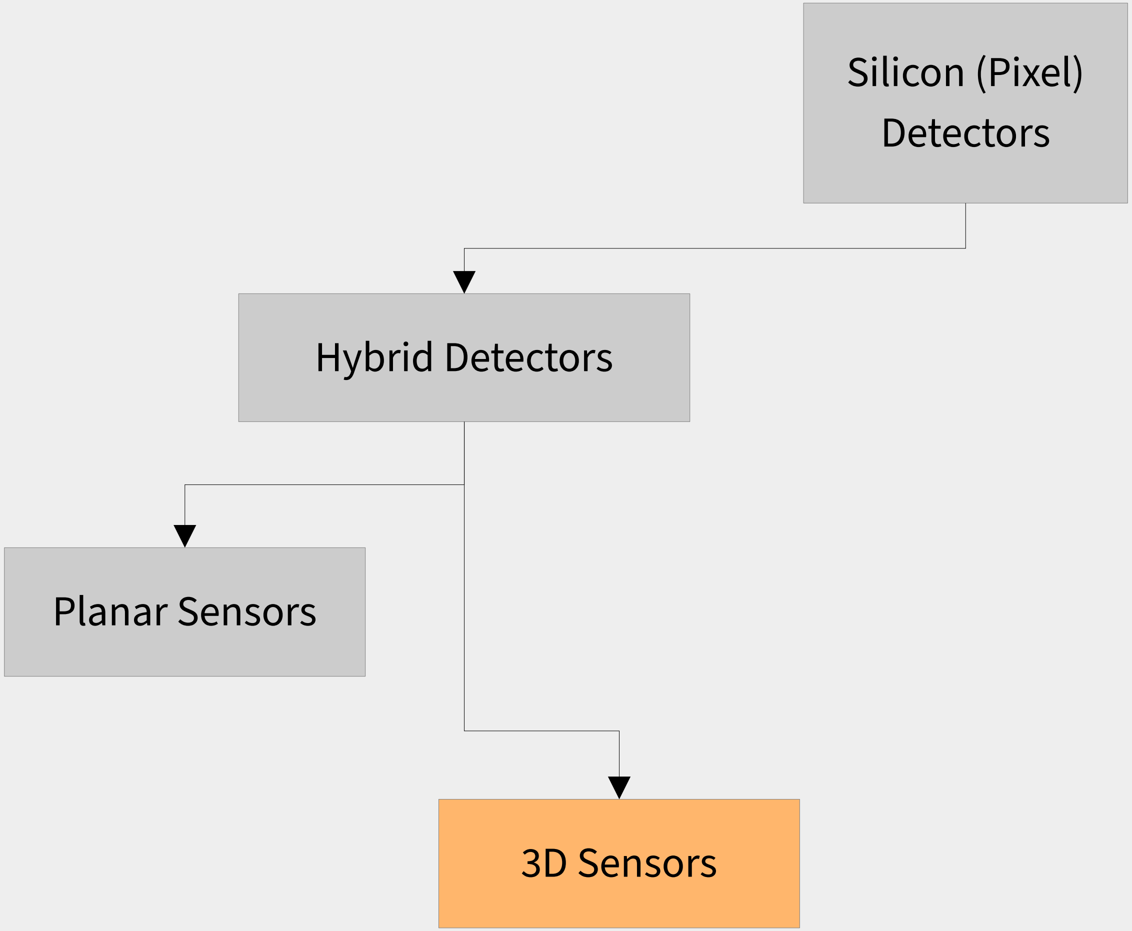
- Goal: development of high-resolution detector for detector at linear accelerator
- Chip-level bump bonding difficult, limitation on pixel pitch







https://doi.org/10.1088/1748-0221/14/06/C06003



Silicon (Pixel) Detectors

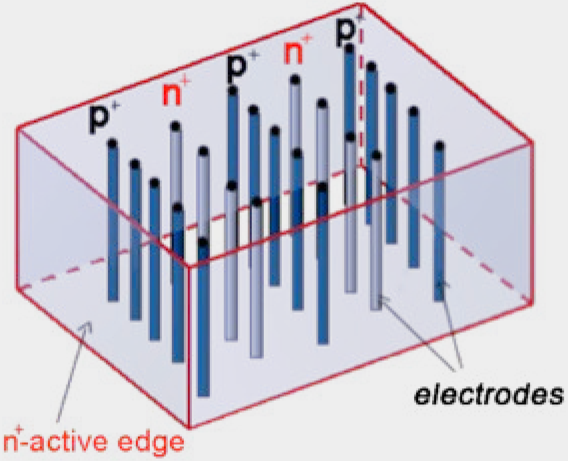
Hybrid Detectors

Planar Sensors

3D Sensors

3D Silicon Sensors

- p- and n-implants implemented as columns through the sensor volume
  → Generation of a horizontal pn-junction

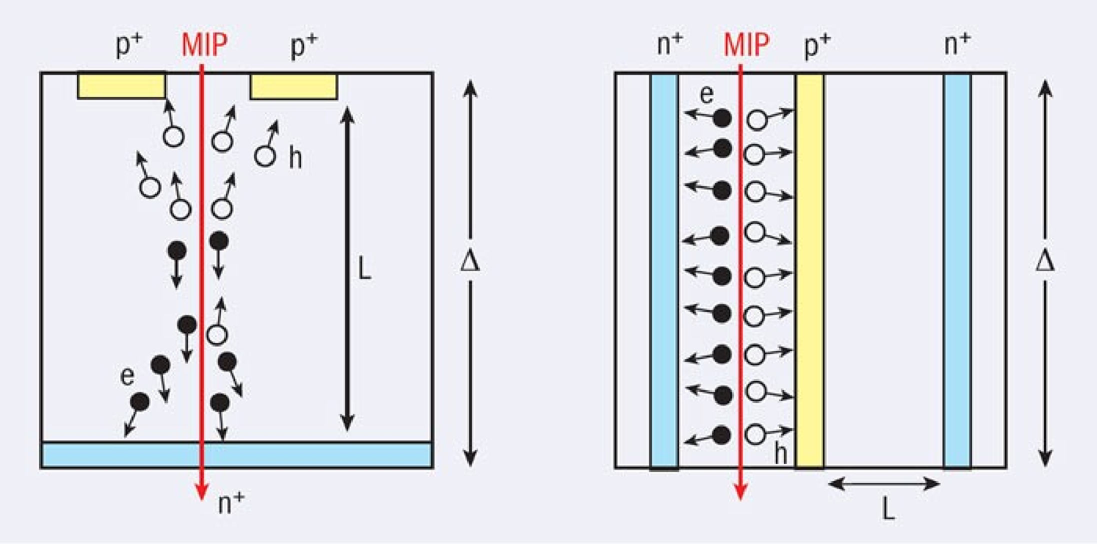


✔ Short drift time → fast!

✔ High (not reduced) signal

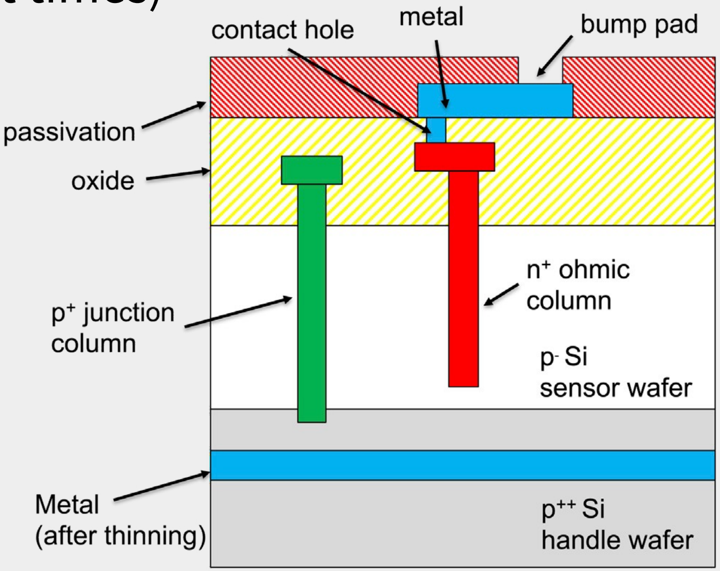
✔ High radiation tolerance

✗ High production costs & time

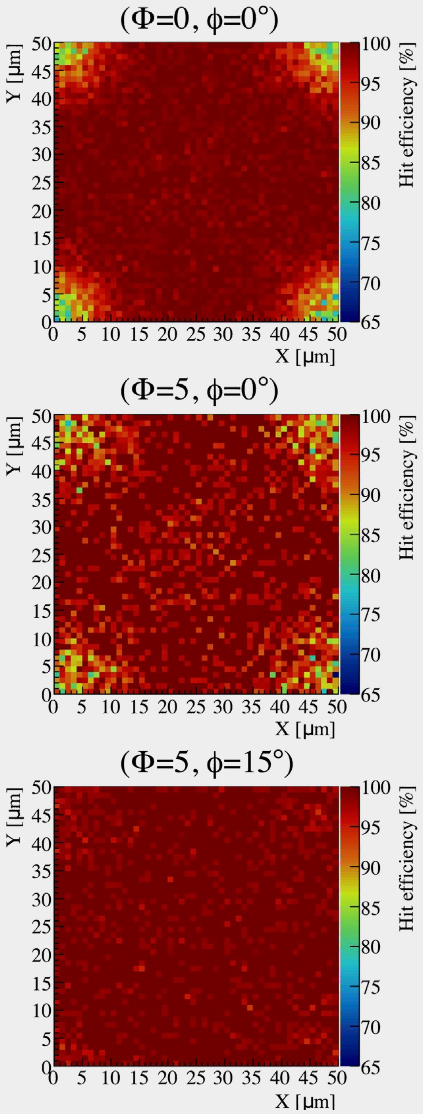


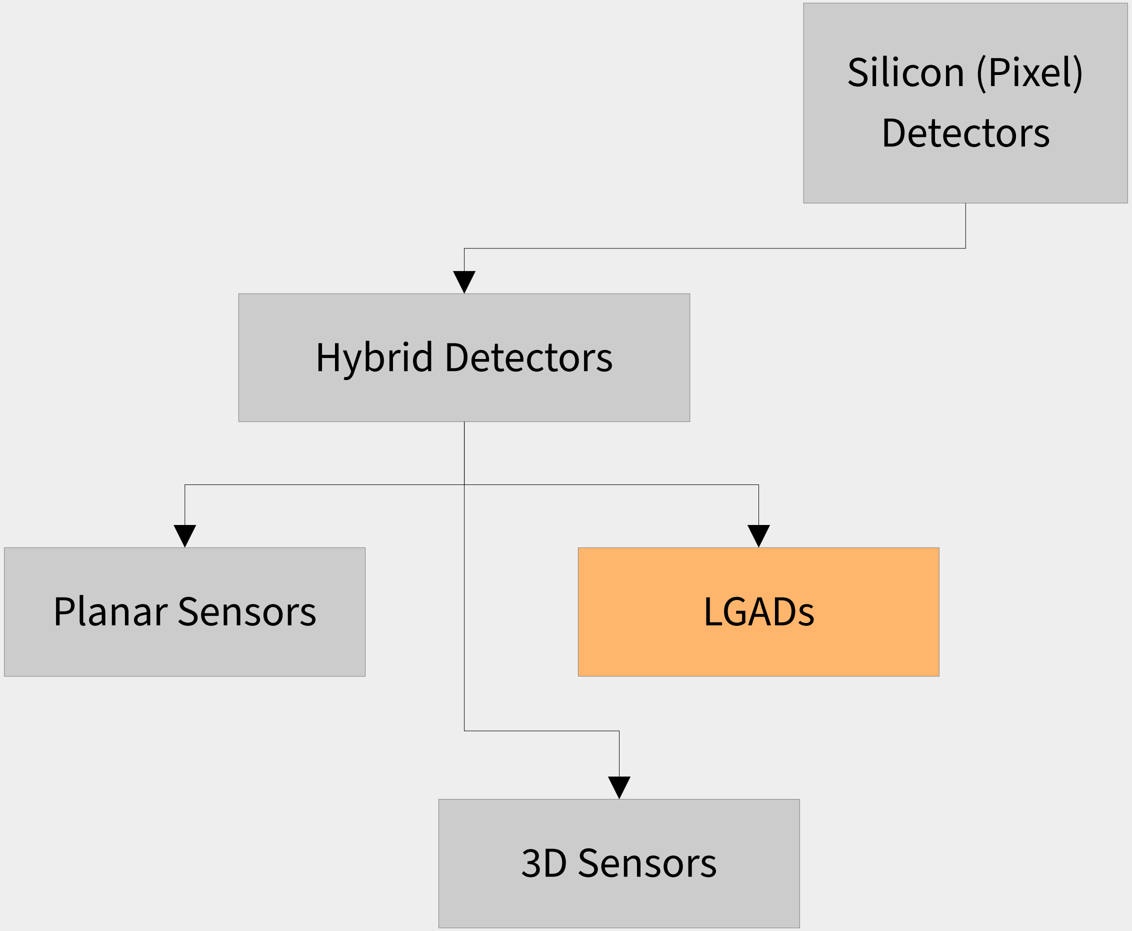
ATLAS ITk 3D Pixel Sensors

- Sensor for new inner tracker of ATLAS experiment
- 3D sensors for innermost layer of pixel detector
  - Very radiation hard (short drift times)
  - Different sensor layouts:
    50 x 50 µm
    25 x 100 µm
- At vertical incidence: inefficiencies at backside columns



