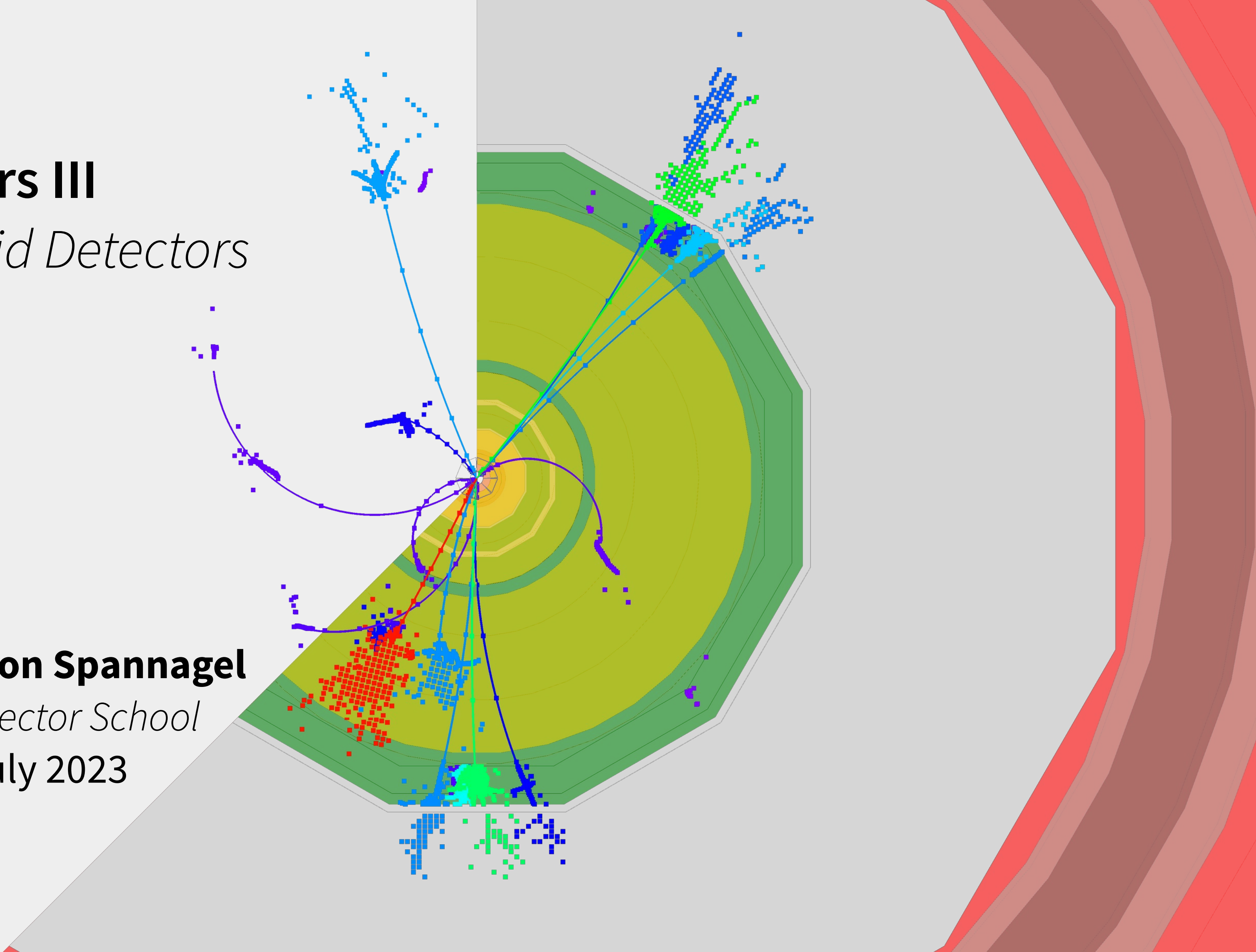
https://www.desy.de/

Silicon Detectors III

Sensors for Hybrid Detectors



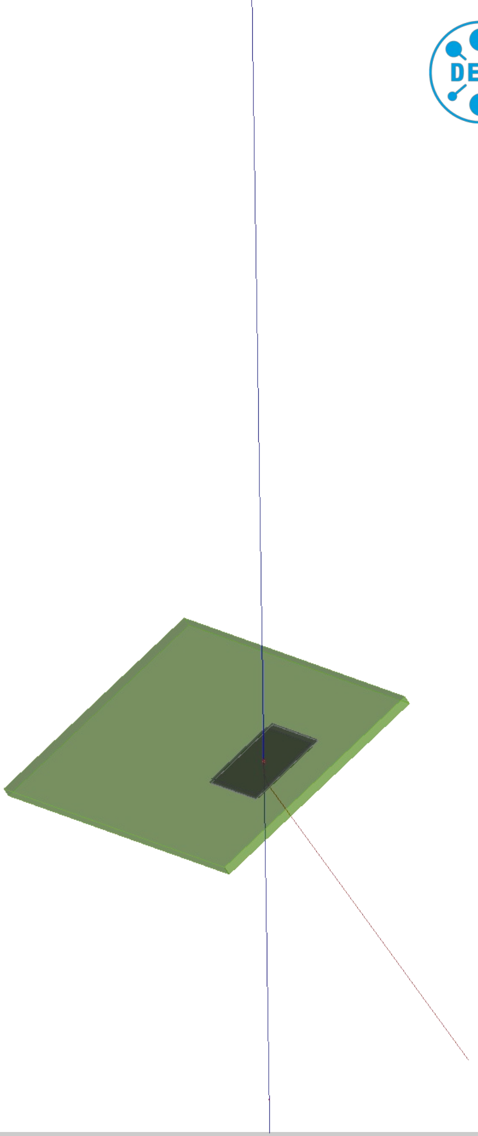
Simon Spannagel

EURIZON Detector School

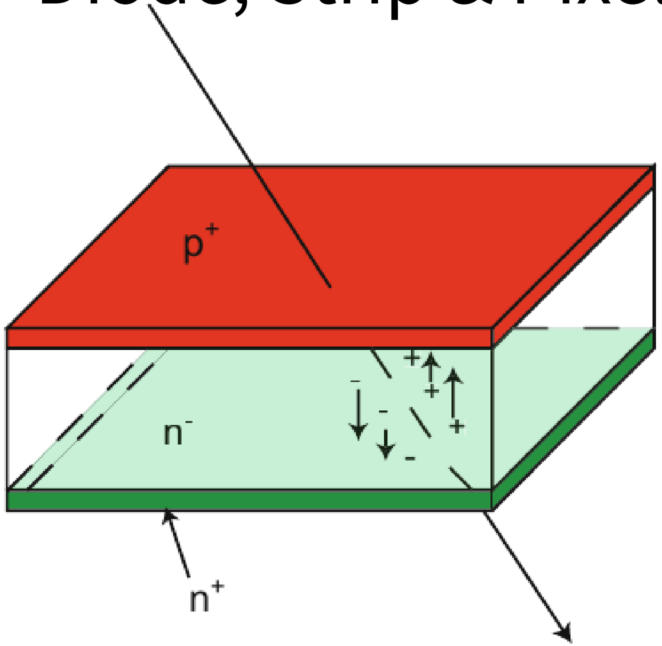
19 July 2023

Recap:

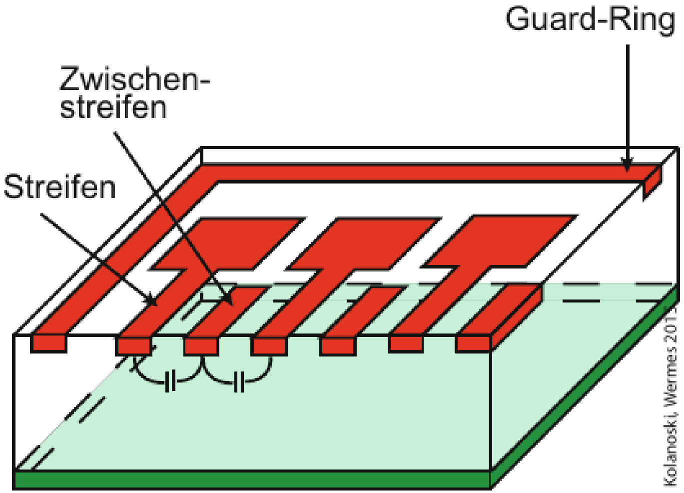
Segmented Silicon Detectors



Diode, Strip & Pixel

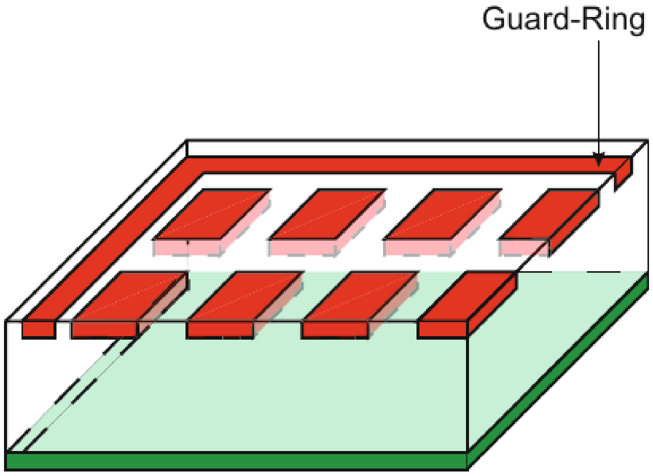


- Simplest geometry
- No position measurement



Kolanoski, Wermes 201

- N channels
- Straight-forward connection to ASIC
- Problem of ghost hits

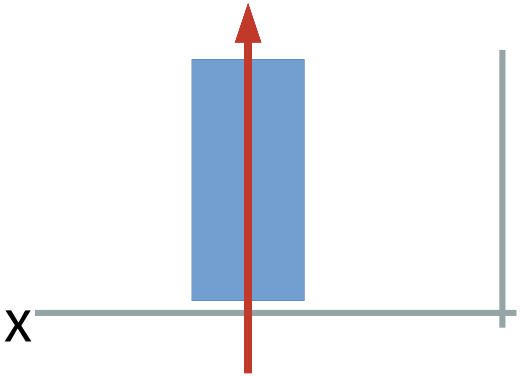


- N^2 channels
- Intrinsic 2D measuremtent
- Issue connecting channels

Spatial Resolution – Summary

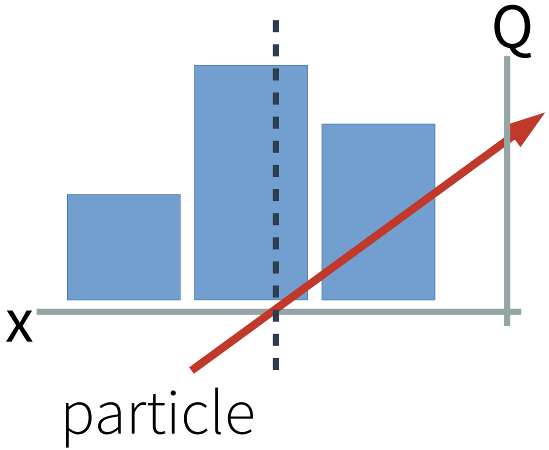
- Just a **single channel** struck:
  precision limited to variance of uniform distribution

$$x = x_i \qquad \rightarrow \qquad \sigma_x = d/\sqrt{12}$$

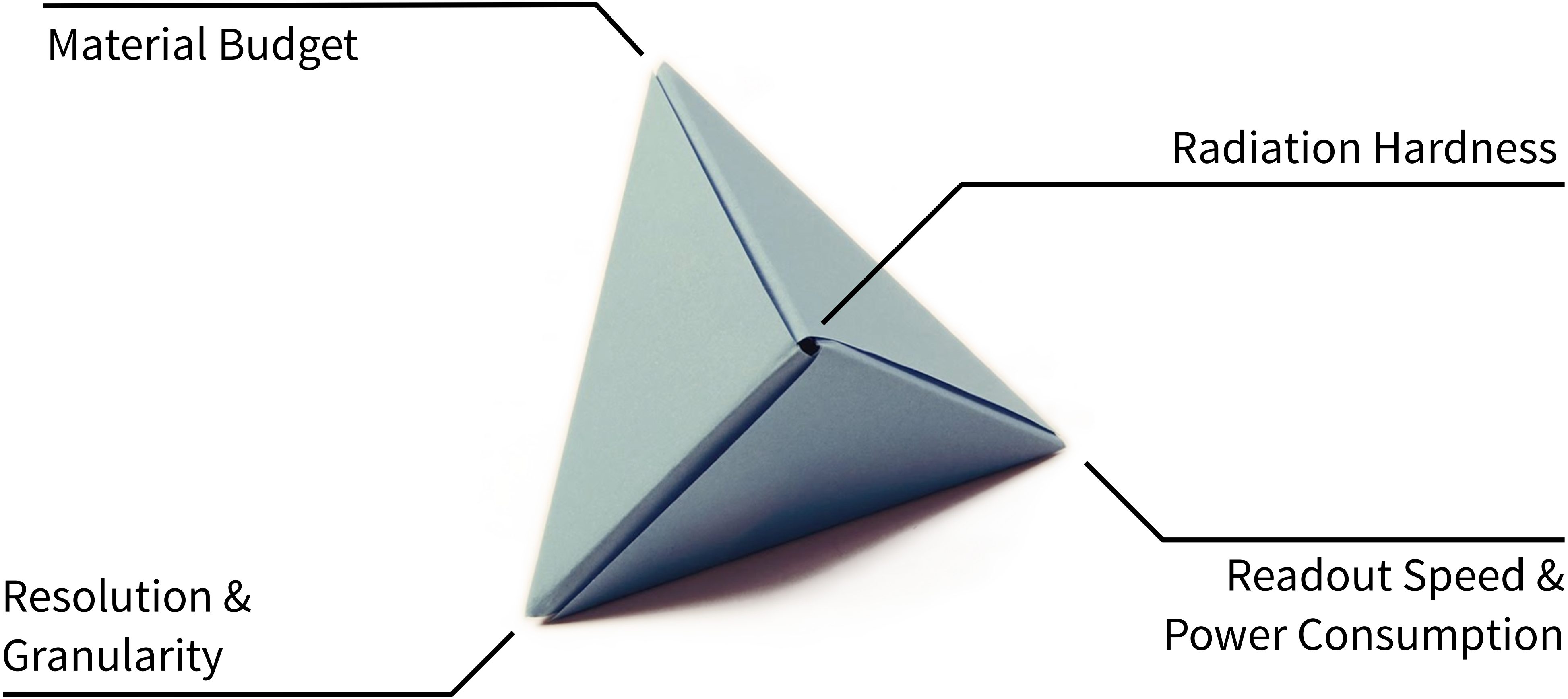


- **Multiple channels** struck (charge sharing):
  interpolation using relative energy / charge distribution