https://doi.org/10.3389/fphy.2021.624668





Silicon (Pixel) Detectors

Hybrid Detectors

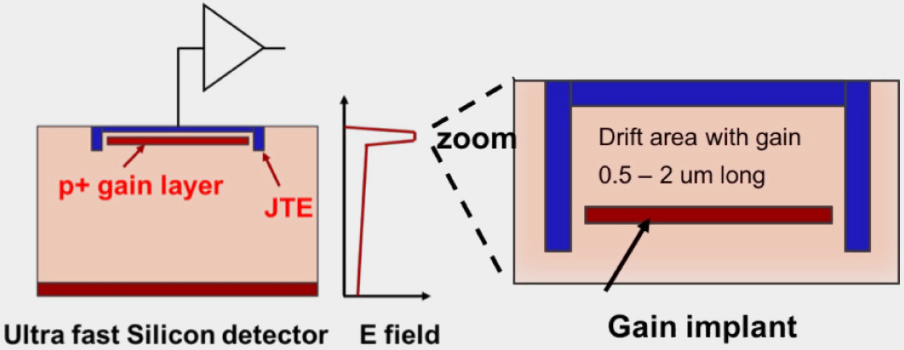
Planar Sensors

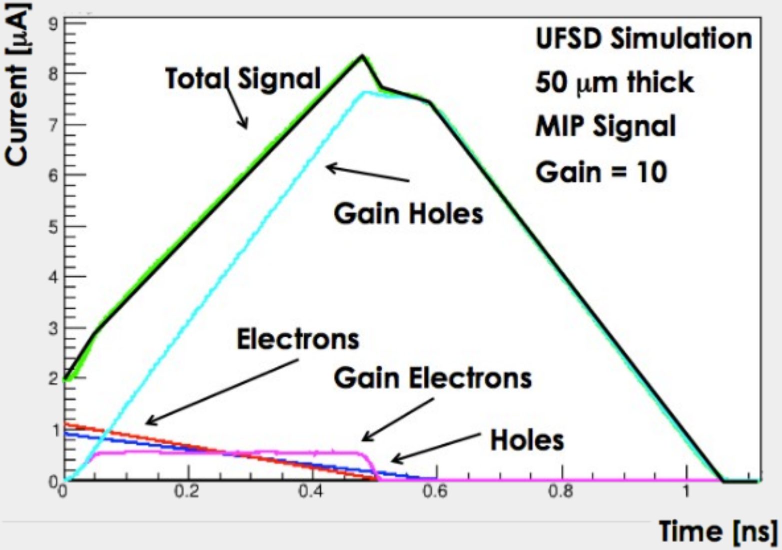
LGADs

3D Sensors

Low Gain Avalanche Diodes (LGADs)

- High electric fields: secondary ionization by charge carriers becomes possible → **Impact Ionization**
  – Similar to charge multiplication in gaseous detectors
- High electric fields in small sensor volume fraction generated via thin doping layer

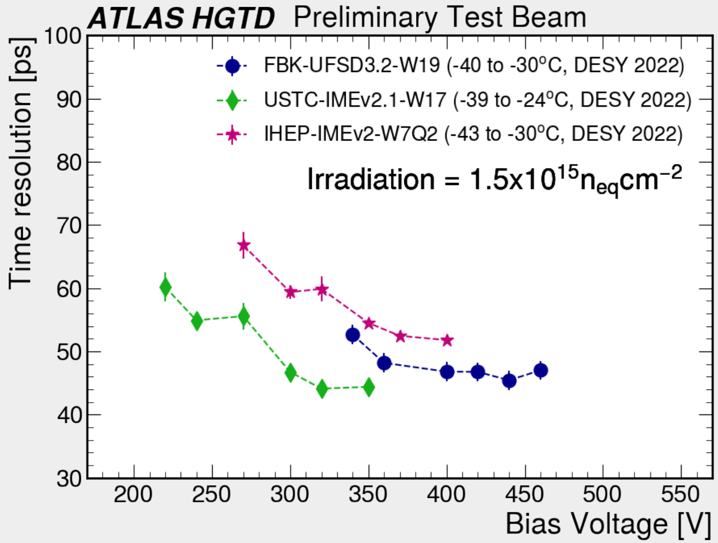


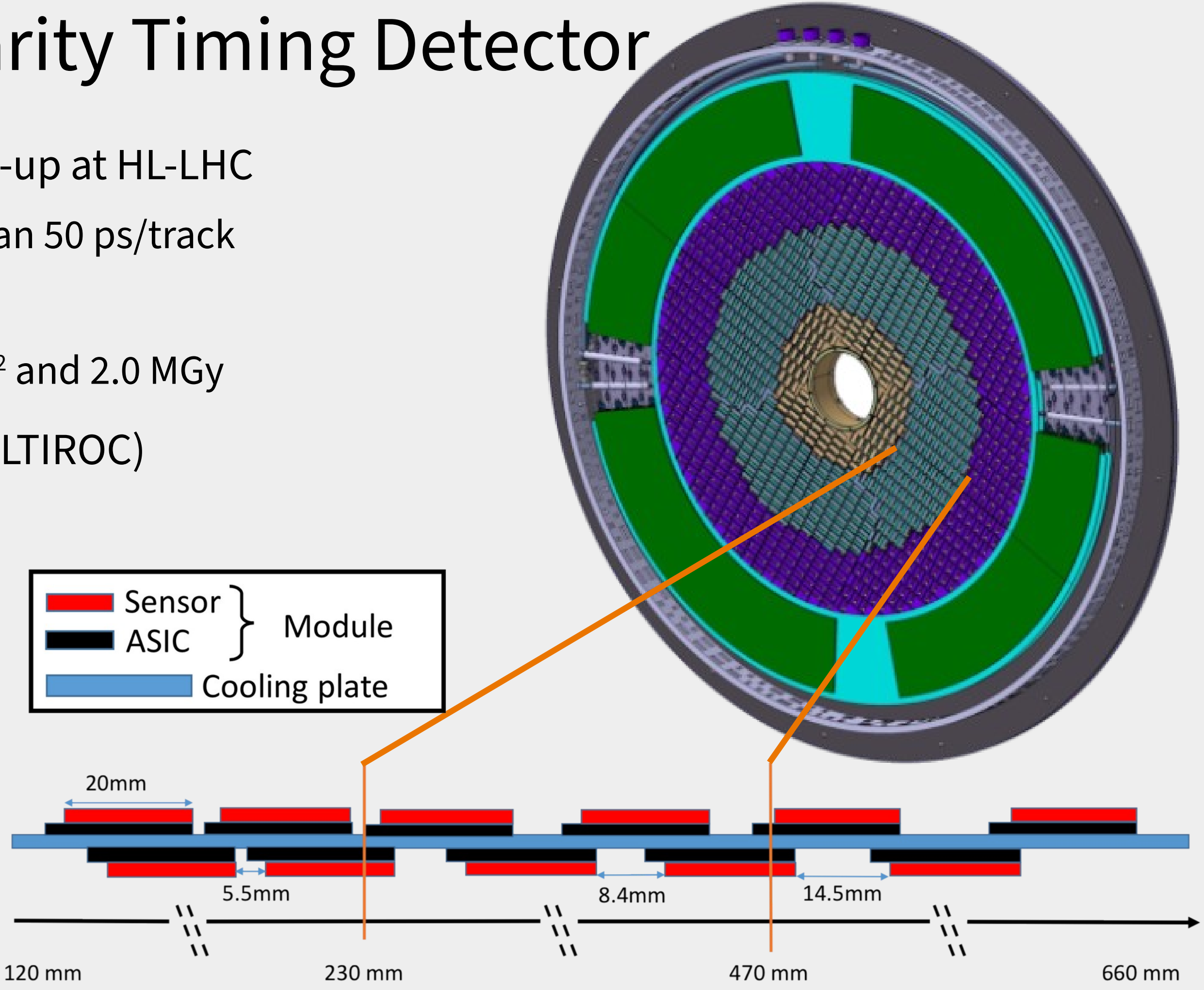


- Different types of LGADs: pads, iLGADs, TI-LGADs, …
- “Typical” silicon detectors: $\sigma > 1\,\mathrm{ns}$
- LGADs (Low Gain Avalanche Diodes) / UFSDs: $\sigma > 30\,\mathrm{ps}$

The ATLAS High Granularity Timing Detector

- Mitigate tracking issues from high pile-up at HL-LHC
  - Required timing resolution better than 50 ps/track
  - ~ 3.7×10^6 channels with 6.4 m^2 area
  - Radiation hardness 2.5×10^{15} N_{eq}/cm^2 and 2.0 MGy
- LGADs with dedicated readout ASIC (ALTIROC)

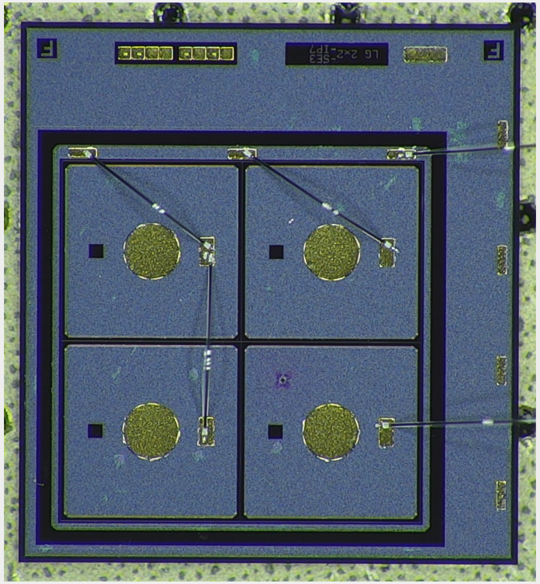


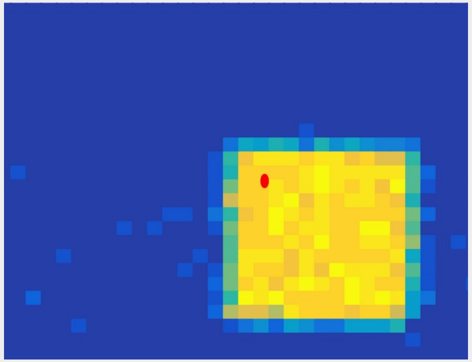


https://doi.org/10.1016/j.nima.2022.166628

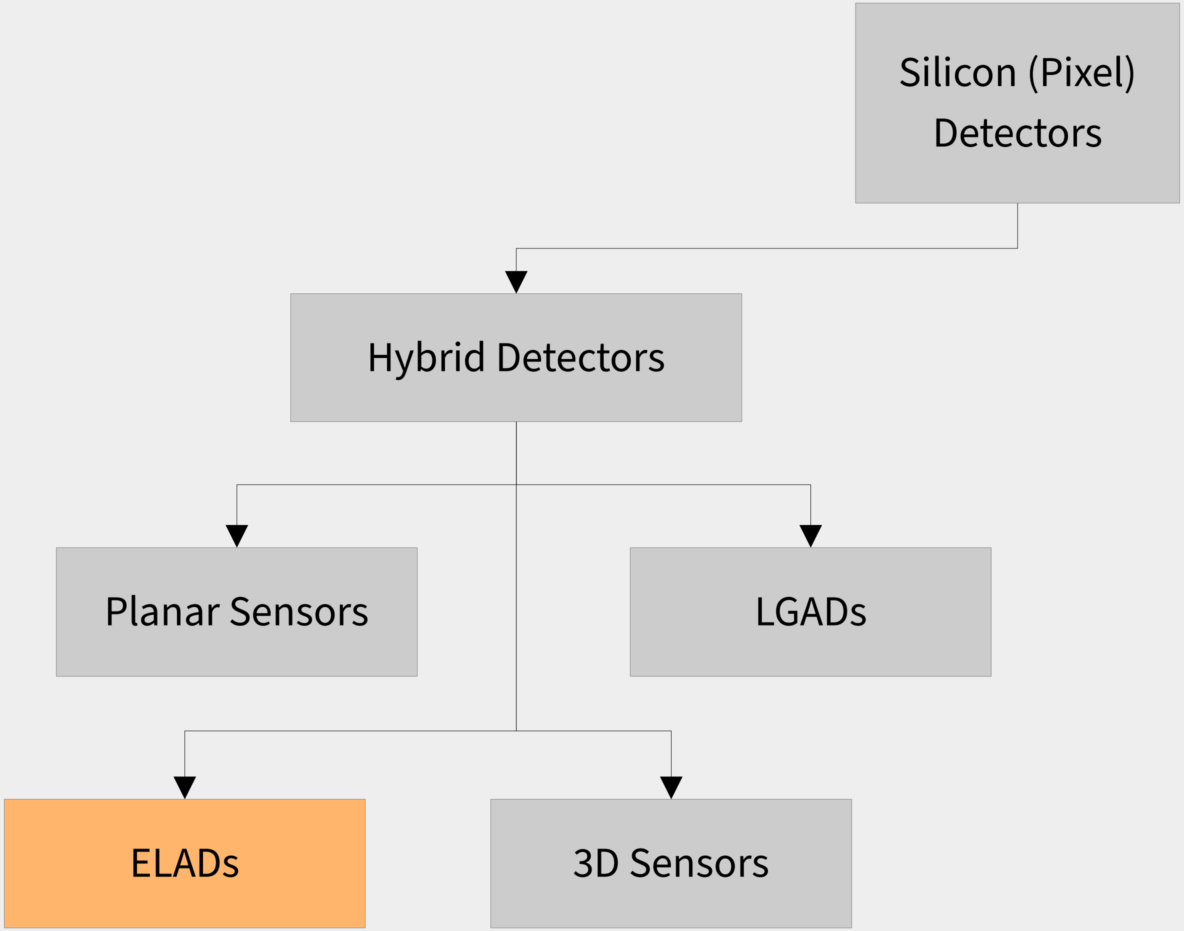
LGAD Mortality – Burnout Events

- Observation: LGADs sometimes suddenly “die”, indication of single destructive event
- Proton testbeam allowed to pin-point impact point of track
- Clear correlation with “crater” location
- Preliminary explanation:
  - With high bias voltages, strong electric fields form locally
  - Combined with high-ionization events (Landau tail)
  - Enough to create conductive path across diode, burnout due to high current density
- Establishing of safe-operation conditions





https://indico.cern.ch/event/1058977/contributions/4865300/



Silicon (Pixel) Detectors

Hybrid Detectors

Planar Sensors

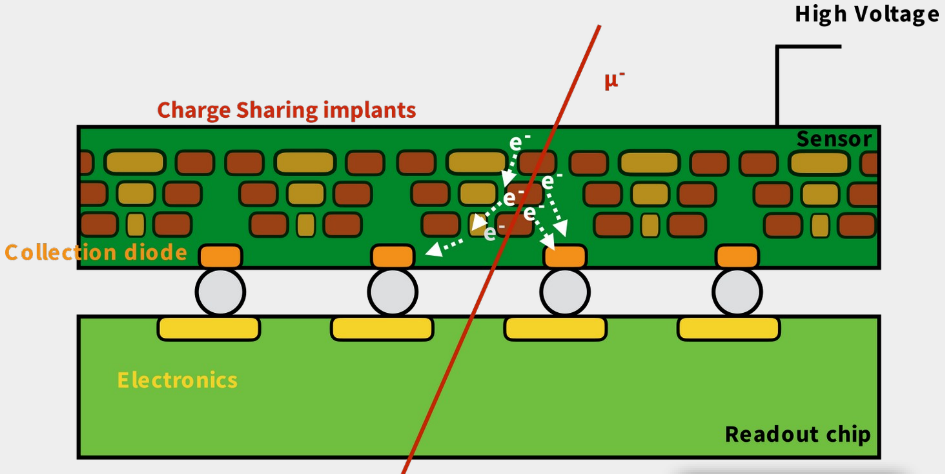
LGADs

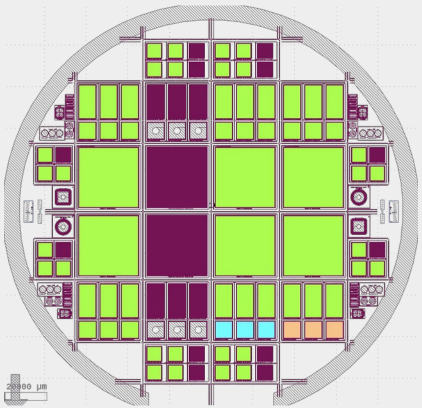
ELADs

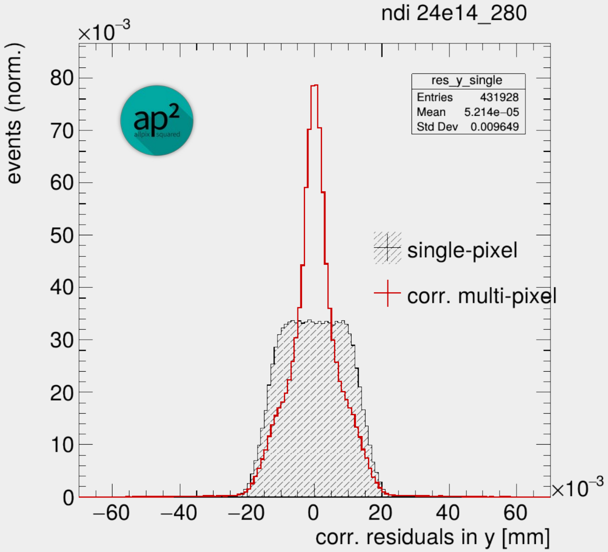
3D Sensors

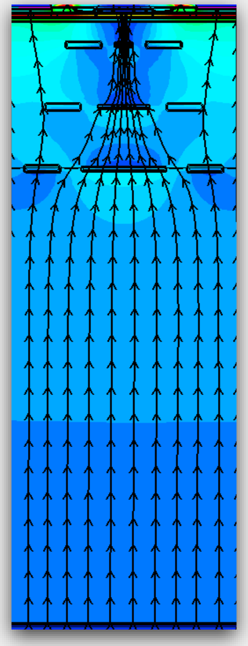
Enhanced Lateral Drift Detectors

- Position resolution in **thin sensors** limited to pitch / √12 (almost no charge sharing)
- New concept: **enhance charge sharing** in Enhanced LAteral Drift sensors (ELAD)
  - Close to theoretical optimum: linear charge sharing
  - Deep implants to alter field, improve resolution
  - Lateral spread of charges during drift, cluster size ~2
- Challenges:
  - Complex production process
  - Low-field regions (recombination)



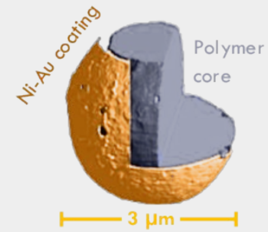


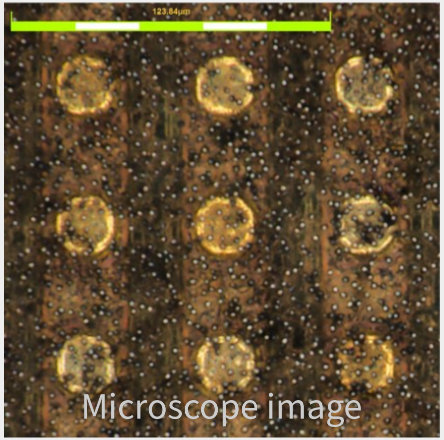




Hybridization with Anisotropic Conductive Film

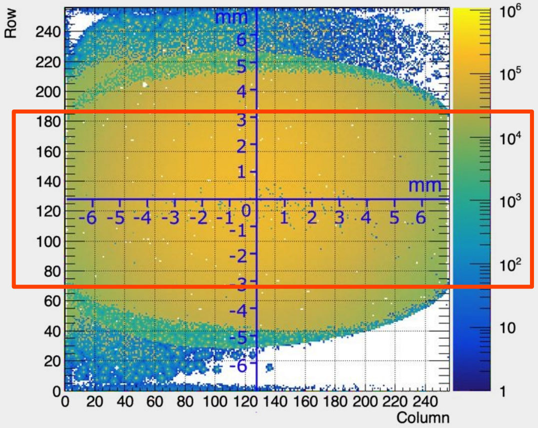
- Alternative to traditional solder-bump bonding
- Adhesive film with conductive micro-particles
  - Stochastically distributed in film
  - Some spheres end up under bond pads, get deformed, establish contact
- Widely used in display industry in one dimension, challenge: 2D distribution

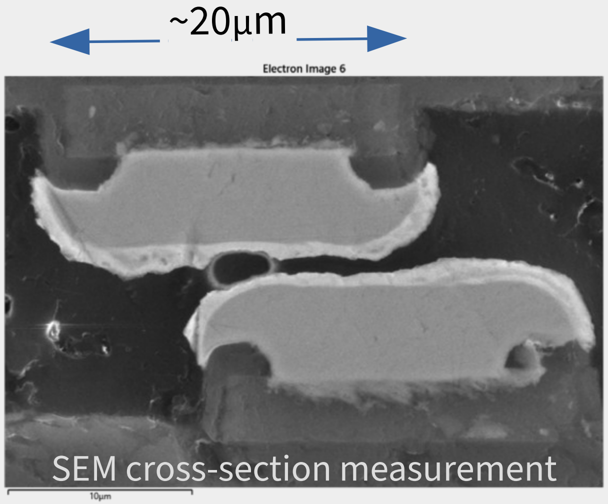




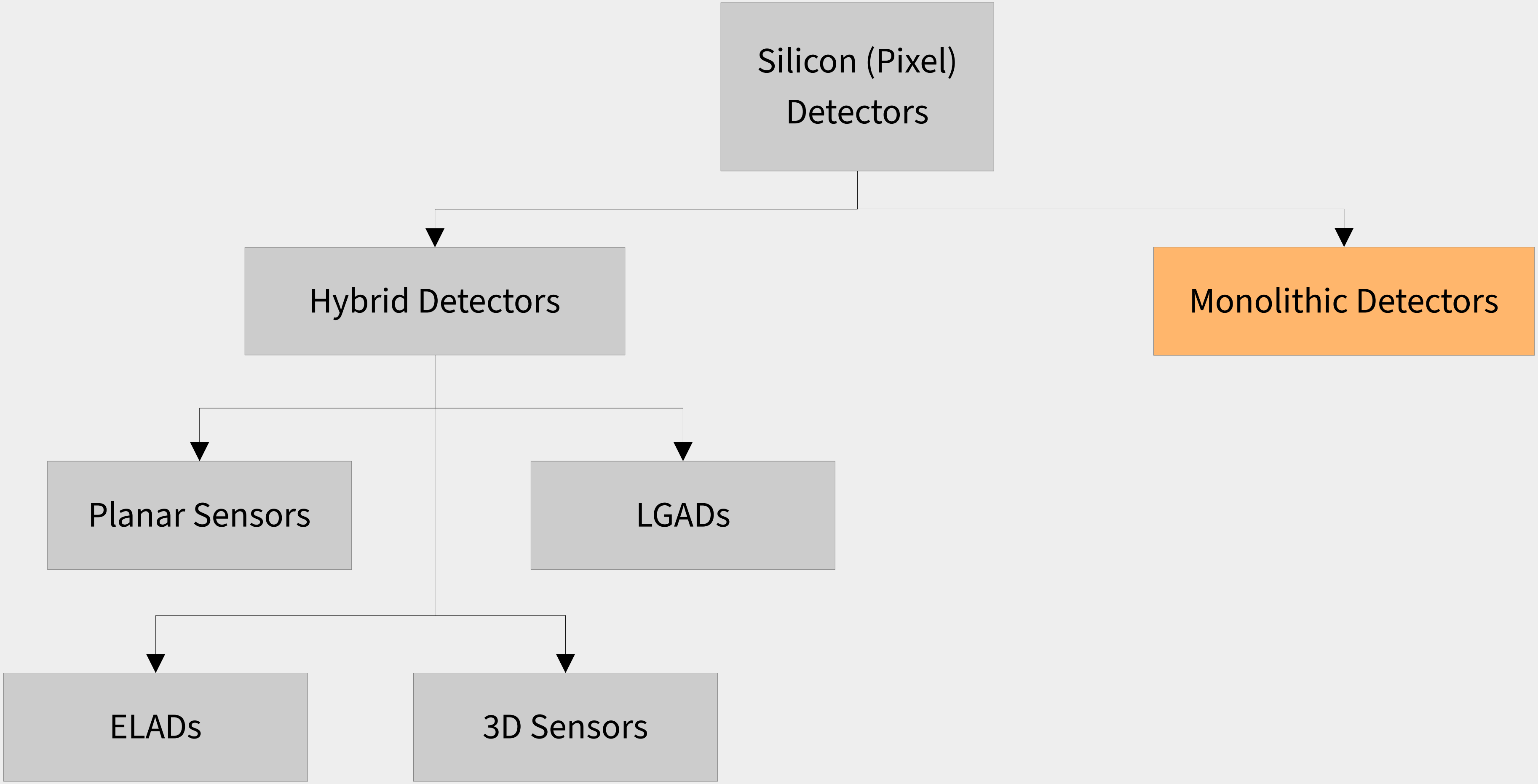
Microscope image

- Requires careful optimization of
  - Film thickness
  - # spheres/area
  - Bonding force…
- Currently early R&D phase