$$x = \frac{\sum_{i=1}^{N} q_i x_i}{\sum_{i=1}^{N} q_i}$$



Challenges for Silicon Detectors



Material Budget

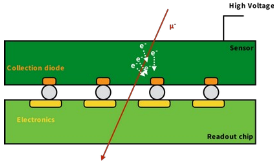
Radiation Hardness

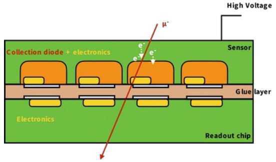
Resolution &
Granularity

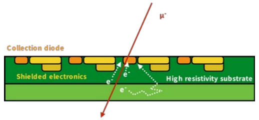
Readout Speed &
Power Consumption

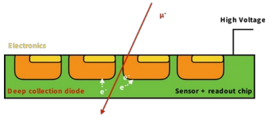
(Some) Silicon Sensor Technologies

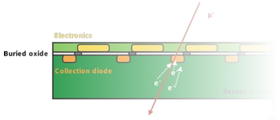
for Vertex & Tracking Detectors











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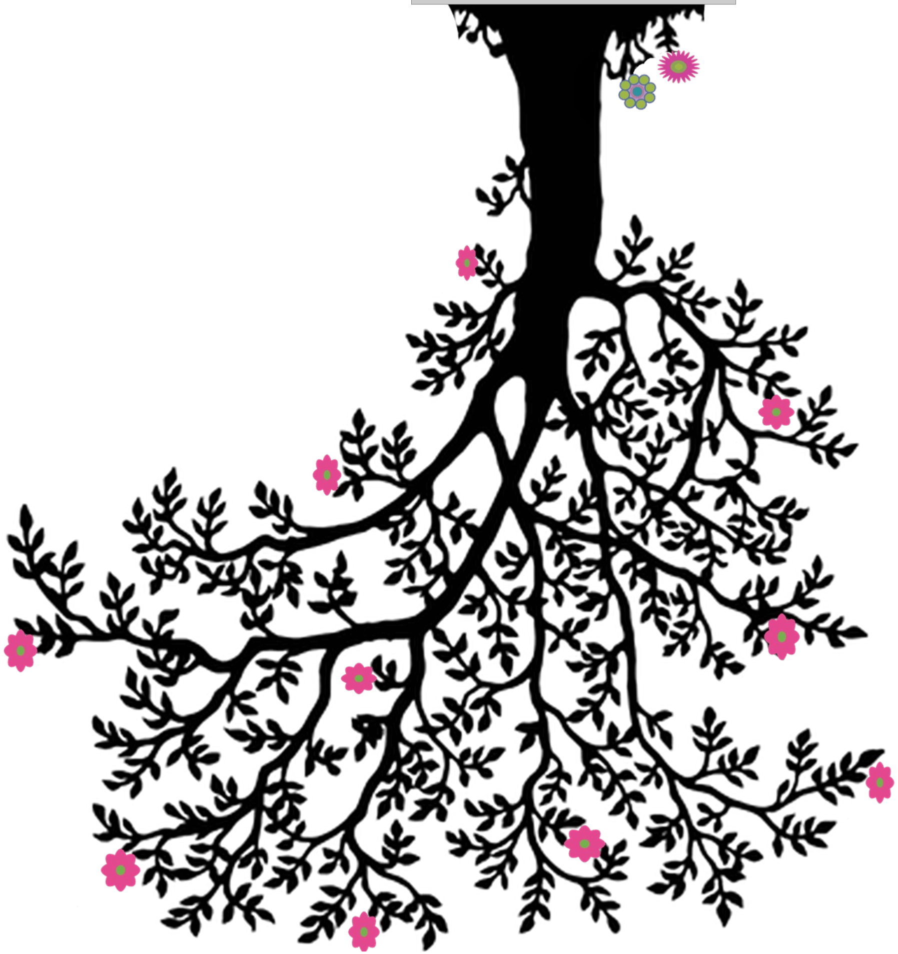
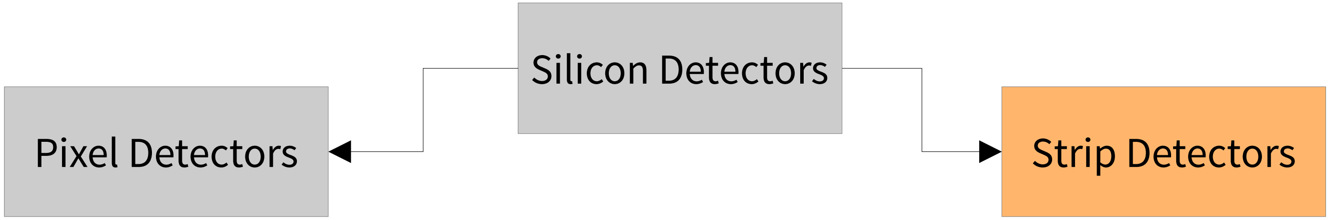
Silicon Detectors





Silicon Detectors

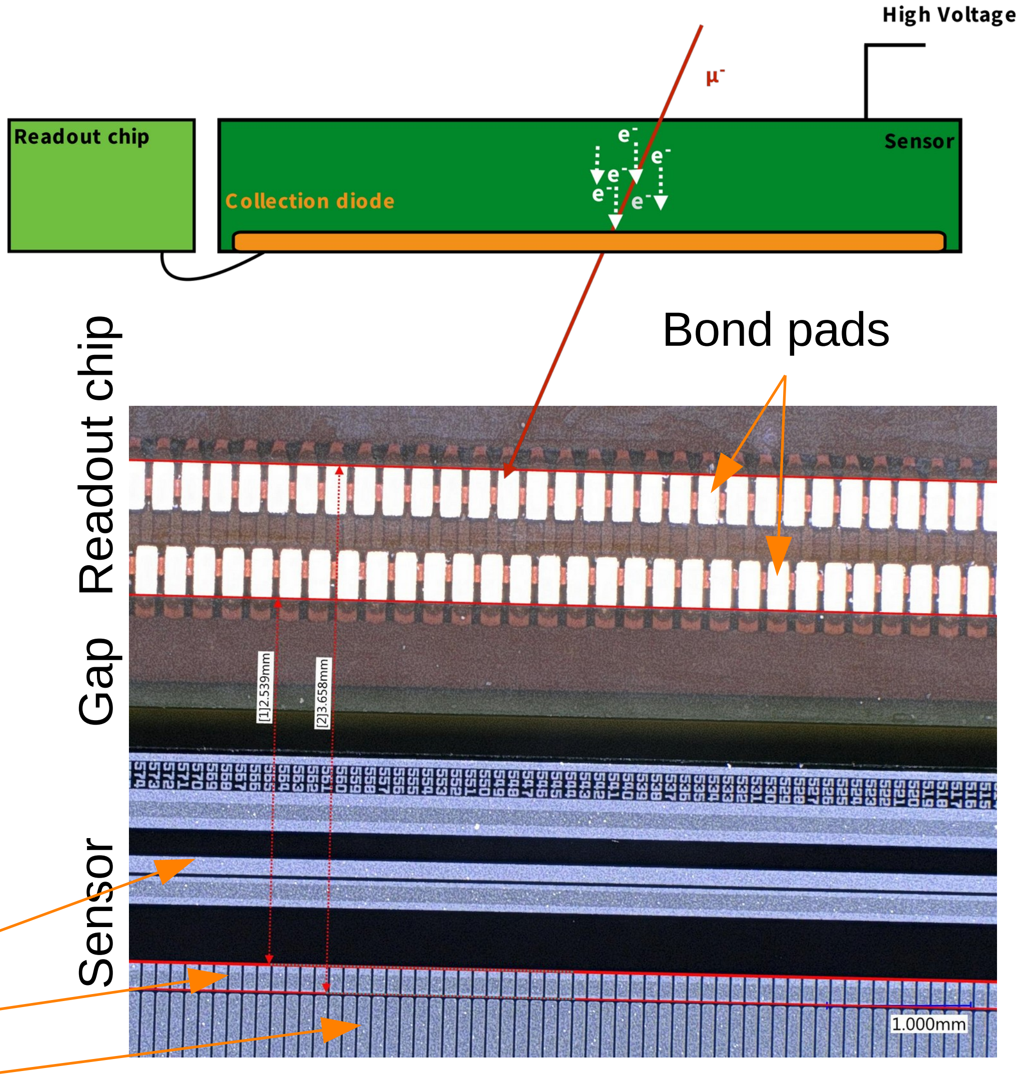
Pixel Detectors

Strip Detectors

Silicon Strip Detectors

- 1D segmentation of electrodes
- Electronics adjacent to sensor
- Connection via wirebonds

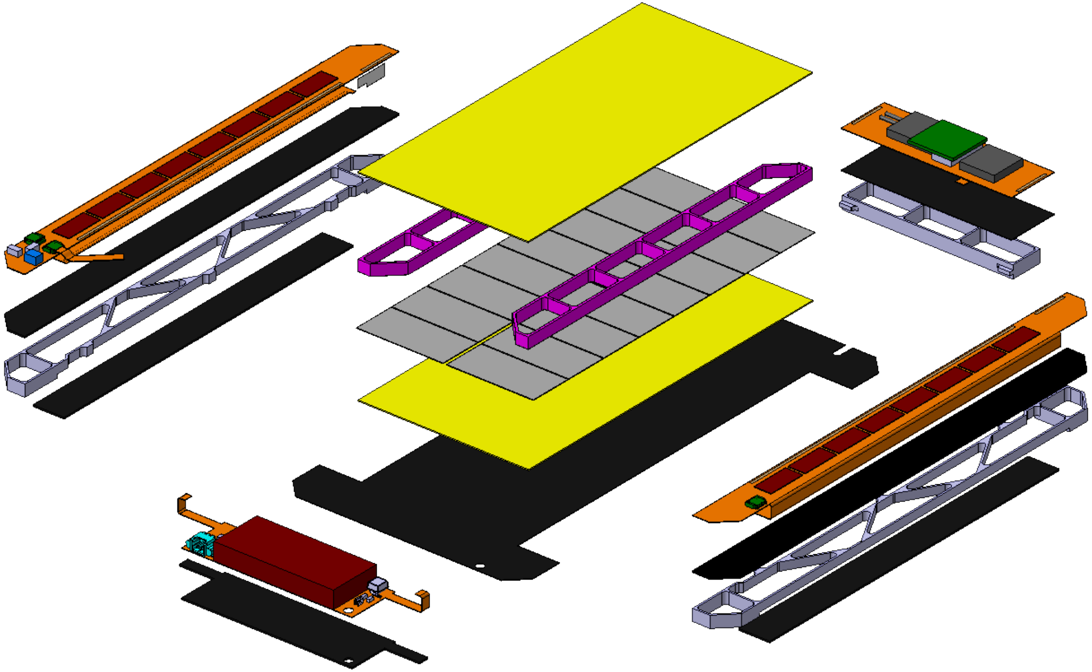
- Used for large-area instrumentation: Large radii from interaction point, large lever arm for momentum measurements



Detector Modules – Complex Structures

- Sensor is only one part of complex system, that contains…
    - Readout ASICs
    - DC-DC converters
    - Optical transmitters
    - Electrical interconnects / flexprints
    - Mechanical support, spacers
    - Thermal contacts
    - …

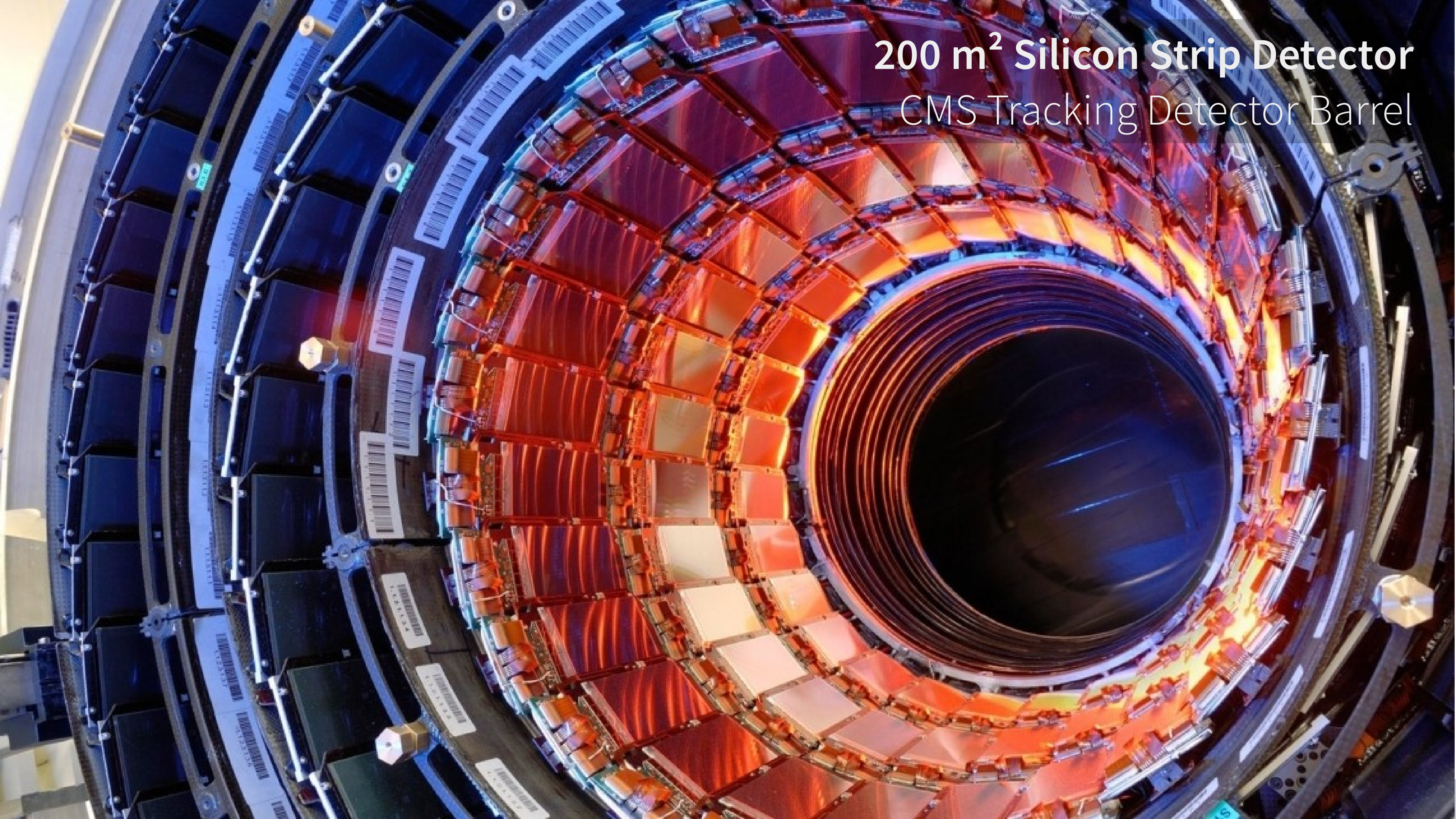
CMS Phase 2 Tracker Upgrade
PS Module exploded view

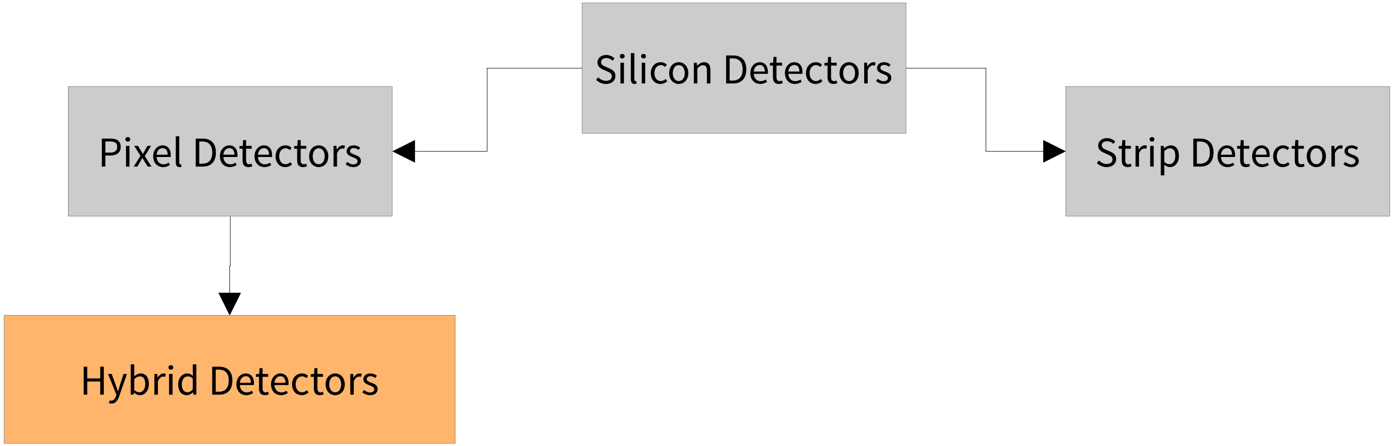


- Very complex to assemble at micrometer precision level!

200 m^2 Silicon Strip Detector

CMS Tracking Detector Barrel





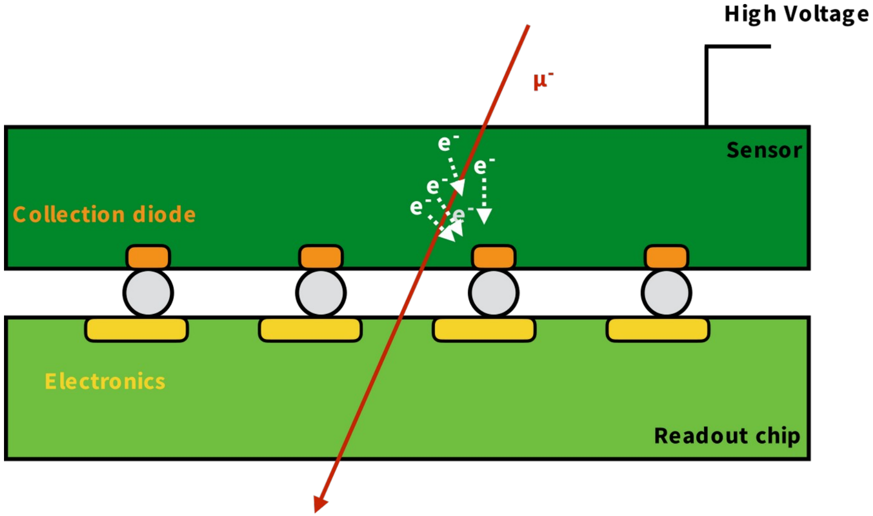
Silicon Detectors

Pixel Detectors

Strip Detectors

Hybrid Detectors

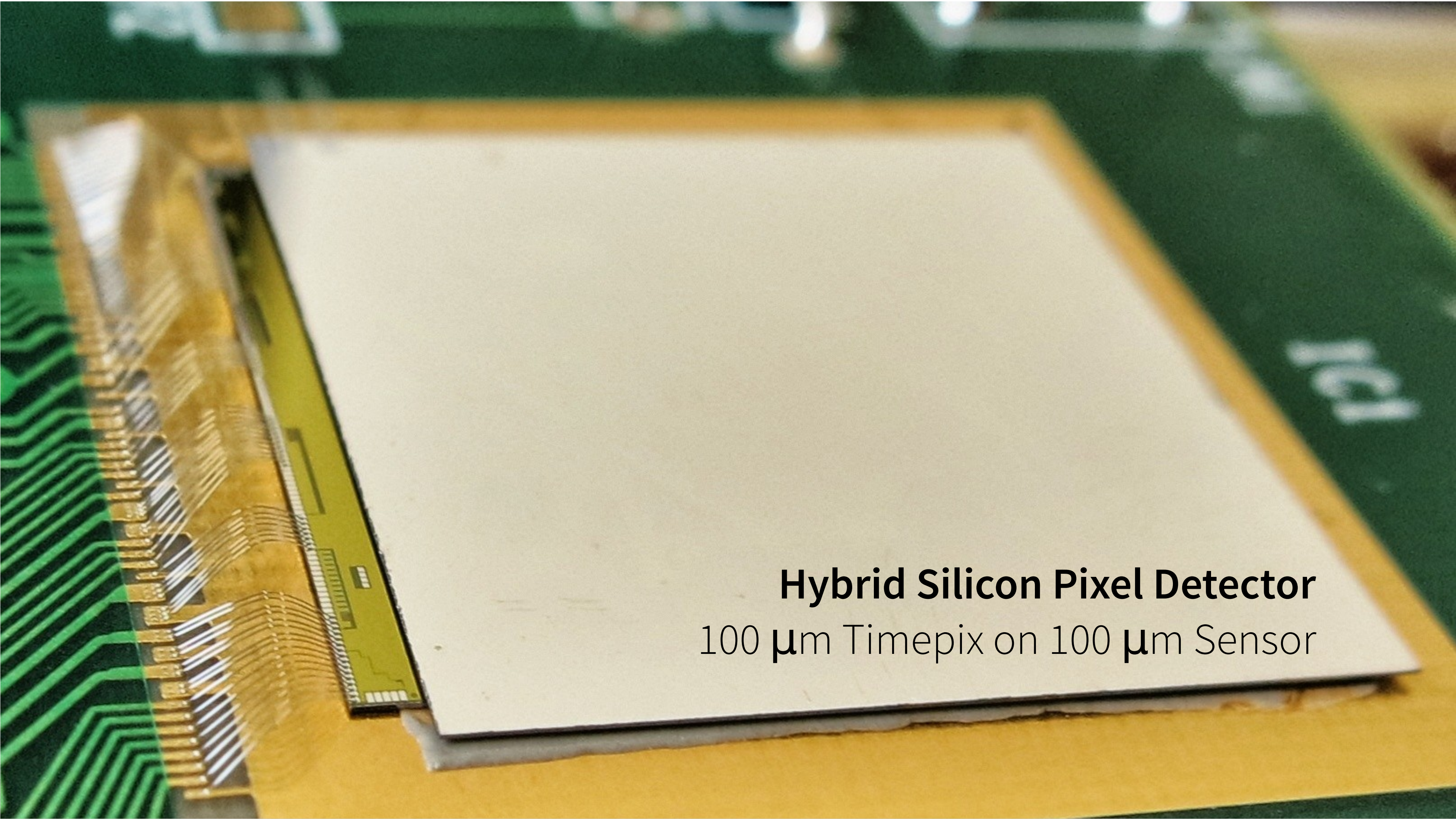
Hybrid Pixel Detectors



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

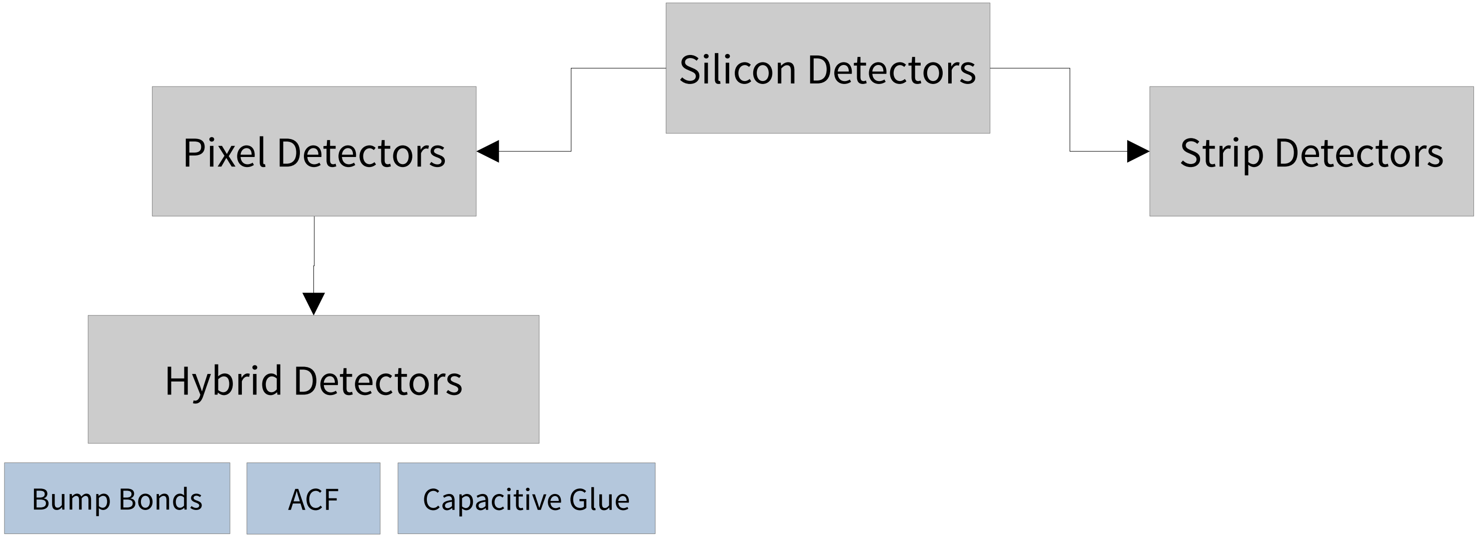
➕ Established mixed-mode CMOS
Complex circuits possible
Small technology nodes available

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



Hybrid Silicon Pixel Detector

100 µm Timepix on 100 µm Sensor


Silicon Detectors

Pixel Detectors

Strip Detectors

Hybrid Detectors

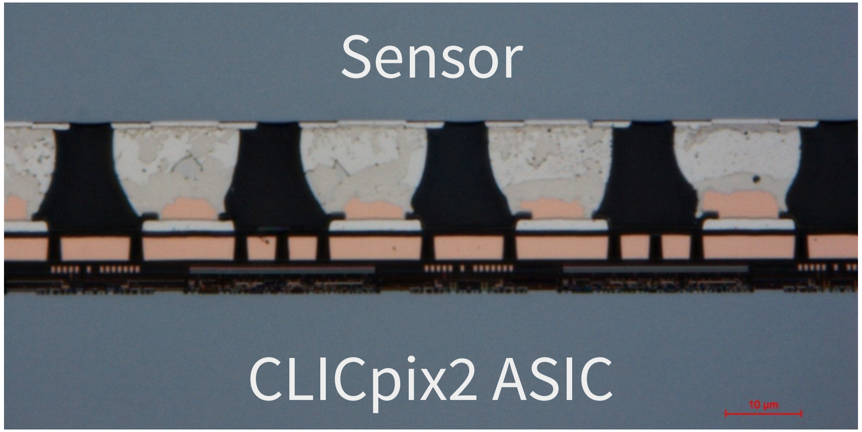
Bump Bonds

ACF

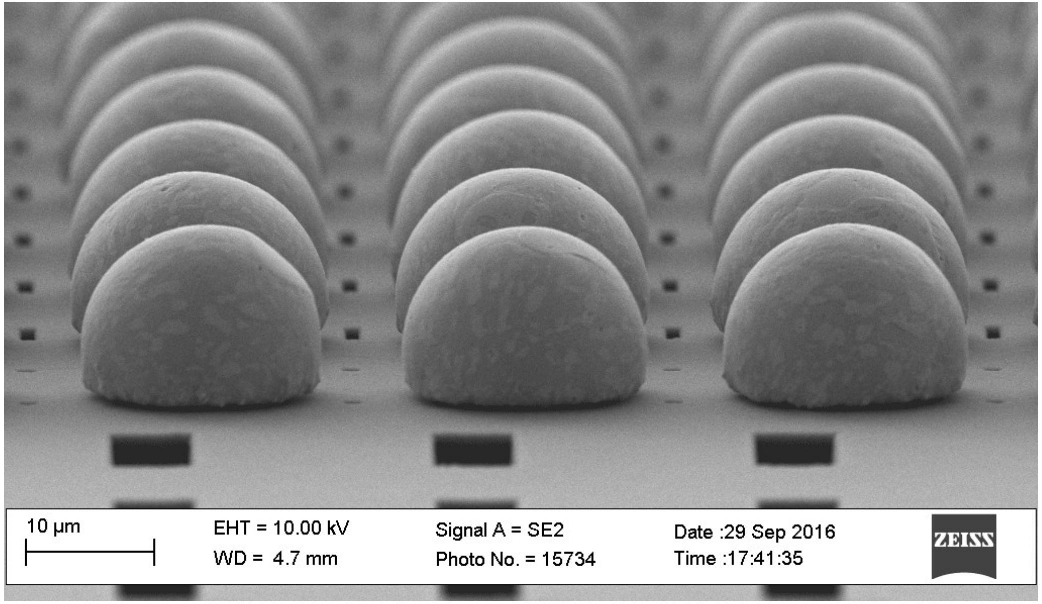
Capacitive Glue

Hybridization: Bump Bond Interconnects

- Different technologies available
- Very common: Bump bonding
  - Size: ~ 20 µm
  - Material: Lead-Tin, Indium, …