SEM cross-section measurement



Silicon (Pixel) Detectors

Hybrid Detectors

Monolithic Detectors

Planar Sensors

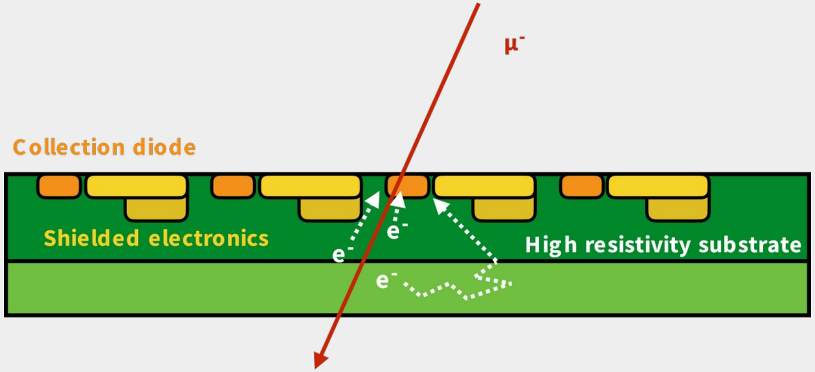
LGADs

ELADs

3D Sensors

Monolithic Silicon Detectors

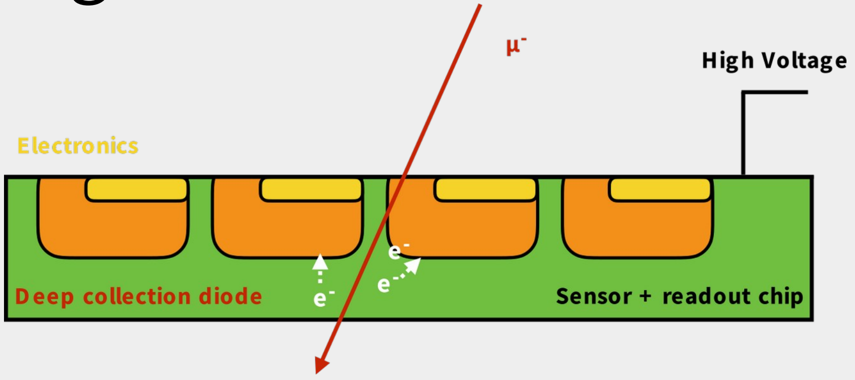
- Also called Monolithic Active Pixel Sensors (MAPS)
  - Electronics & sensor: same wafer
  - Fully integrated: amplification, discrimination & readout
- Shield electronics via additional implants
- Different approaches
  - Deep collection diode surrounding electronics
  - Separate shielding & collection diode

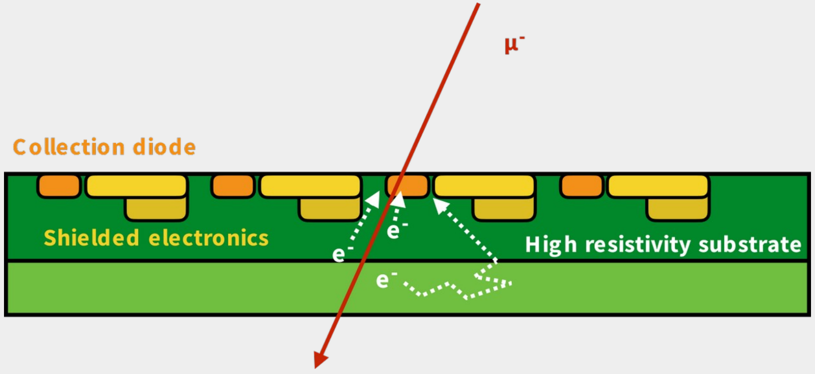


+ Lower mass than hybrids
No bump-bonding
Cheaper (large scale) manufacturing

− Smaller depletion volume & signal
Intricate sensor design
Limited in-pixel functionality

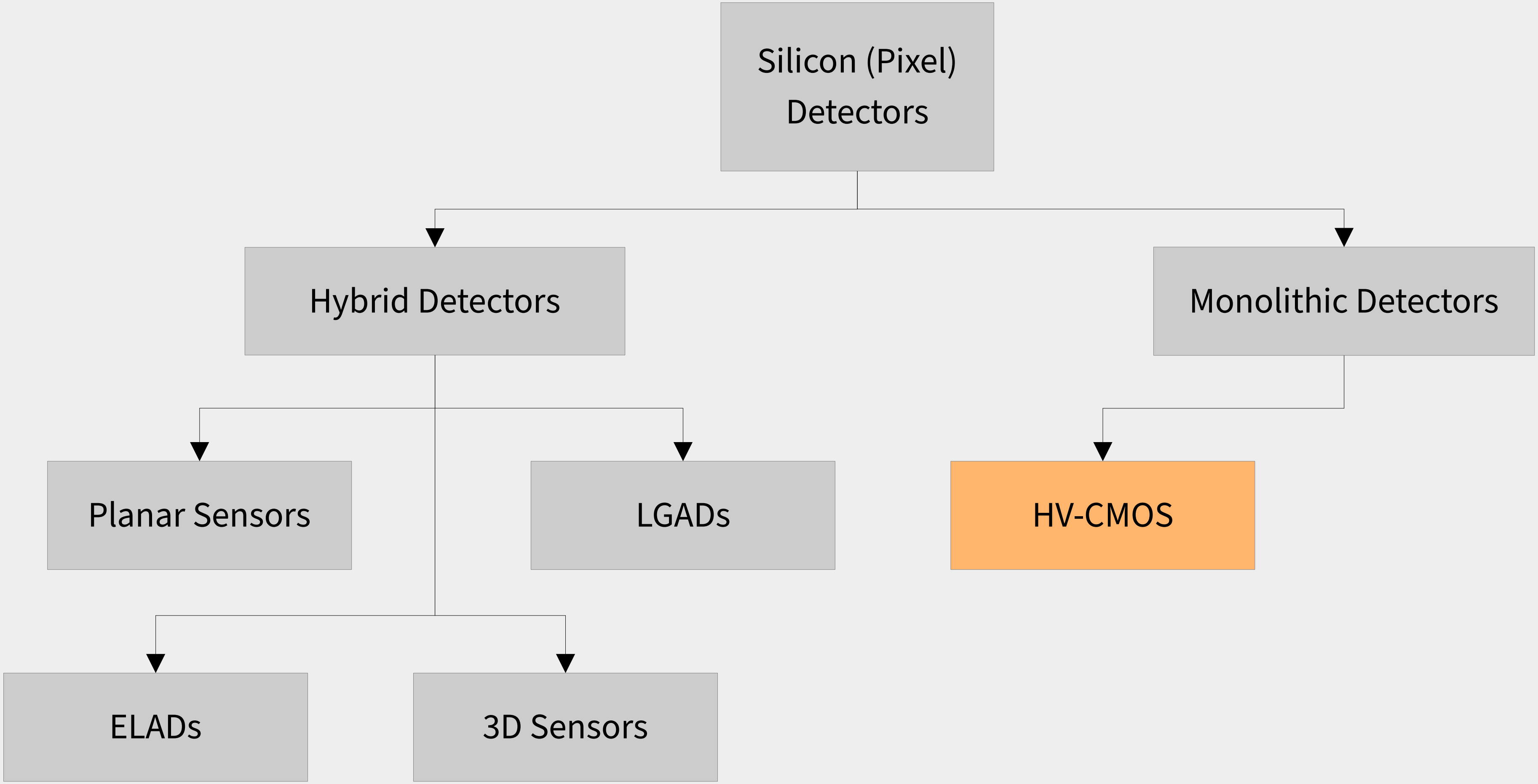
Large & Small Collection Electrode





- Shield electronics via deep collection diode around electronics
  - Allows high bias voltage to be applied
  - Fast & large signal, large depletion volume
- Challenge: large collection diode leads to
  - large input capacitance
  - increased power consumption

- Electronics outside charge-collection well
  - Requires high-resistivity material (e.g. epitaxial layer) to allow depletion
  - Small collection diode leads to small capacitance
- Challenge: effect of p-well potential on electric field / charge collection



Silicon (Pixel) Detectors

Hybrid Detectors

Monolithic Detectors

Planar Sensors

LGADs

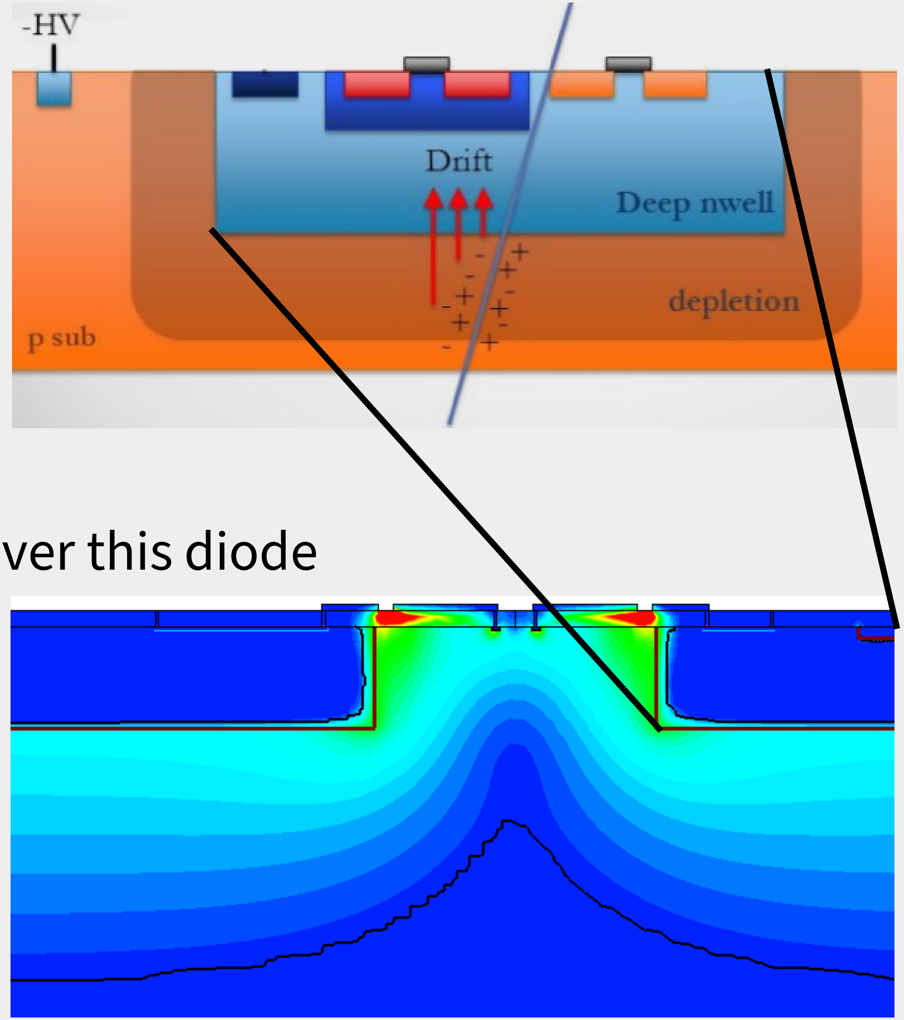
HV-CMOS

ELADs

3D Sensors

HV-CMOS Sensors

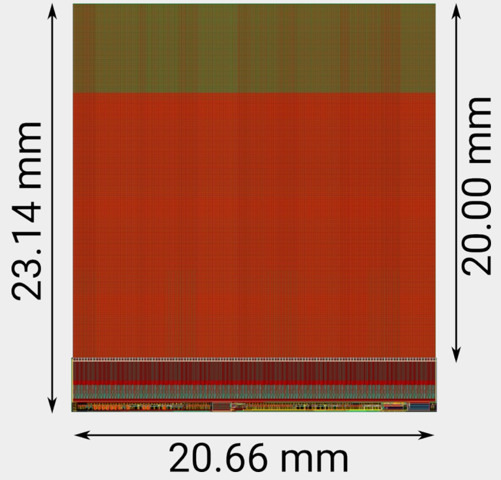
- Place all transistors inside deep well
- Deep well acts as electrode
  - *pn*-junction forms between deep well and substrate
- Possible to apply high voltage O(10-100V) over this diode
  - High electric field allows for fast charge collection via drift
  - Need to be careful about strong fields near surface