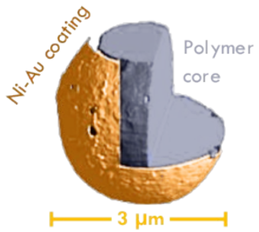
https://doi.org/10.1088/1748-0221/14/06/C06003

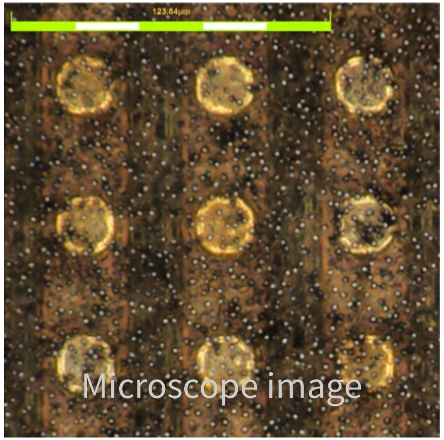


- Different placement techniques
  - Solder spheres → individual chips
  - Via lithography → wafer-level

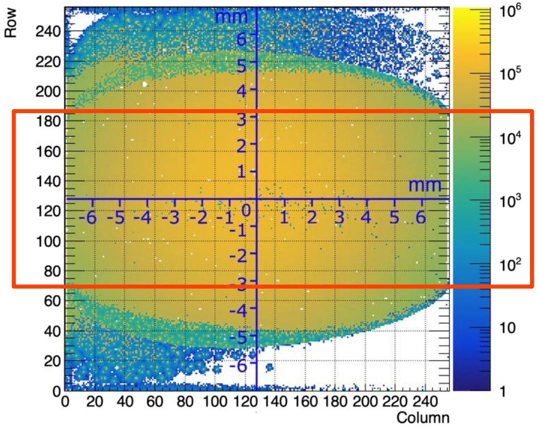
Hybridization: Anisotropic Conductive Film

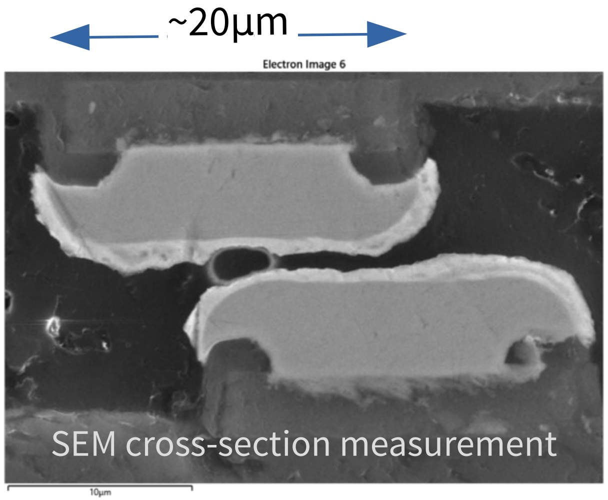
- Alternative to traditional solder-bump bonding
- Adhesive film with conductive micro-particles
  - Stochastically distributed in film
  - Some spheres end up under bond pads, get deformed, establish contact
- Widely used in display industry in one dimension, challenge: 2D distribution



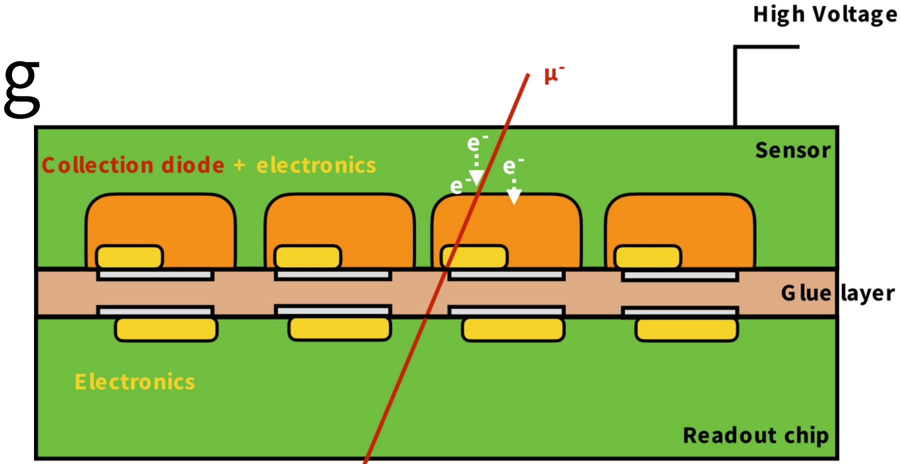


- Requires careful optimization of
  - Film thickness
  - # spheres/area
  - Bonding force…
- Currently in R&D phase

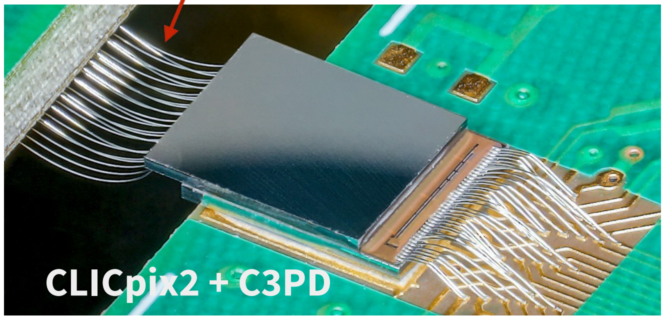




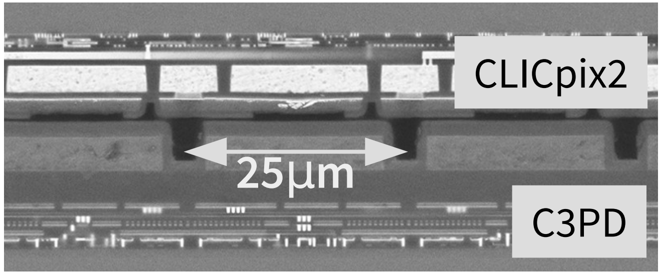
Hybridization: Capacitive Coupling

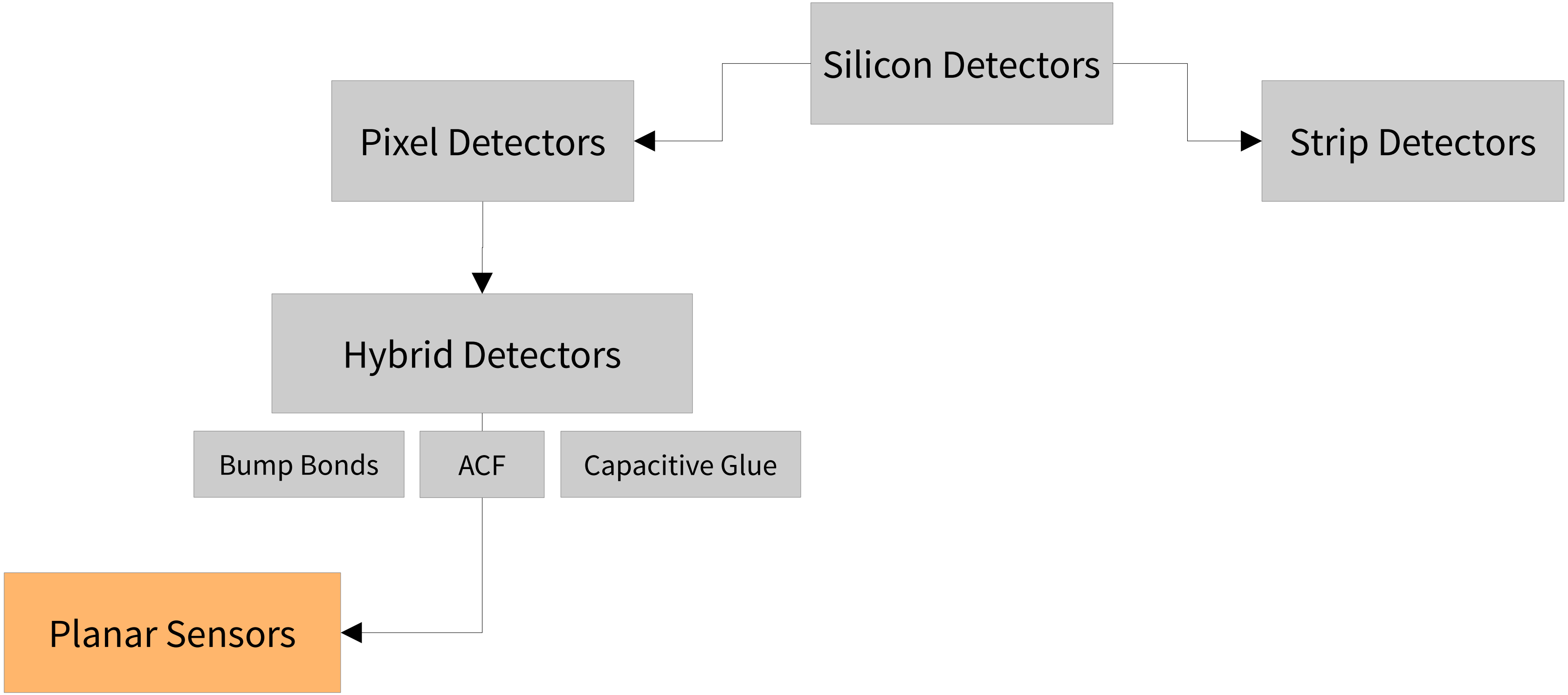


- Combination of “traditional” readout chip and active sensor
- Only analog part (amplification) in sensor



- Advantages:
  - Large signal from amplifier while rather simple circuitry in sensor
  - Can use full feature set of readout chip CMOS process
- Challenges:
  - Gluing requires precise alignment
  - Main influence: distance – good uniformity required
  - Requires connecting & powering two chips





Silicon Detectors

Pixel Detectors

Strip Detectors

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Bump Bonds

ACF

Capacitive Glue

Planar Sensors

Planar Silicon Sensors

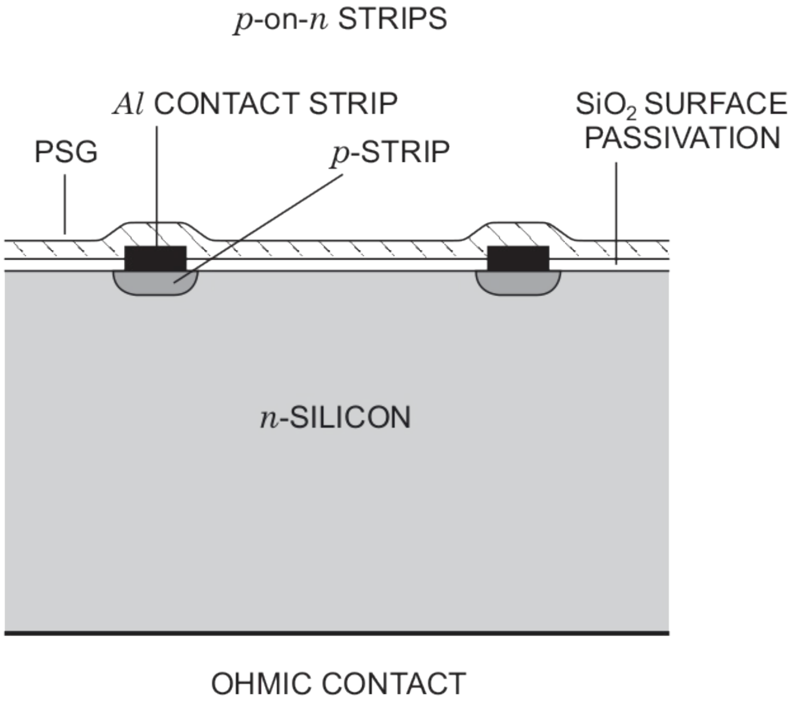
typical doping (p-in-n sensor):
$N_A \approx 10^{15}\ cm^{-3}$
$N_D \approx 10^{12}\ cm^{-3}$

- Asymmetric pn-junctions, here: *p*-in-*n*
- Lightly doped *n* bulk sensor material
- Thin, highly-doped *p* implant
- Segmentation of implant: separate channels
- Backside: layer of highly doped n^+ as ohmic contact

✔ Straight-forward production,
Well-studied sensor designs

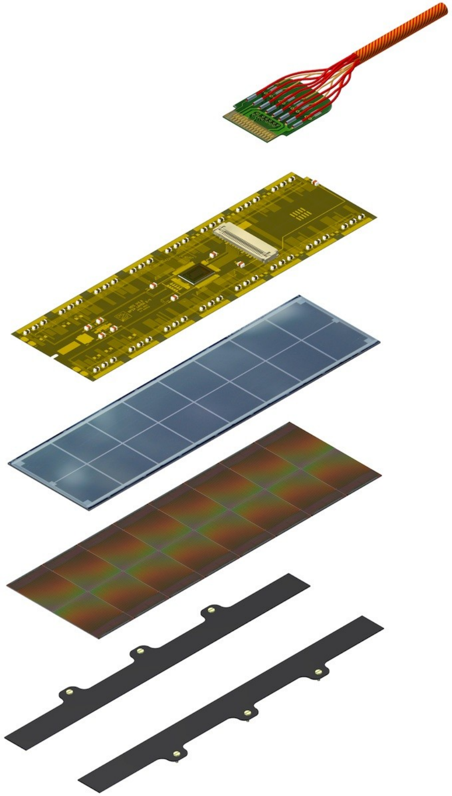
✔ 100% “fill factor” / fully efficient

✗ Long drift times lead to charge loss after irradiation



H. Spieler

Example: CMS Pixel Detector



Twisted pair cable

HDI (High Density Interconnect, signal and power handling)

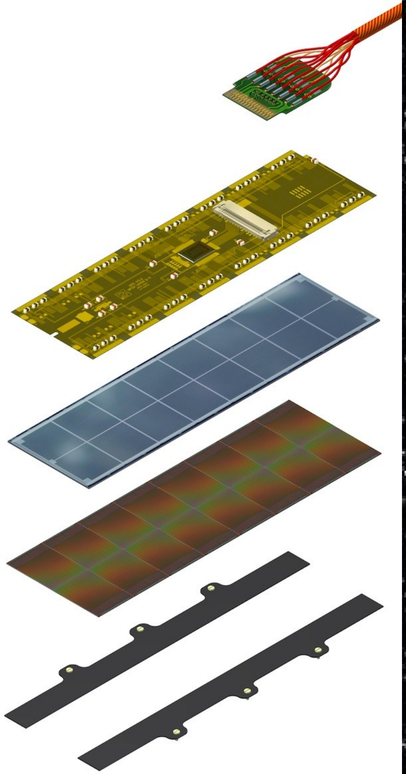
n^+-in-n silicon sensor

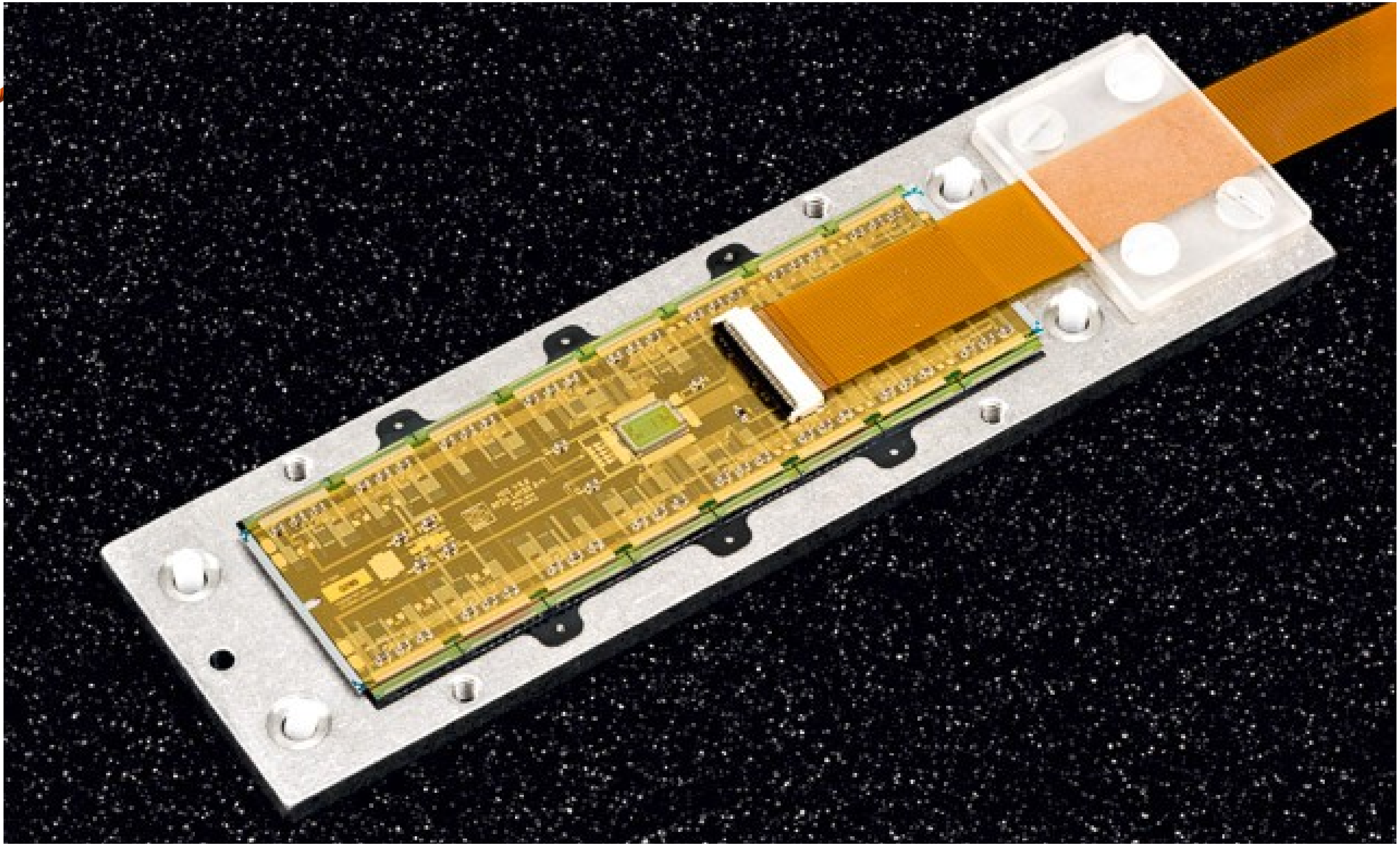
16 readout chips, bump bonded to sensor

Base strips for mounting

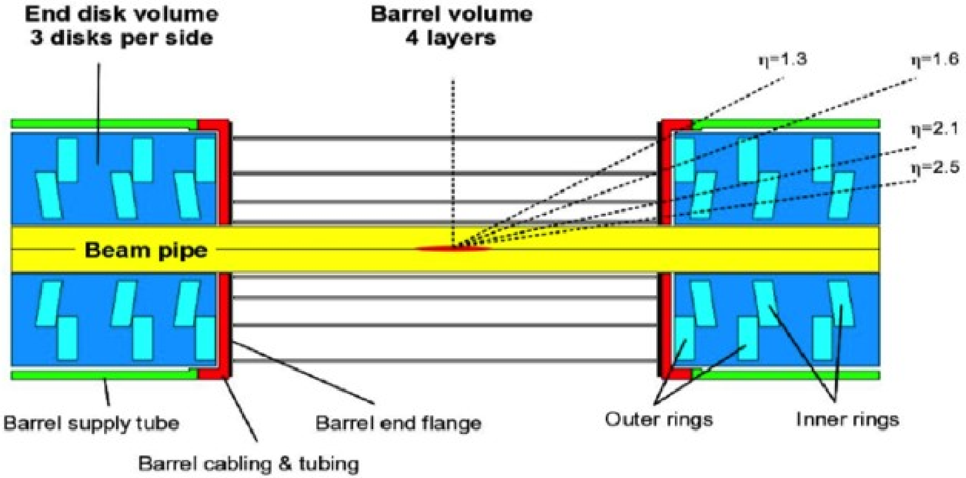
- Sensor:
  - n^+-in-n sensor technology
  - 285 μm thickness
  - 150 x 100 μm pitch
- Module:
  - 52 x 80 = 4160 pixels/chip
  - 16 chips → 4160 x 16 = 66560 pixels/module
  - Total size: 64.8 x 16.2 mm

Example: CMS Pixel Detector

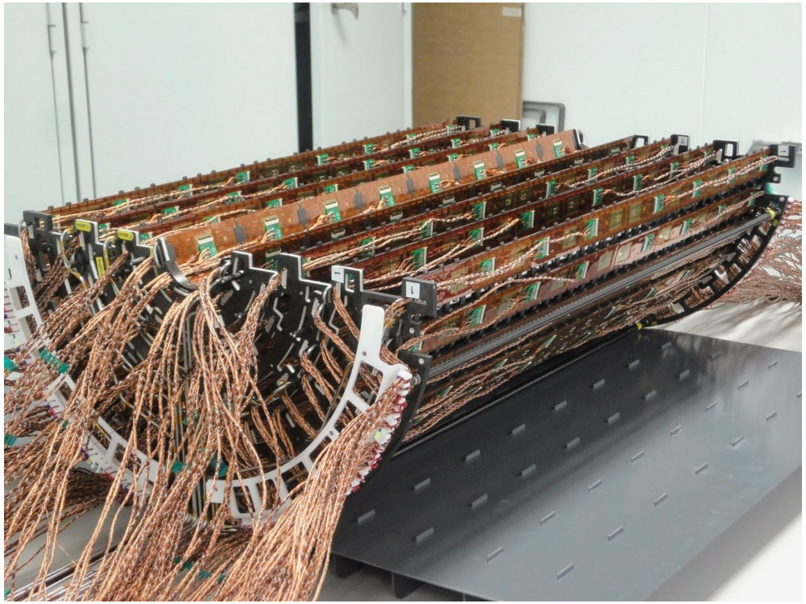




Example: CMS Pixel Detector



- Innermost part of the CMS Detector
  - Four *barrel* layers
    - Radii: 3.0, 6.8, 10.2, 16.0 cm
    - Length: 54.9 cm
  - Three *endcap* layers per side
    - Radii: 4.5 – 16.1 cm
- Total number of modules: **1856**
- *124 MPix* – with 25 ns time resolution
- Spatial resolution: > 5 μm

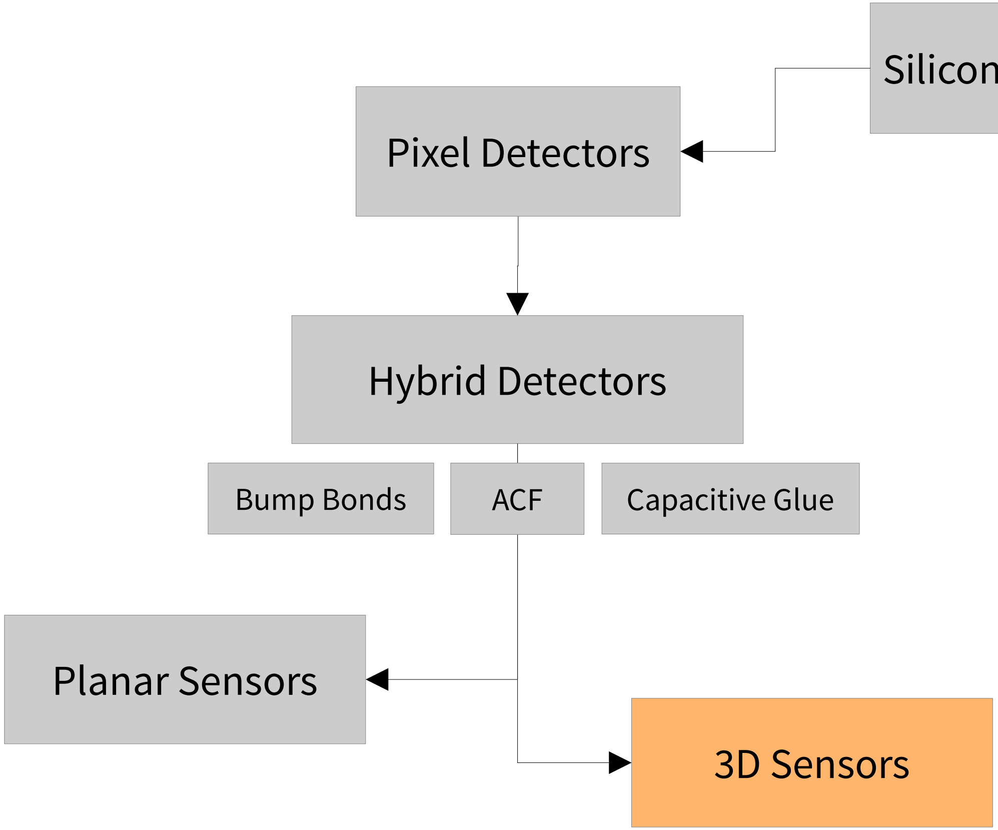


Installation of the Phase I Pixel Detector

CMS Experiment @ LHC

Endcap and Halfbarrel

CMS Phase I Pixel DeteCtor



Silicon Detectors

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Hybrid Detectors

Bump Bonds

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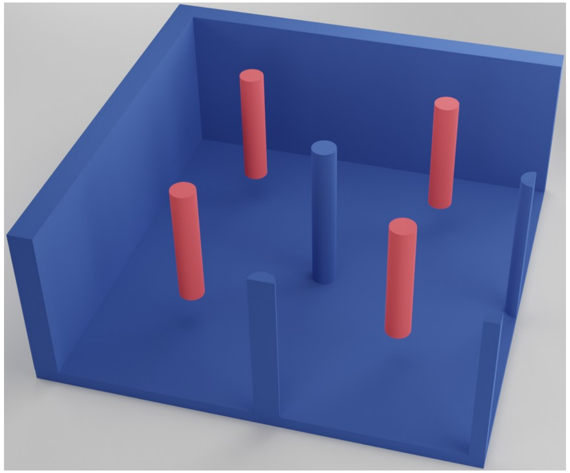
Planar Sensors

3D Sensors

3D Silicon Sensors



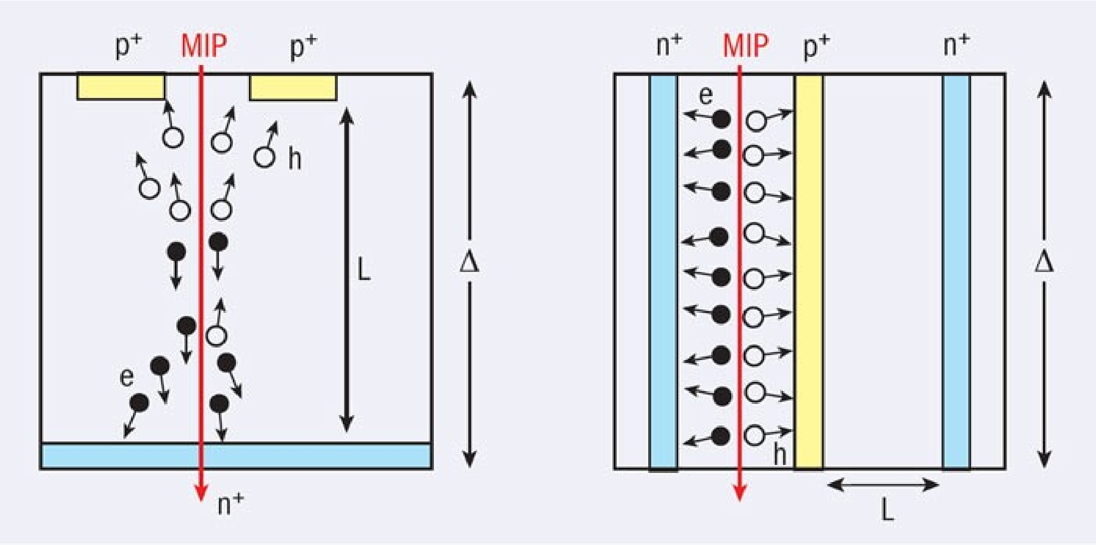
- p- and n-implants implemented as columns
- Vertical implants: horizontal pn-junction
- Electric field forms horizontally between columns

✔ Short drift time → fast!