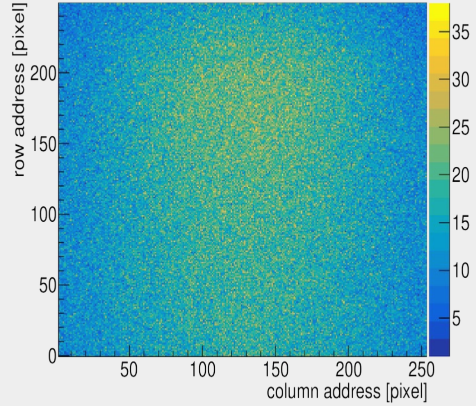


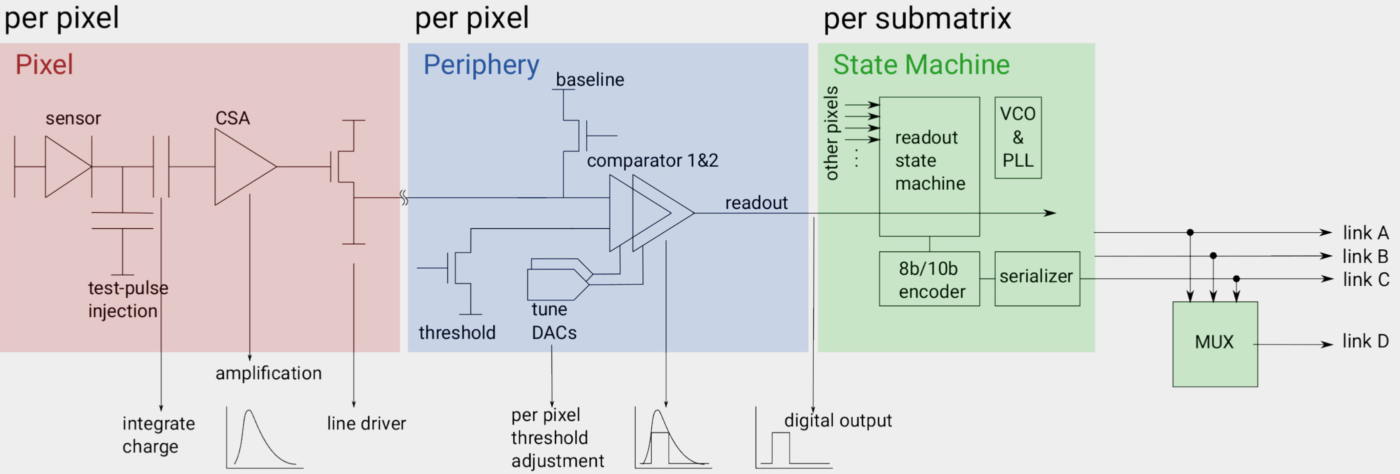
Annie Meneses

The MuPix10 HV-MAPS

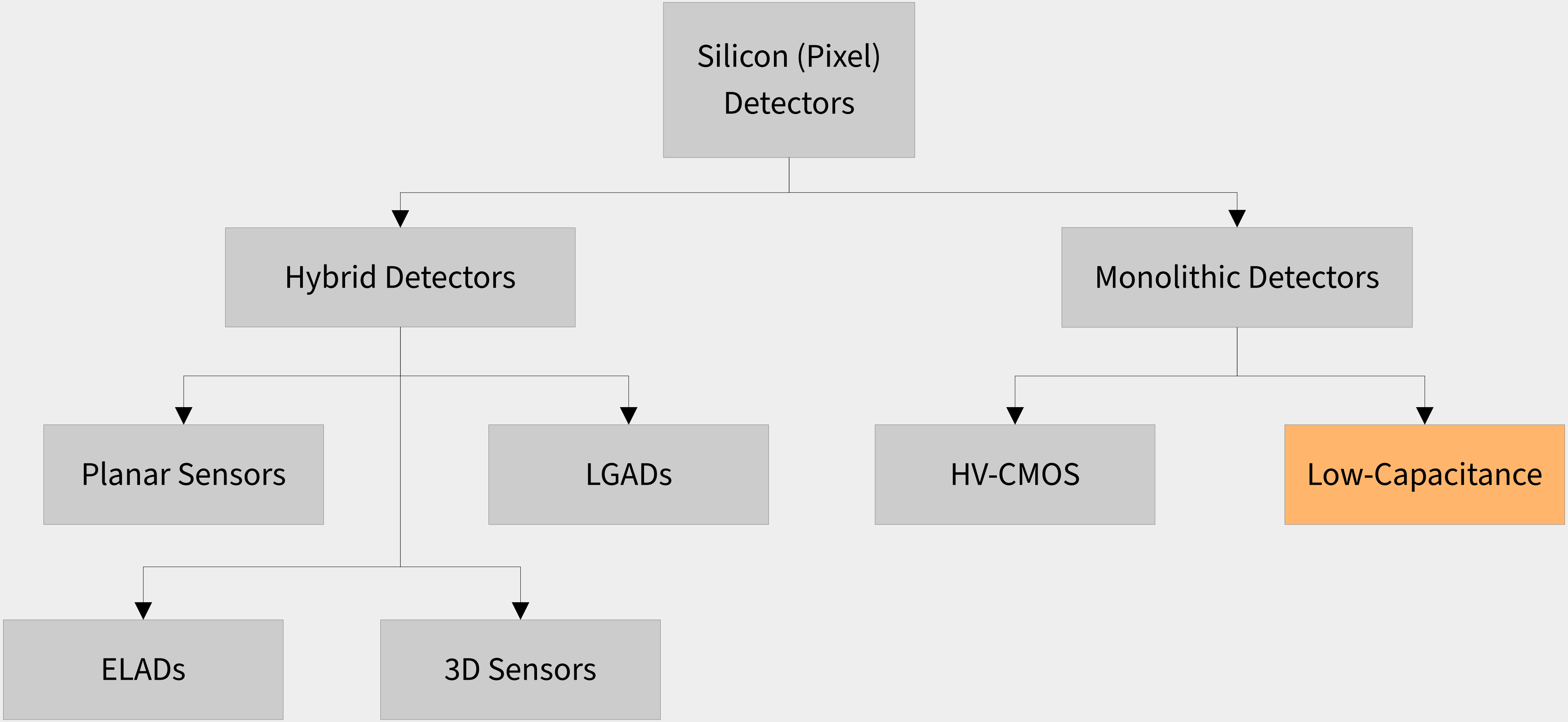
- Designed for the mu3e experiment at PSI
  - 180 nm HV-CMOS technology
  - Matrix of 256 x 250 pixels with pitch of 80 x 80 μm^2
  - Energy + time measurement per pixel







https://arxiv.org/abs/2012.05868



Silicon (Pixel) Detectors

Hybrid Detectors

Monolithic Detectors

Planar Sensors

LGADs

HV-CMOS

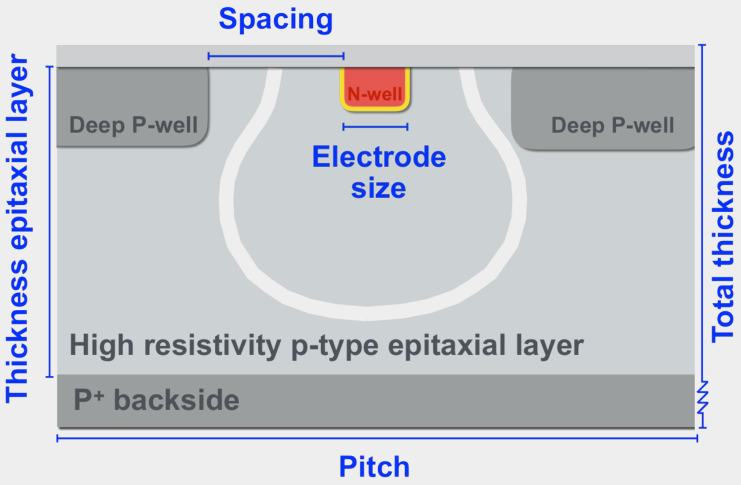
Low-Capacitance

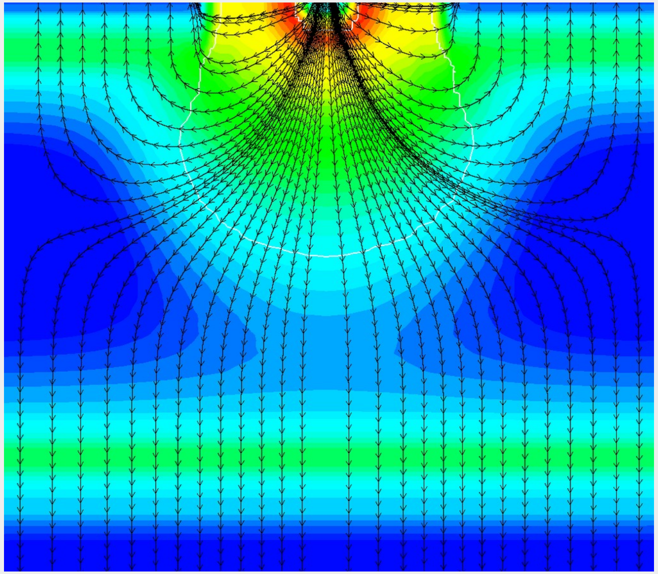
ELADs

3D Sensors

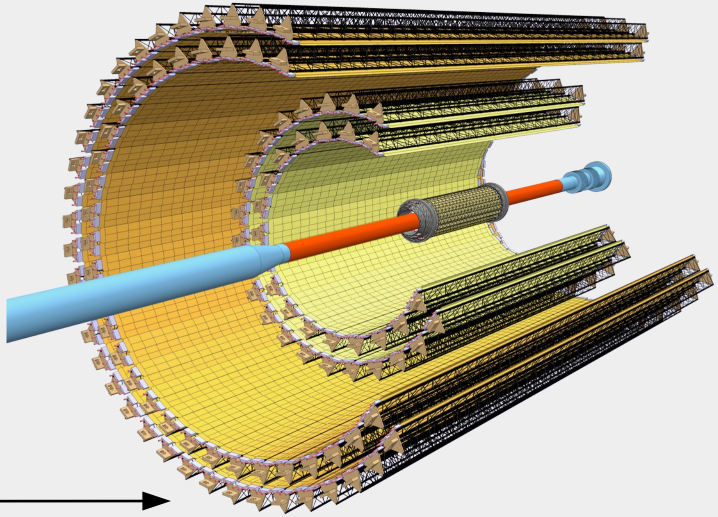
Low-Capacitance CMOS Sensors

- Instead of using well as electrode:
  place next to deep well
  - Small sensor capacitance, low noise O(~10e)
  - Requires high-resistivity material
  - No requirement for HV-compatible process
- Can only apply low bias voltage O(< 6V)
  - Only small volume depleted,
    partially collecting charge via diffusion
  - Requires detailed field optimization

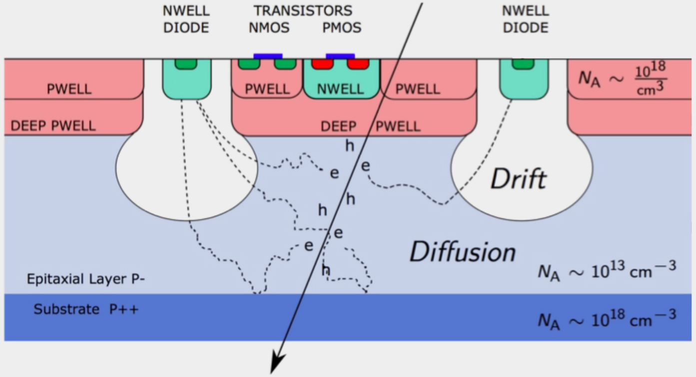


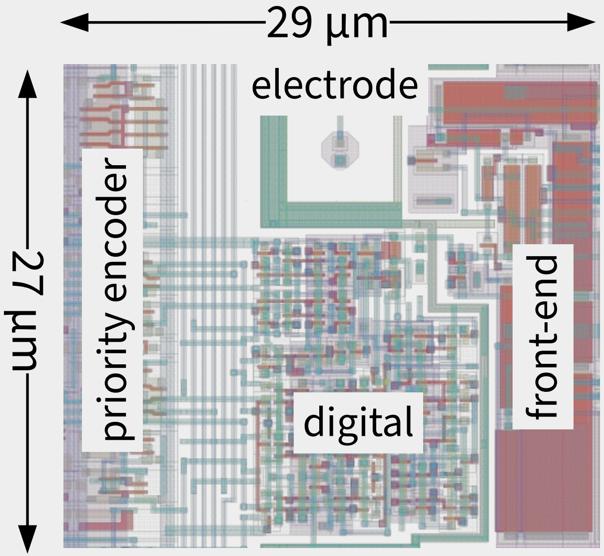


The ALPIDE Sensor of the ALICE ITS2

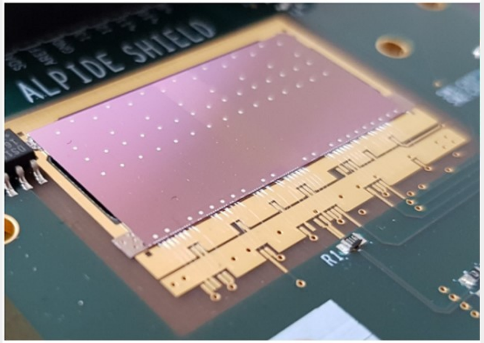


- Full Inner Tracking System: 24’000 ALPIDE chips, one of the first large-scale detectors with MAPS
- ALPIDE – MAPS in 180 nm CMOS imaging technology
  - 512 × 1024 pixels of 29 µm x 27 µm pitch
  - Binary detection & readout (hit/no hit)
  - Optimized for low power consumption
  - Produced on epitaxial layers of 18 – 30 µm