✔ High radiation tolerance

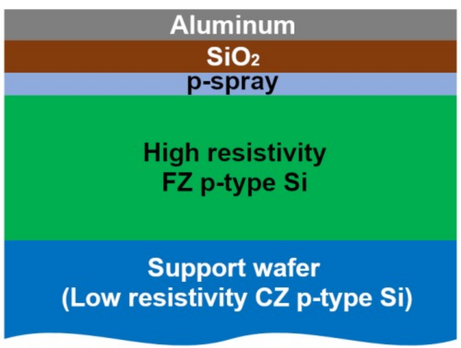
✗ High production costs & time

✗ Inefficiencies at vertical incidence

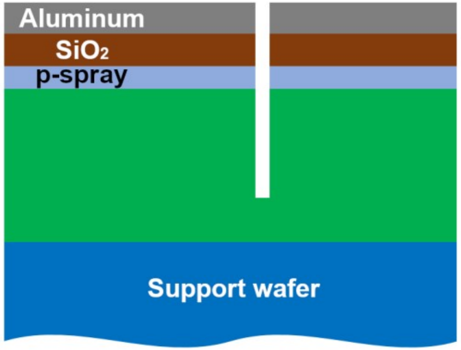


3D Silicon Sensors: Production

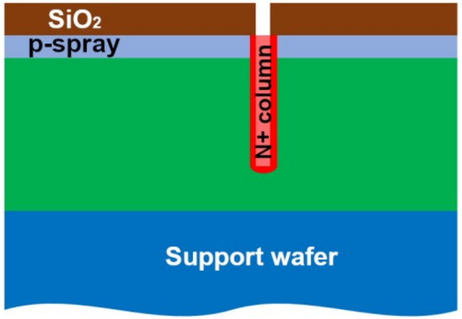
- DRIE (Deep Reactive Ion Etching): used in industry for MEMS, TSVs, …



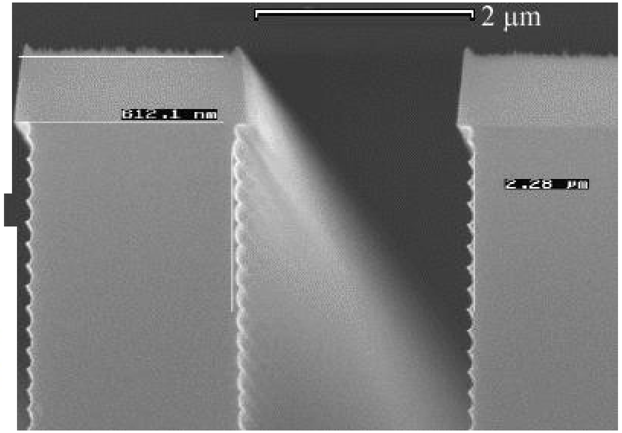
surface preparation

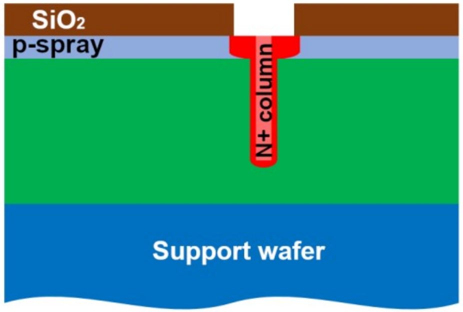


Lithography, DRIE etching

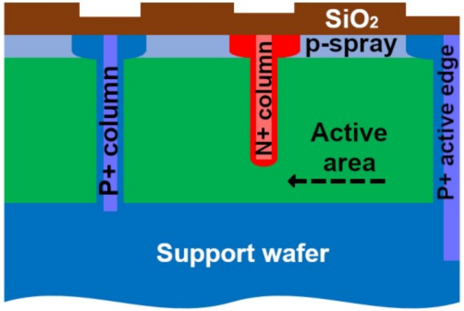


Polysilicon filling & doping

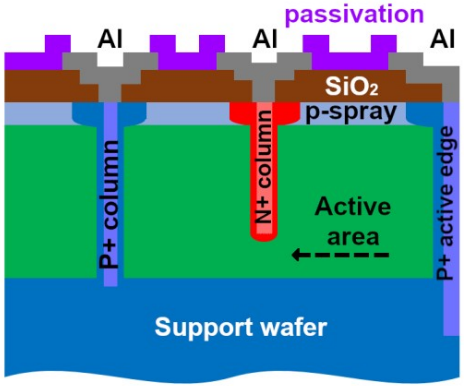




Lithography, n+ (surface) doping



Repeat for p columns…

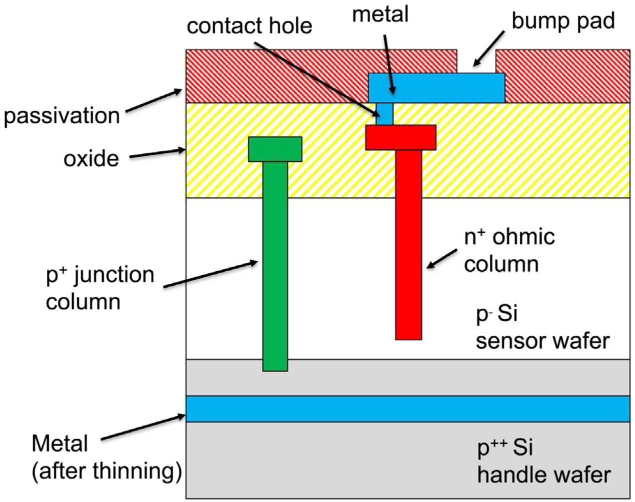


Standard surface processing

https://iopscience.iop.org/article/10.1088/1748-0221/17/08/P08003

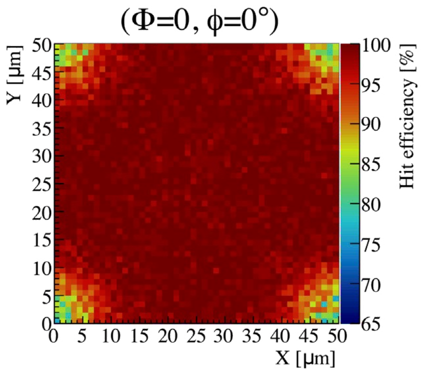
Example: ATLAS ITk 3D Pixel Sensors

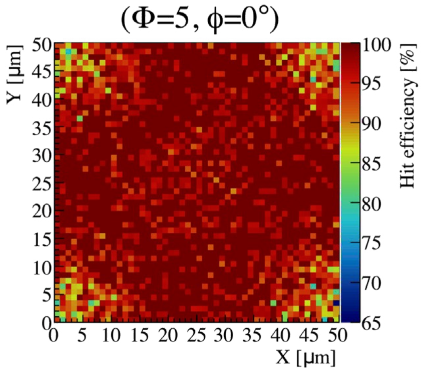
- Sensor for new inner tracker of ATLAS experiment
- 3D sensors for innermost layer of pixel detector
  - Very radiation hard (short drift times)
  - Different sensor layouts:
    50 x 50 µm
    25 x 100 µm

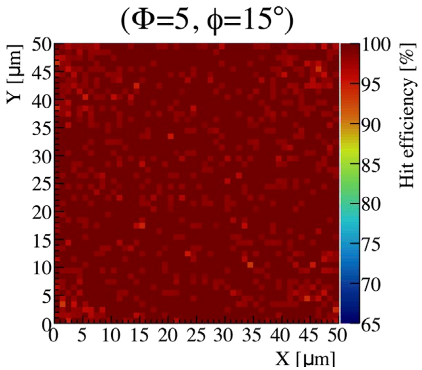


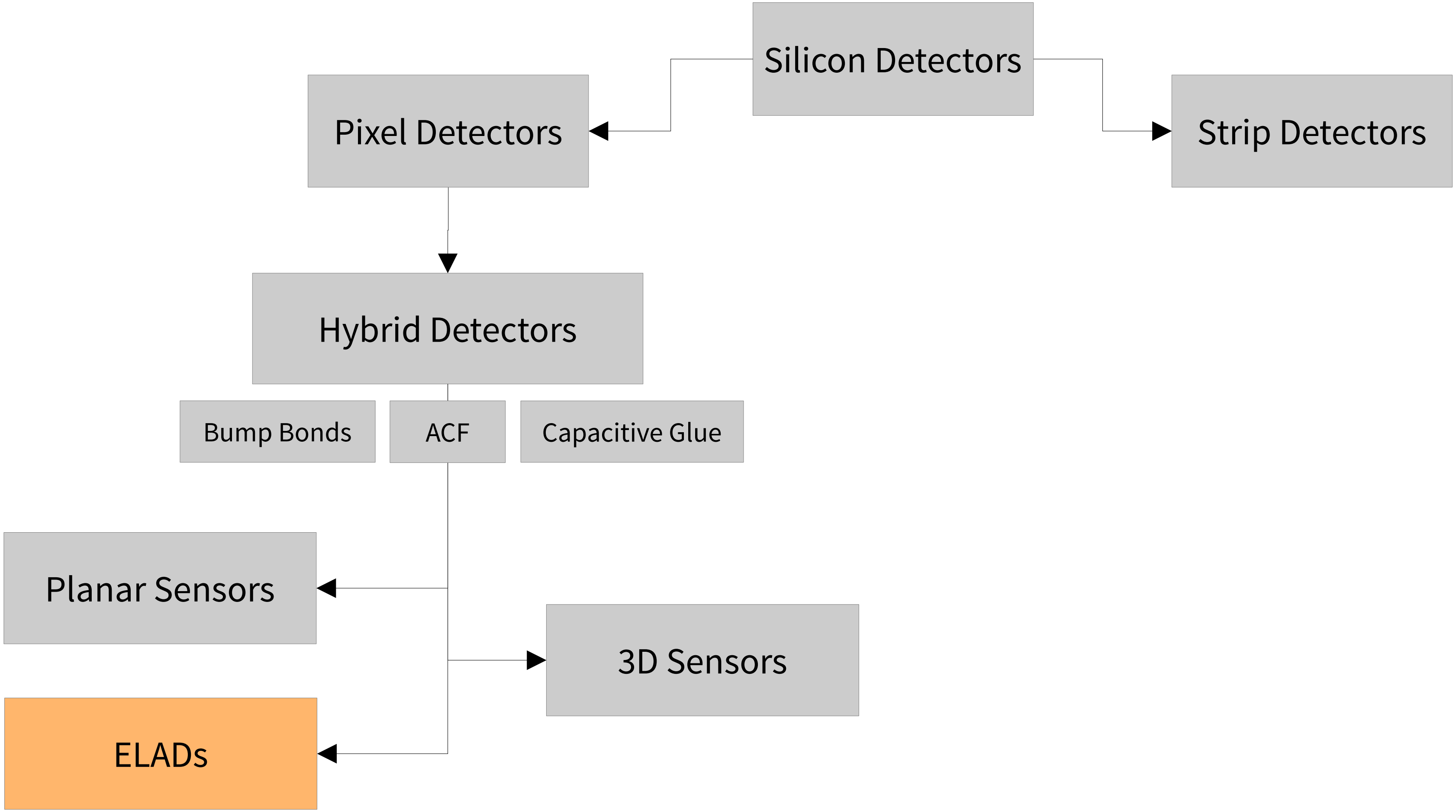
- At vertical incidence:
  inefficiencies at backside columns
- Recovered even at slight inclination

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









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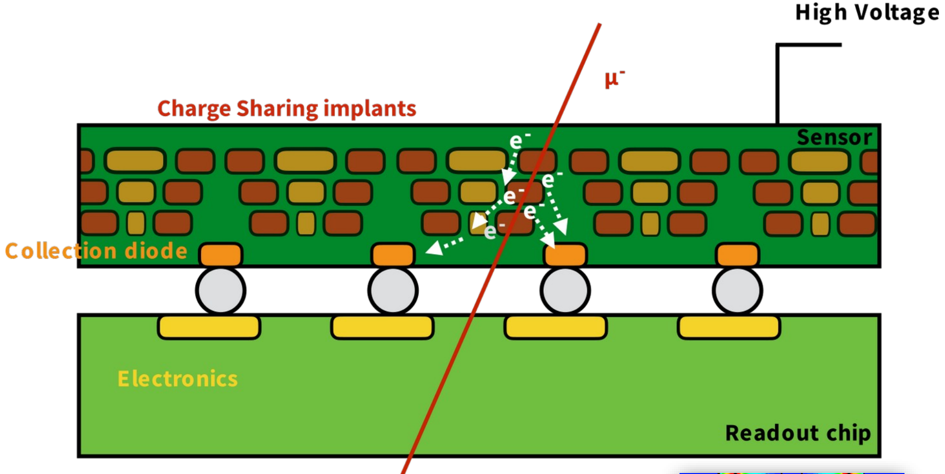
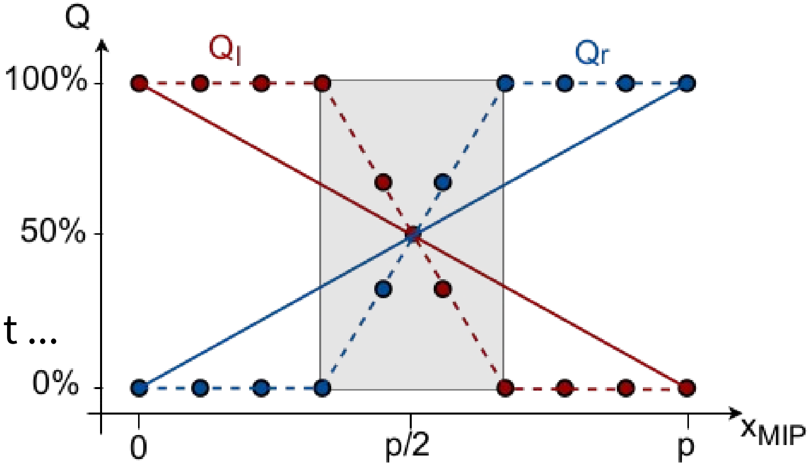
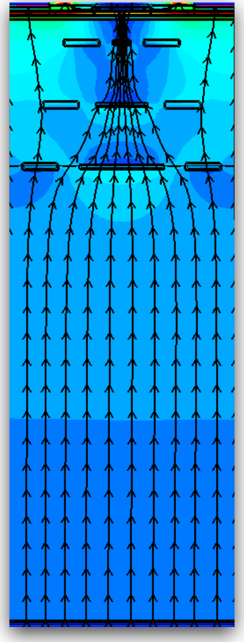
ELADs

Enhanced Lateral Drift Detectors

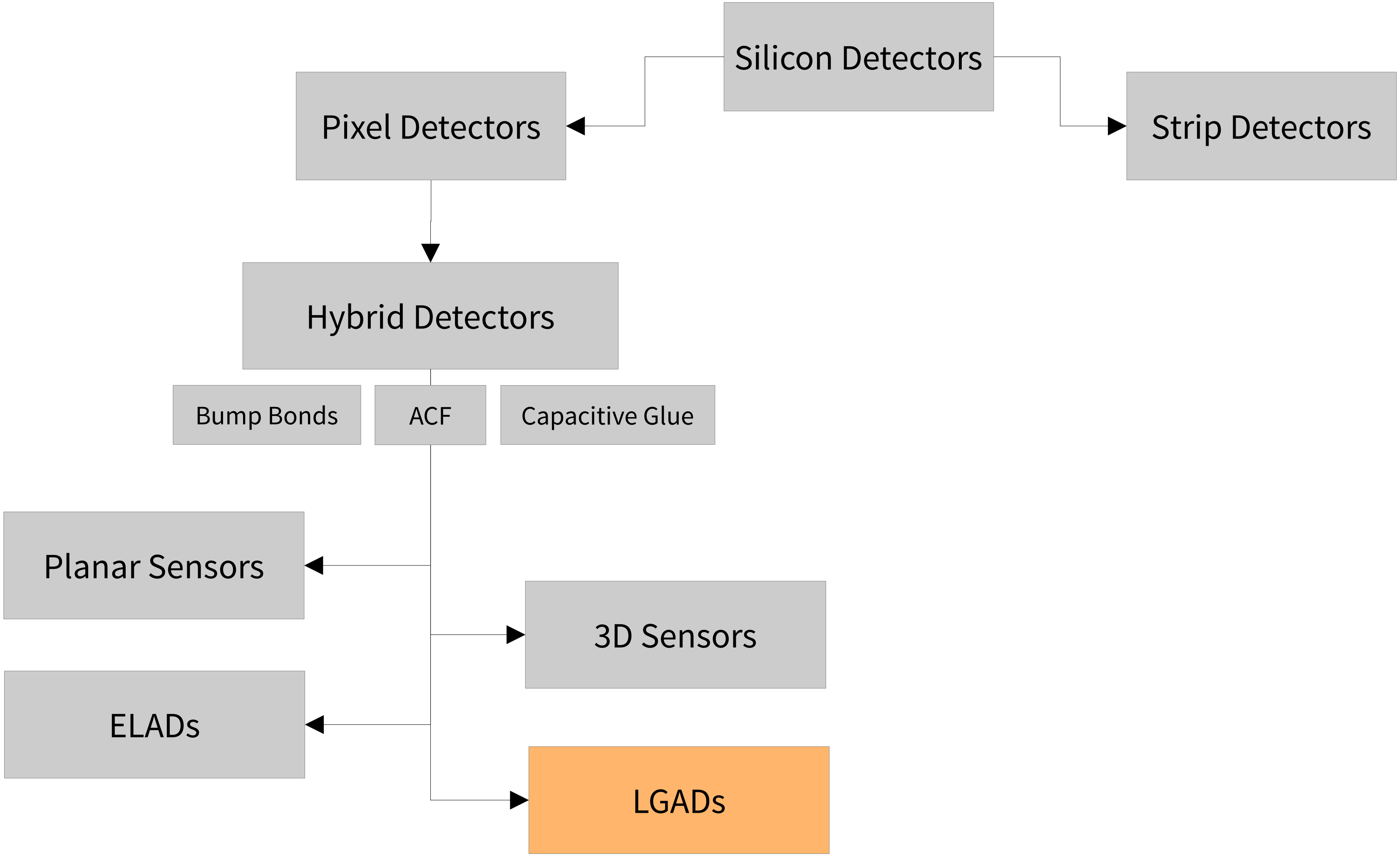


- Position resolution in **thin sensors** limited to d / √12 (almost no charge sharing)
- Concept: **enhance charge sharing** in Enhanced LAteral Drift sensors (ELAD)
  - Close to theoretical optimum: linear charge sharing
  - Deep implants to alter field, improve resolution
  - Lateral spread of charges during drift





- Challenges:
  - Complex production process: epi-growth / implant / epi-growth / implant …
  - Low-field regions (recombination)



Silicon Detectors

Pixel Detectors

Strip Detectors

Hybrid Detectors

Bump Bonds

ACF

Capacitive Glue

Planar Sensors

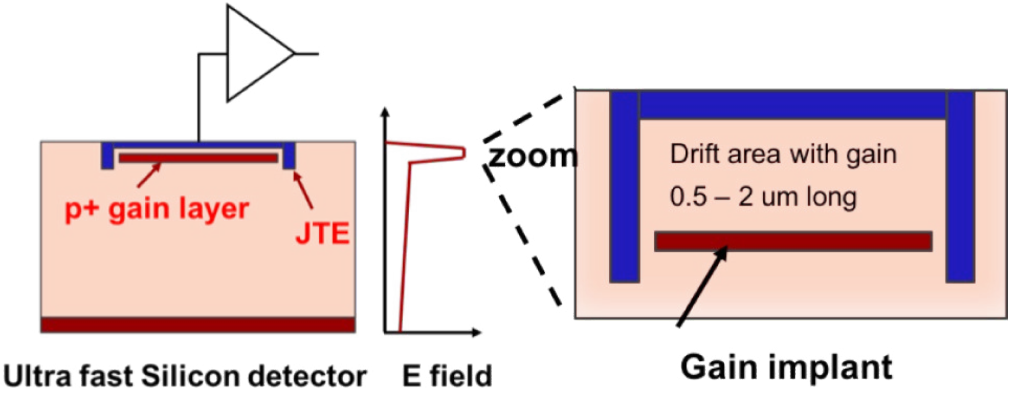
3D Sensors

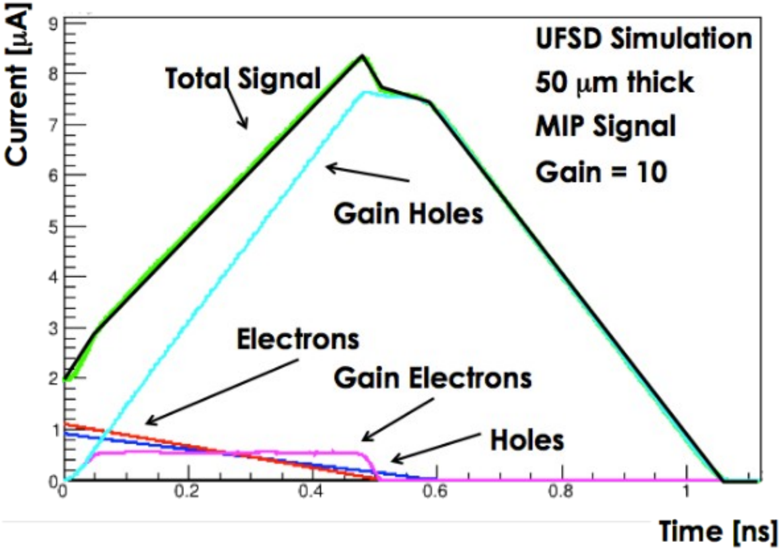
ELADs

LGADs

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

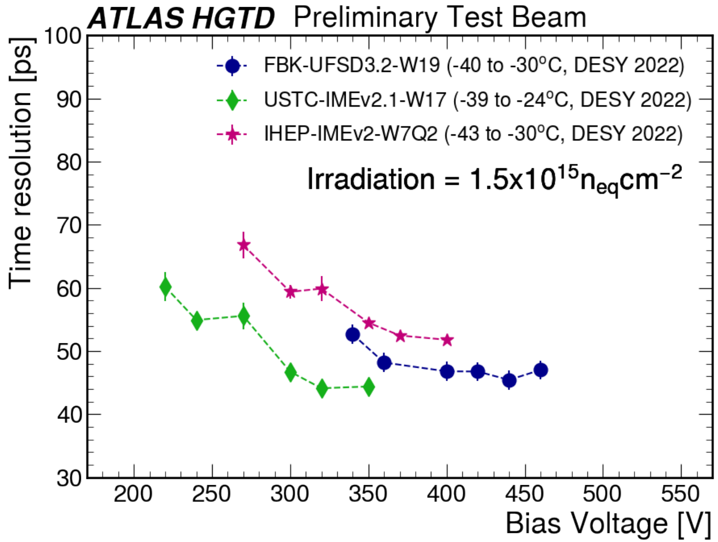


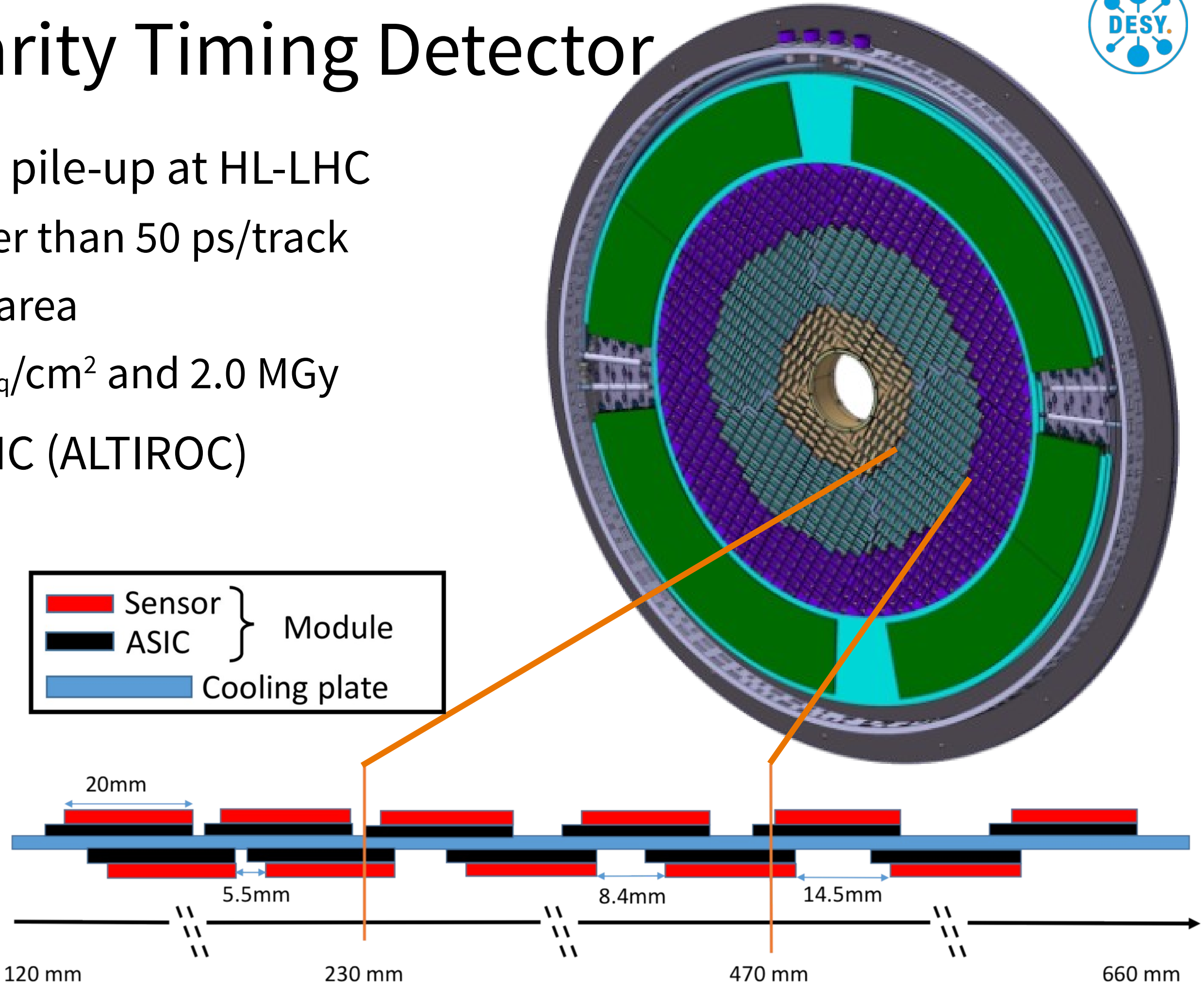


- Different types of LGADs: pads, iLGADs, TI-LGADs, …
- "Typical" silicon detectors: $\sigma > 1\,\mathrm{ns}$
- LGADs (Low Gain Avalanche Diodes) / UFSDs: $\sigma > 30\,\mathrm{ps}$