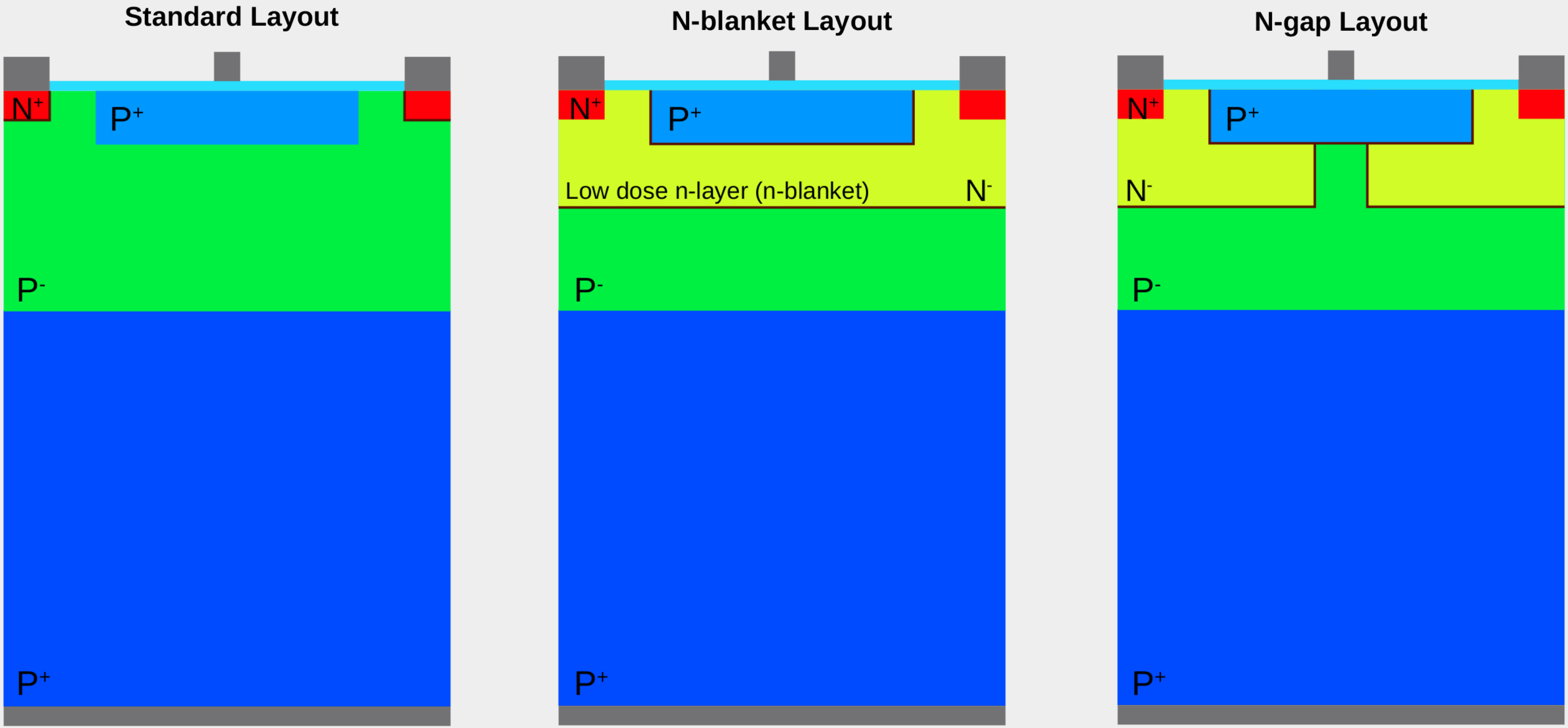


ALPIDE pixel cell



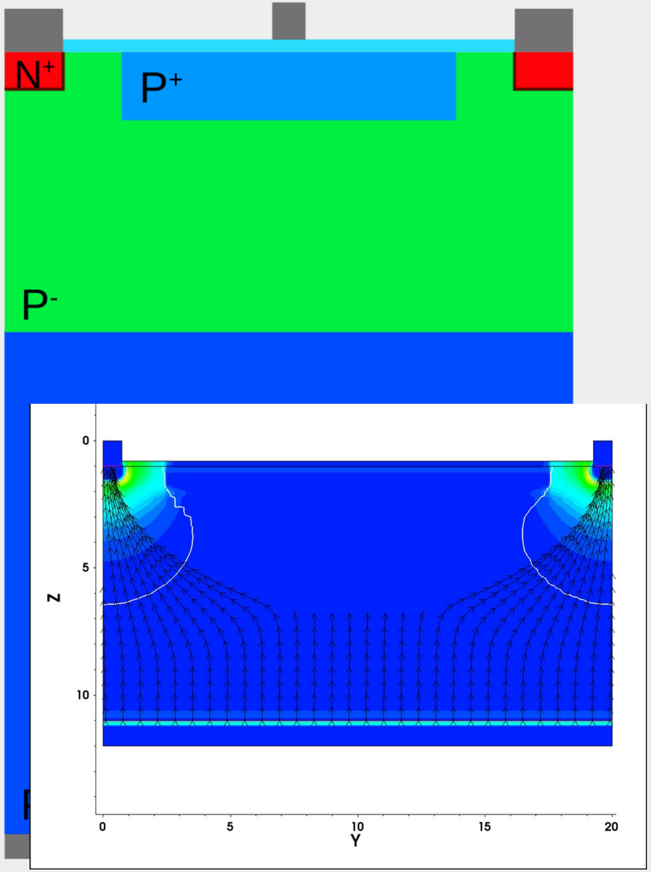
http://dx.doi.org/10.1016/j.nima.2016.05.016

Sensor Layouts – Improving Signal Formation

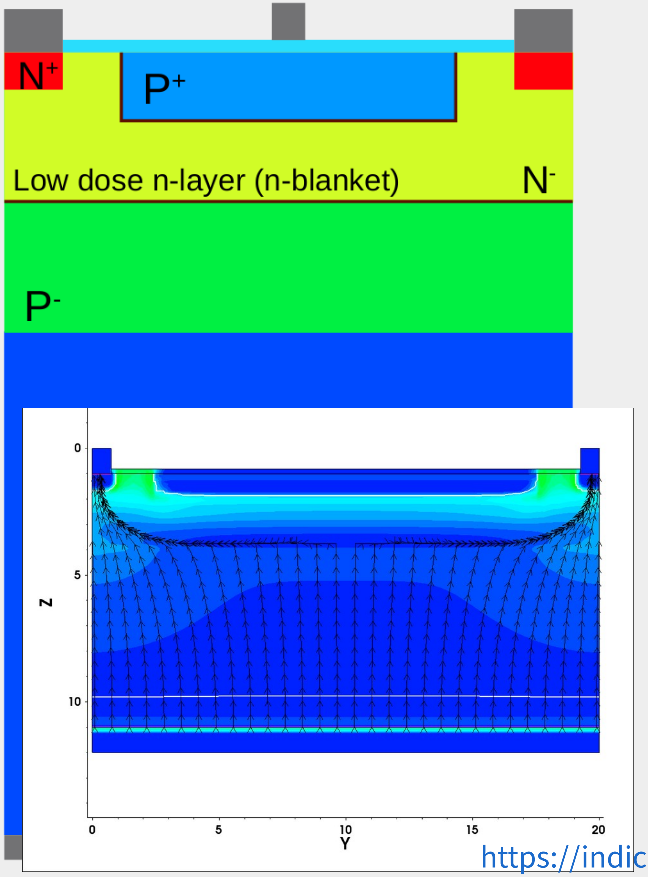


Sensor Layouts – Improving Signal Formation

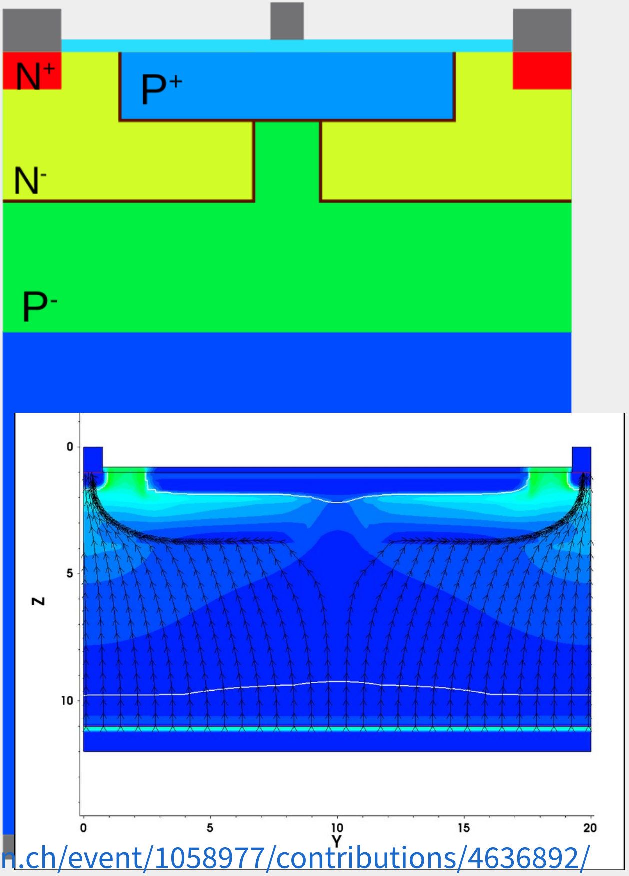
Standard Layout



N-blanket Layout

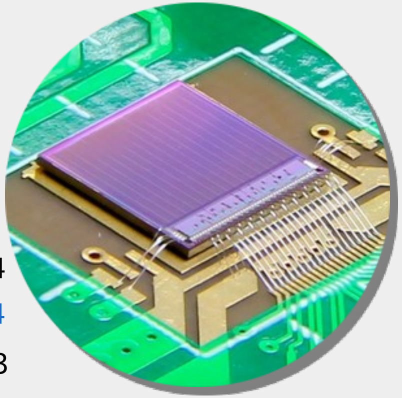


N-gap Layout



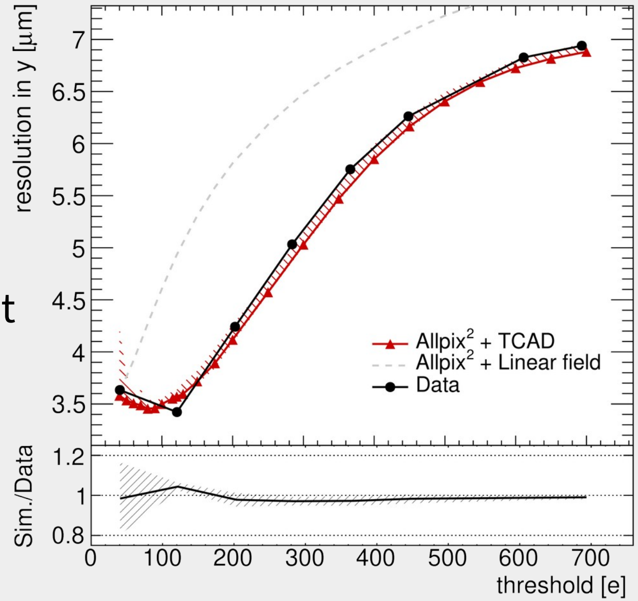
https://indico.cern.ch/event/1058977/contributions/4636892/

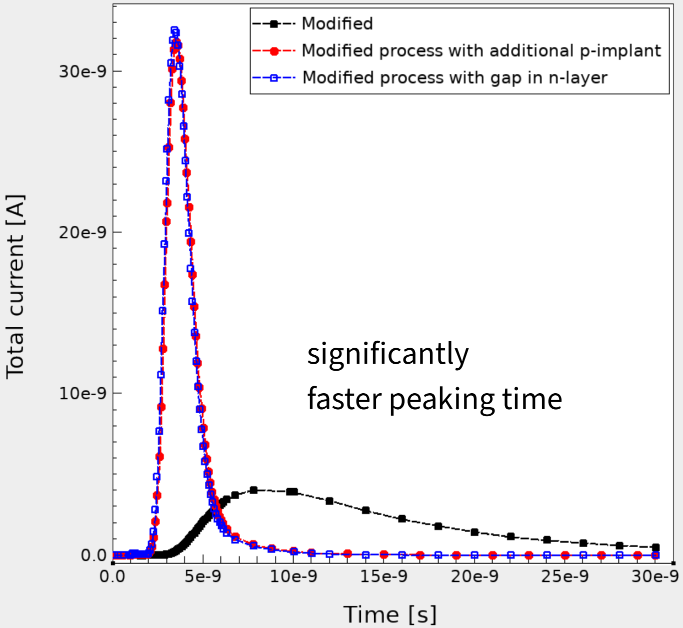
The CLICTD MAPS Prototype



NIMA 964 (2020) 163784
doi:10.1016/j.nima.2020.163784
IEEE TNS, vol. 67, no. 10 (2020), 2263
doi:10.1109/TNS.2020.3019887

- Silicon detector prototype for CLIC tracking detector
  - 180 nm CMOS imaging process, small collection electrode
  - Pixel pitch: 37.5 µm x 30 µm, 30 µm epitaxial layer
  - Fully-integrated sensors, ToA/ToT measurement
- Test bench for sensor designs
  - Optimizations e.g. for prompt signal formation
  - Spatial resolution studies

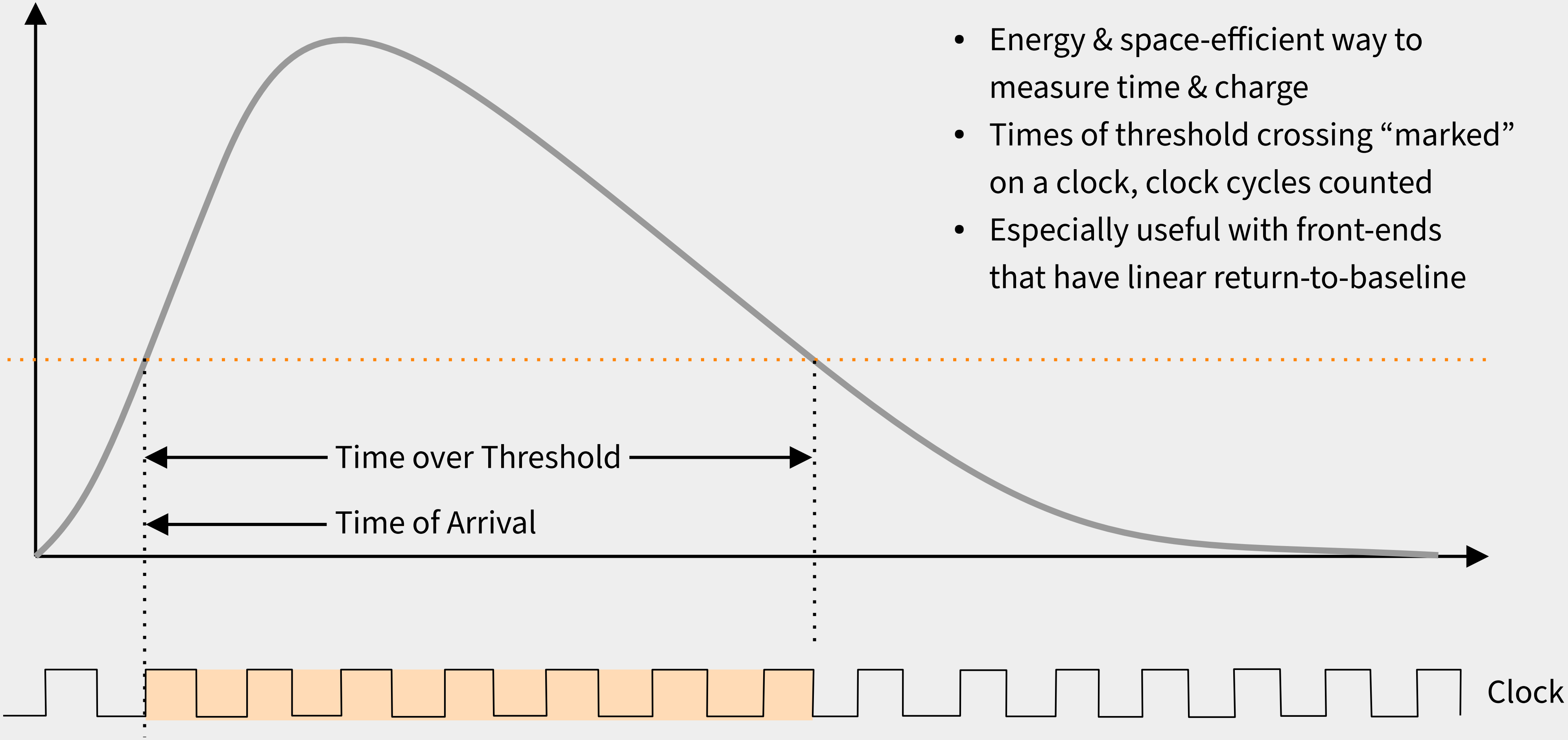


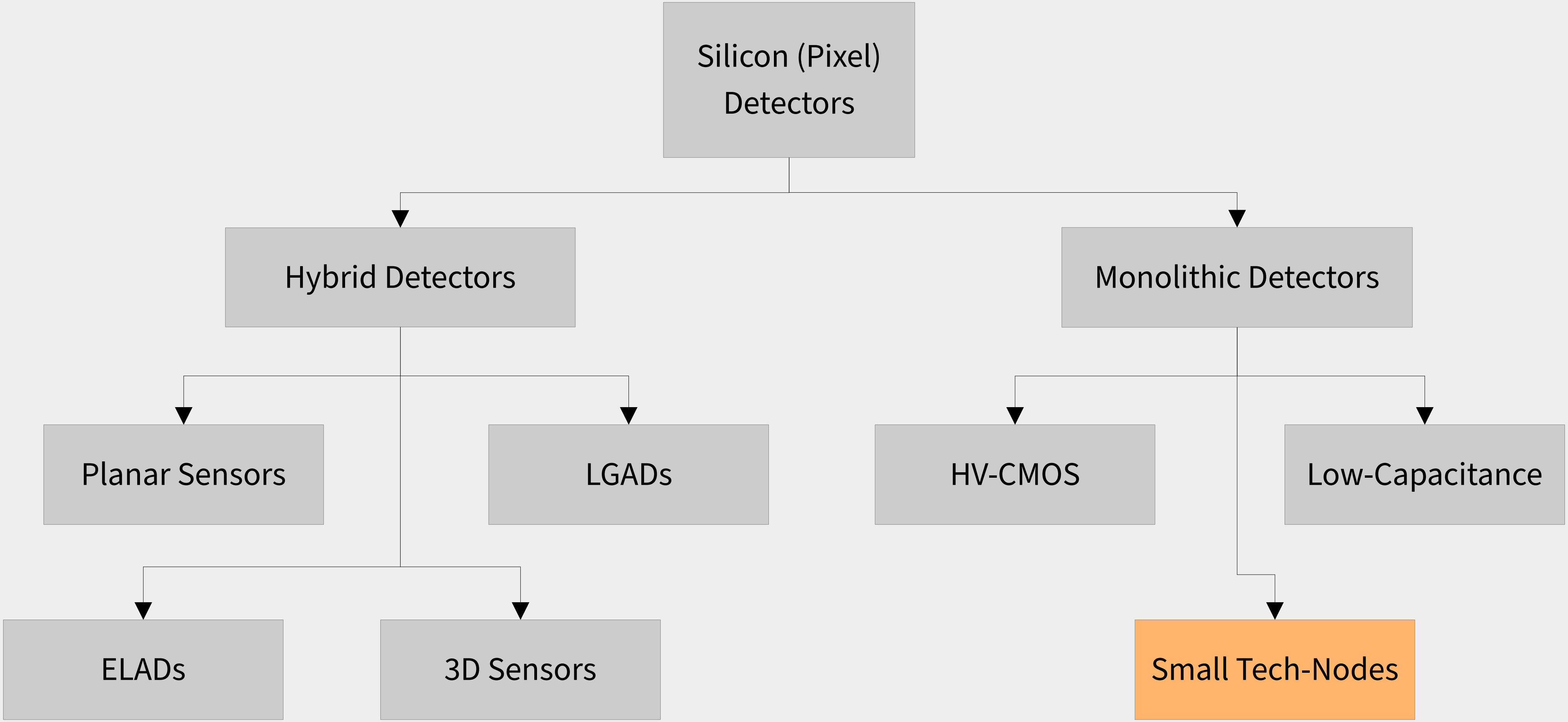


significantly
faster peaking time

Time of Arrival & Time over Threshold

- Energy & space-efficient way to measure time & charge
- Times of threshold crossing “marked” on a clock, clock cycles counted
- Especially useful with front-ends that have linear return-to-baseline





Silicon (Pixel) Detectors

Hybrid Detectors

Monolithic Detectors

Planar Sensors

LGADs

ELADs

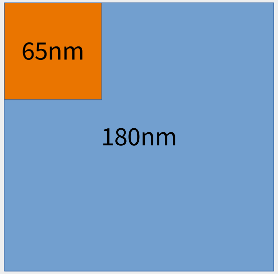
3D Sensors

HV-CMOS

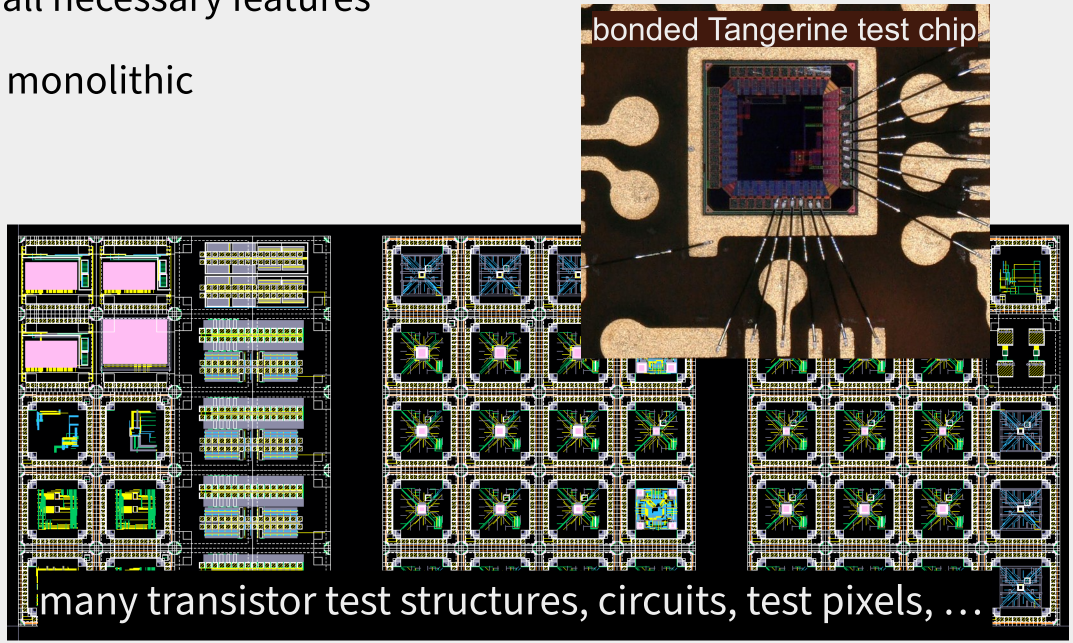
Low-Capacitance

Small Tech-Nodes

Smaller CMOS Nodes for Increased Logic Density



- **New CMOS imaging technologies** become available from foundries
- E.g. 65nm CMOS imaging process – under investigation for HEP detectors
  - Lower analog/digital power consumption
  - Higher logic density, allow pixels ≤ 25 µm with all necessary features
  - Bridging gap in front-end capabilities hybrid ↔ monolithic
- Issues to overcome:
  - Accessibility of technologies from vendors
  - Analog circuitry stays almost same size, only digital parts scale well
  - Needs to be **tested as particle detectors**!

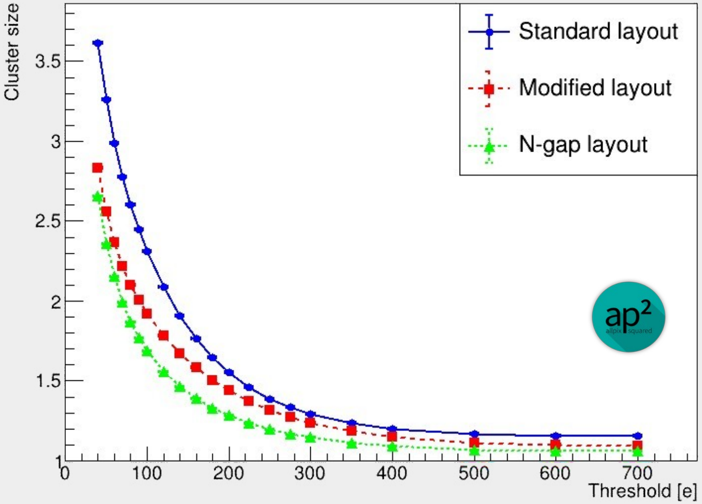


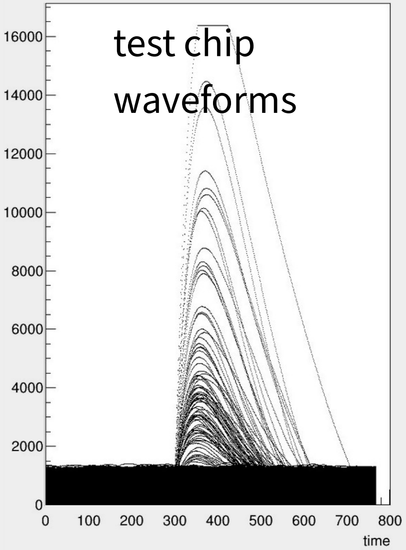
bonded Tangerine test chip

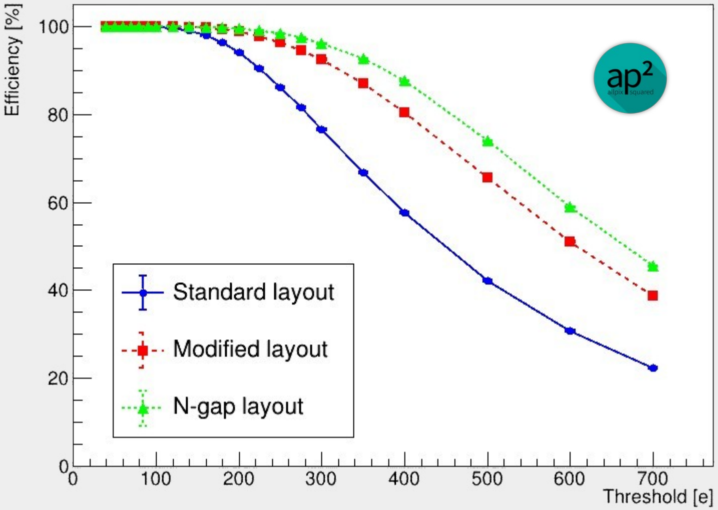
many transistor test structures, circuits, test pixels, …

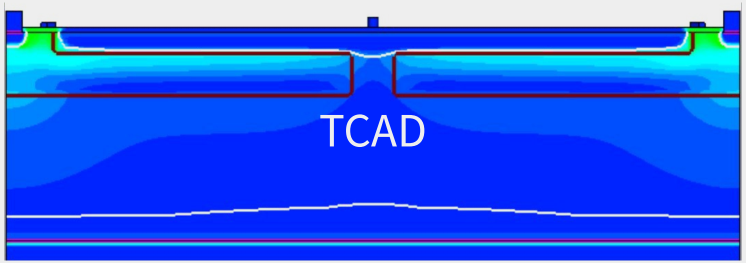
Understanding a new Technology

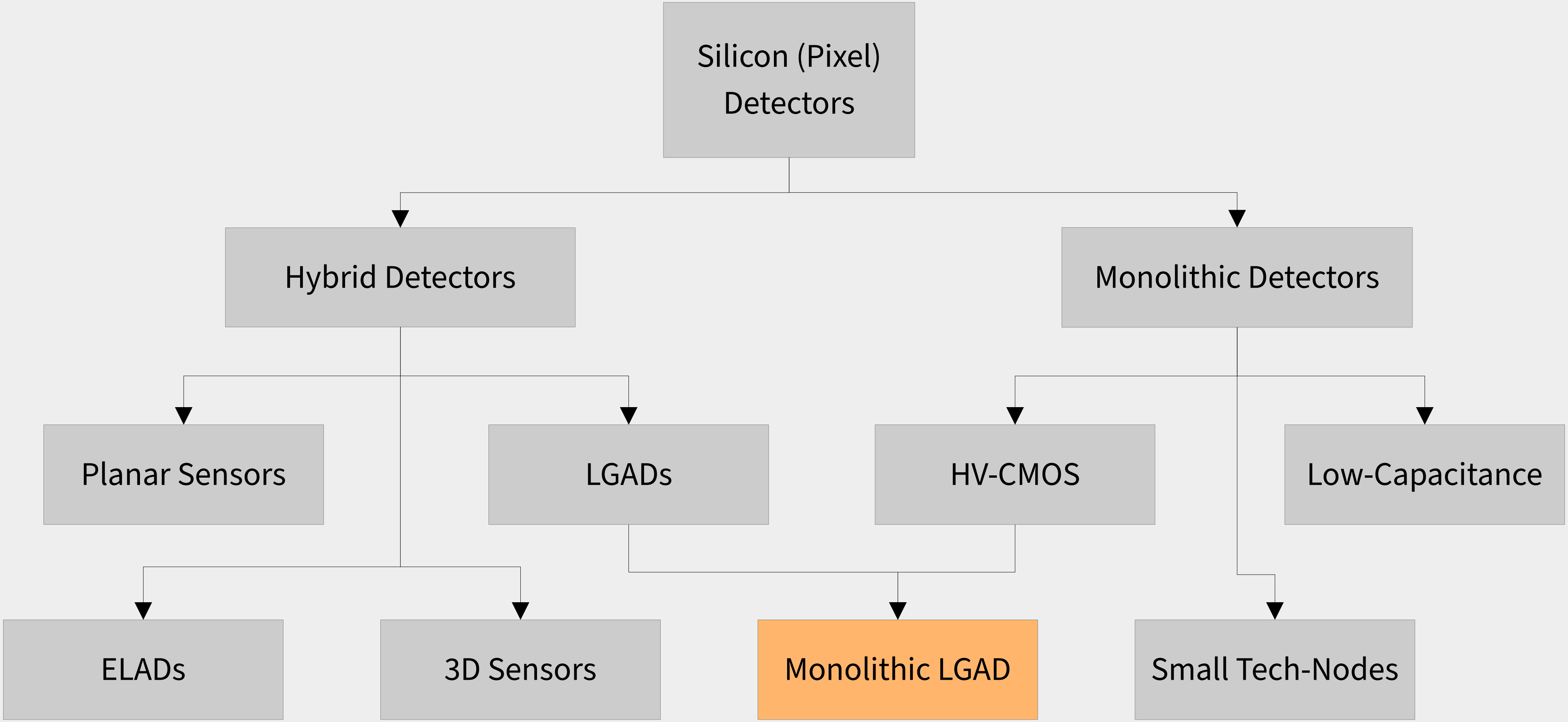
- Extensive **TCAD & Monte Carlo simulations** to optimize sensor response
  - Signal formation time
  - Efficiency
  - Cluster size, resolution
- **Compare to data from prototypes** to gain understanding of the technology




test chip waveforms




TCAD


Silicon (Pixel) Detectors

Hybrid Detectors

Monolithic Detectors

Planar Sensors

LGADs

HV-CMOS

Low-Capacitance

ELADs

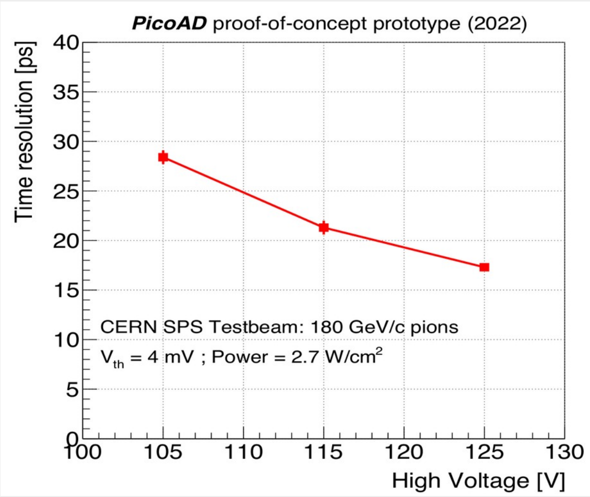
3D Sensors

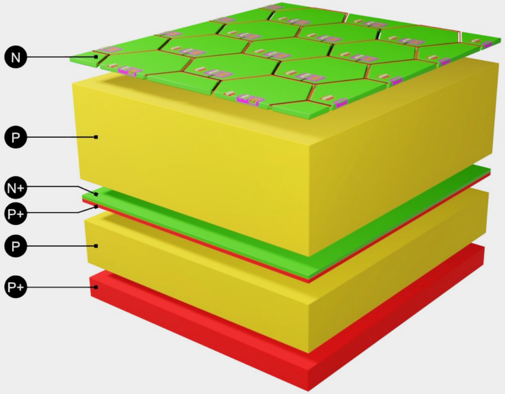
Monolithic LGAD

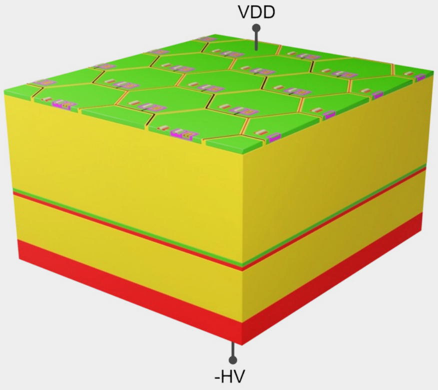
Small Tech-Nodes

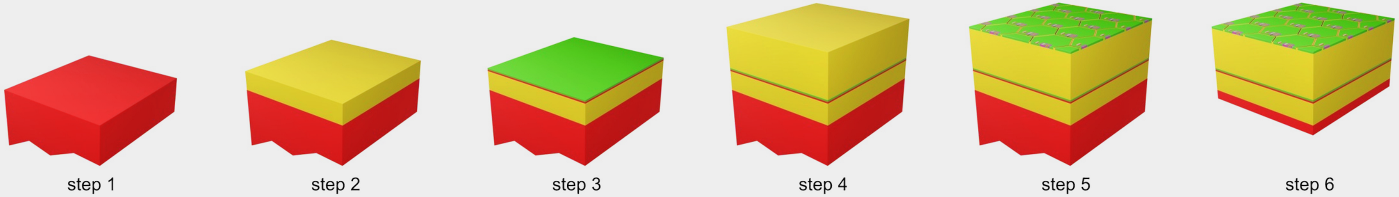
Timing in MAPS Sensors

- Investigation of embedding LGAD-like gain layer in MAPS
- Requires multi-step processing
- Promising results from PicoAD prototype



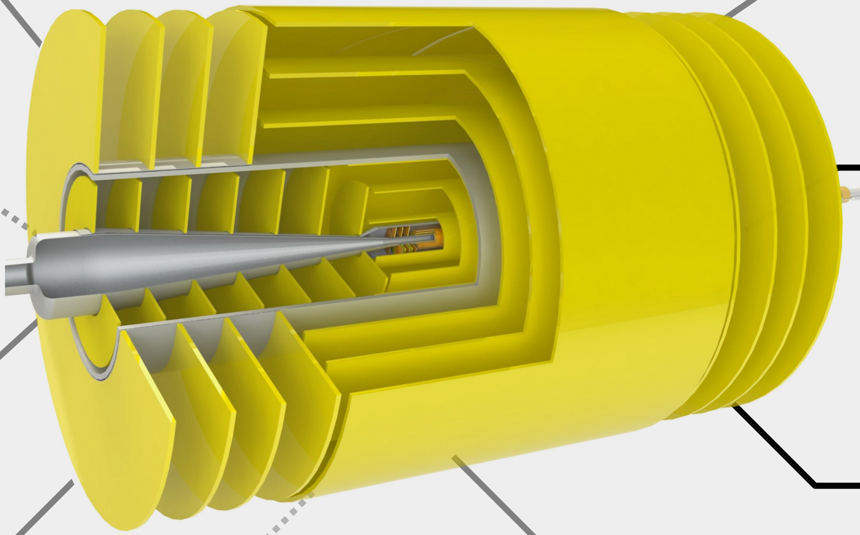






https://indico.cern.ch/event/1058977/contributions/4631550/

New Sensors Open Up New Opportunities



Powering

Machine interface

Cooling

Front-end electronics

Magnet

CLICdp

Mechanical support

Data transmission

Sensors

Module design


DESY.