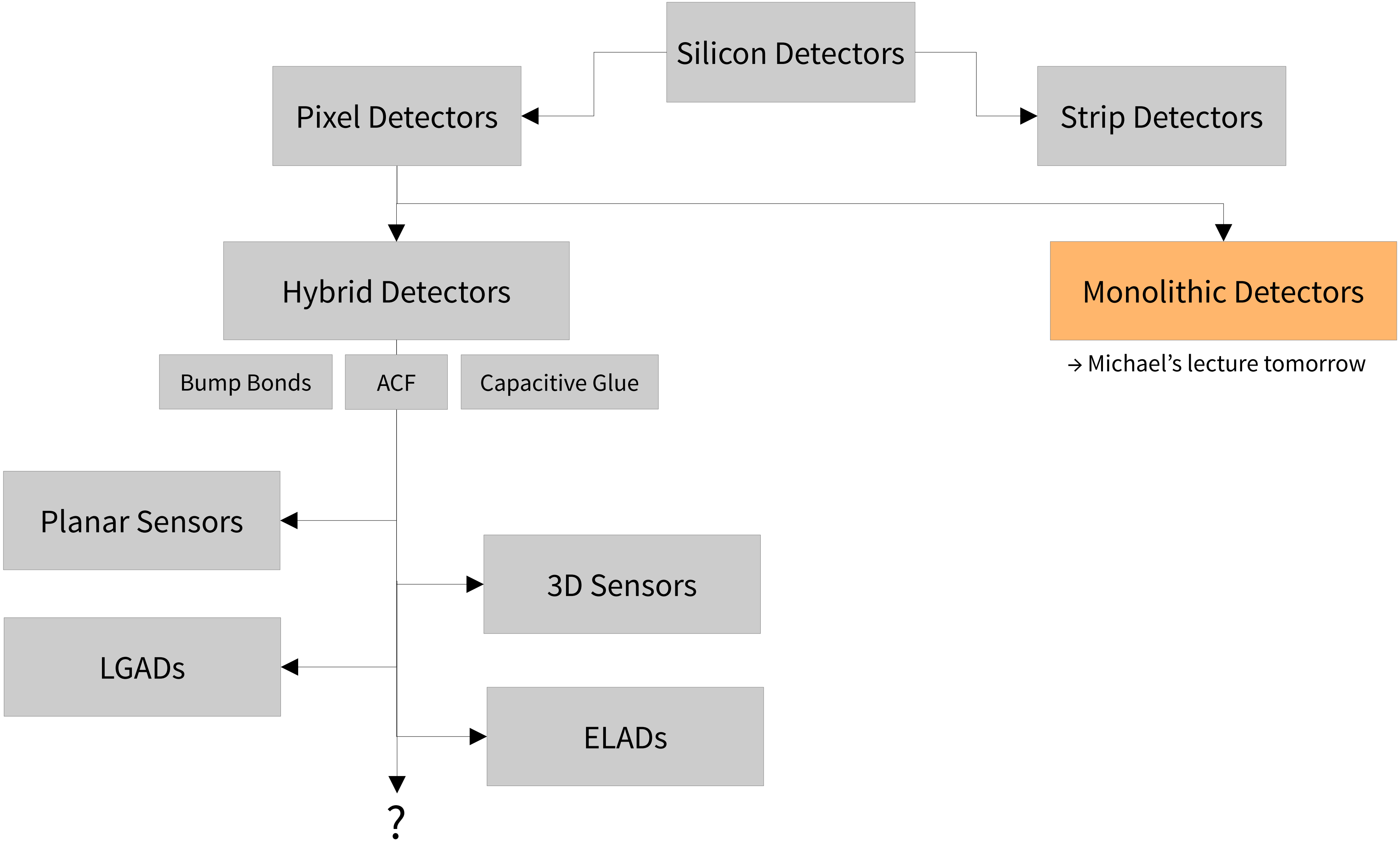
The ATLAS High Granularity Timing Detector

- 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 $2.5 \times 10^{15}\ N_{eq}/cm^2$ and 2.0 MGy
- LGADs with dedicated readout ASIC (ALTIROC)





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


Silicon Detectors

Pixel Detectors

Strip Detectors

Hybrid Detectors

Monolithic Detectors

→ Michael’s lecture tomorrow

Bump Bonds

ACF

Capacitive Glue

Planar Sensors

3D Sensors

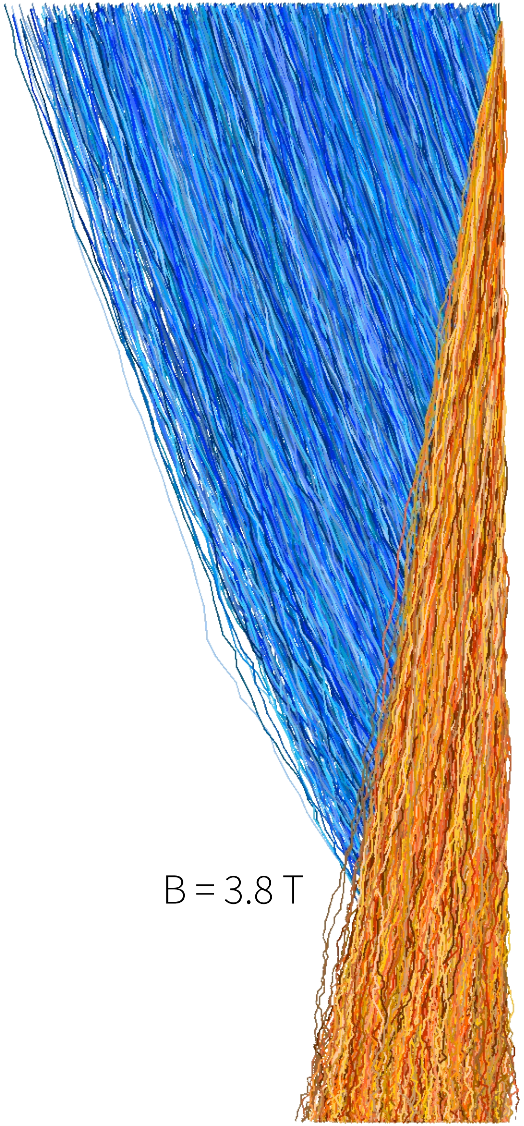
LGADs

ELADs

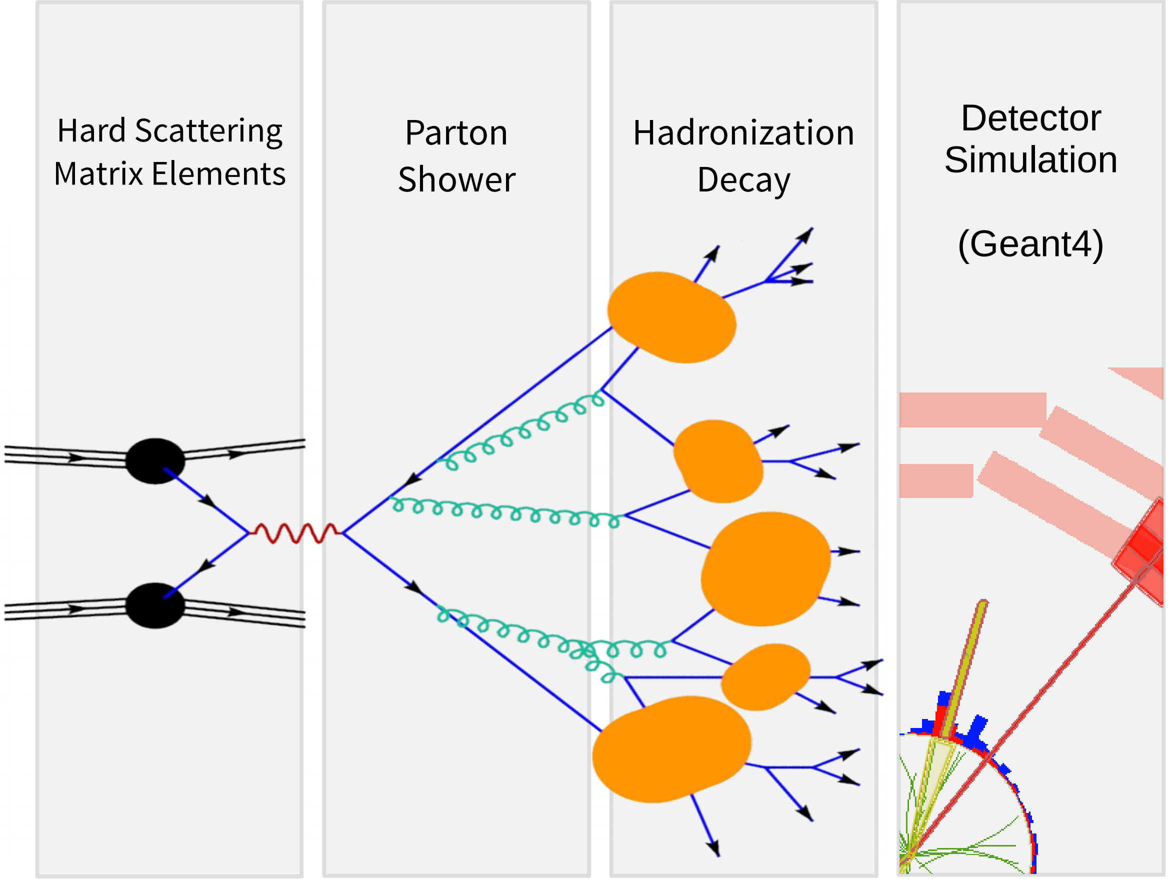
?

Understanding Your Detector

…by Means of Monte Carlo Simulations



Monte Carlo from Start to End



Hard Scattering
Matrix Elements

Parton
Shower

Hadronization
Decay

Detector
Simulation

(Geant4)

Geant4 – GEometry ANd Tracking

→ Lab Exercise 10

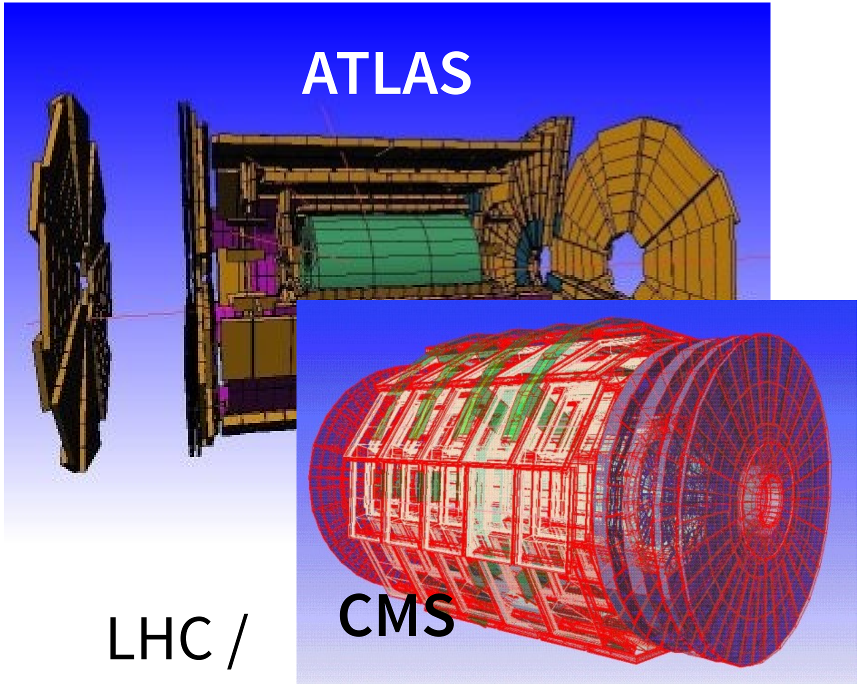
- Toolkit to simulate interaction of particles with matter
- Open Source project, written in C++ using Object Orientation
- Typically new feature versions are released once a year

- It is a **toolkit** → a collection of tools for simulations
  - Coding is ***always*** required for simulations
  - There is not such concept as "Geant4 defaults"

- Learning-by-reading: examples in source code
  - **Basic examples:** overview of the Geant4 tools
  - **Extended examples:** showing specific Geant4 functionalities
  - **Advanced Examples:** Geant4 tools in real-life applications

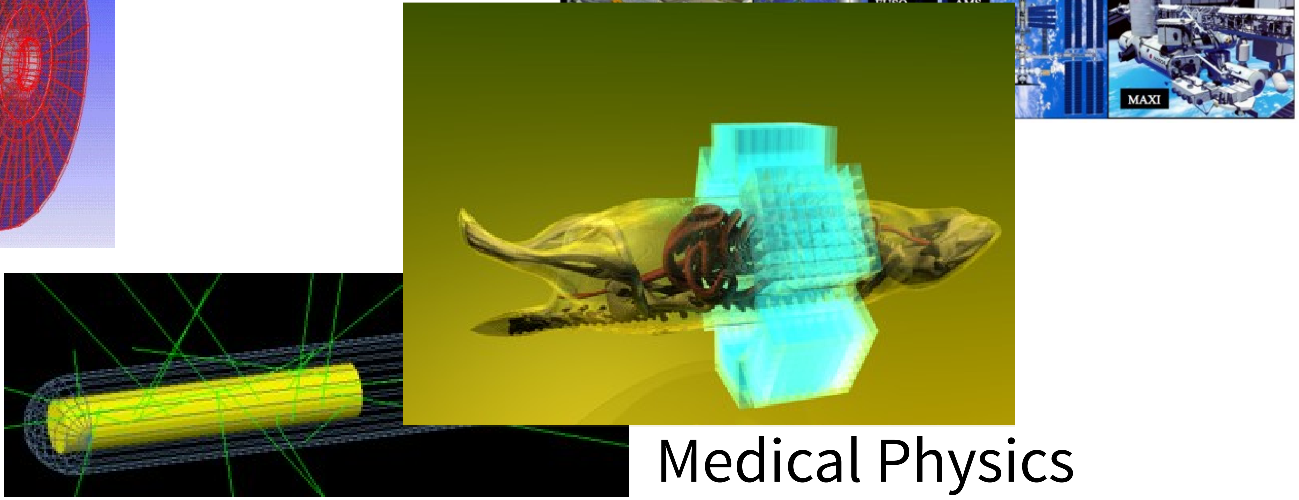
```
int main(int argc, char** argv) {
    G4RunManager* runManager = new G4RunManager;
    runManager->SetUserInitialization(new MyDetectorConstruction());

    // Physics list
    G4VModularPhysicsList* physicsList = new MyPhysicsList;
    physicsList->SetVerboseLevel(1);
    runManager->SetUserInitialization(physicsList);

    // User actions initialization
    runManager->SetUserInitialization(new MyActionInitialization());

      ...
```

Applications wherever particles are involved…



LHC / particle physics

Satellites / Space



Medical Physics

Core Concepts of Geant4

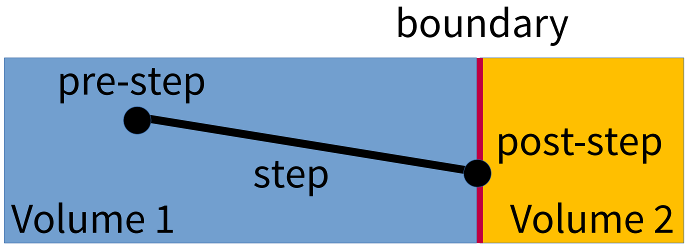
The Basic concepts at the core of Geant4 are:

- **The run** represents a set of events which share a common setup:
  geometry, beam type and configuration of physics processes.
- **The event** represents all information (tracks, interaction) that result from one or more initial particles
- **A process** is usually a physics process - something which results from the interaction of a particle with an atom of the material it is crossing.
- **The track** represents the snapshot of the current state of simulating one particle track, and stores information on the particle creation
- **The step** represents how the current particle is being moved

Tracking in Geant4

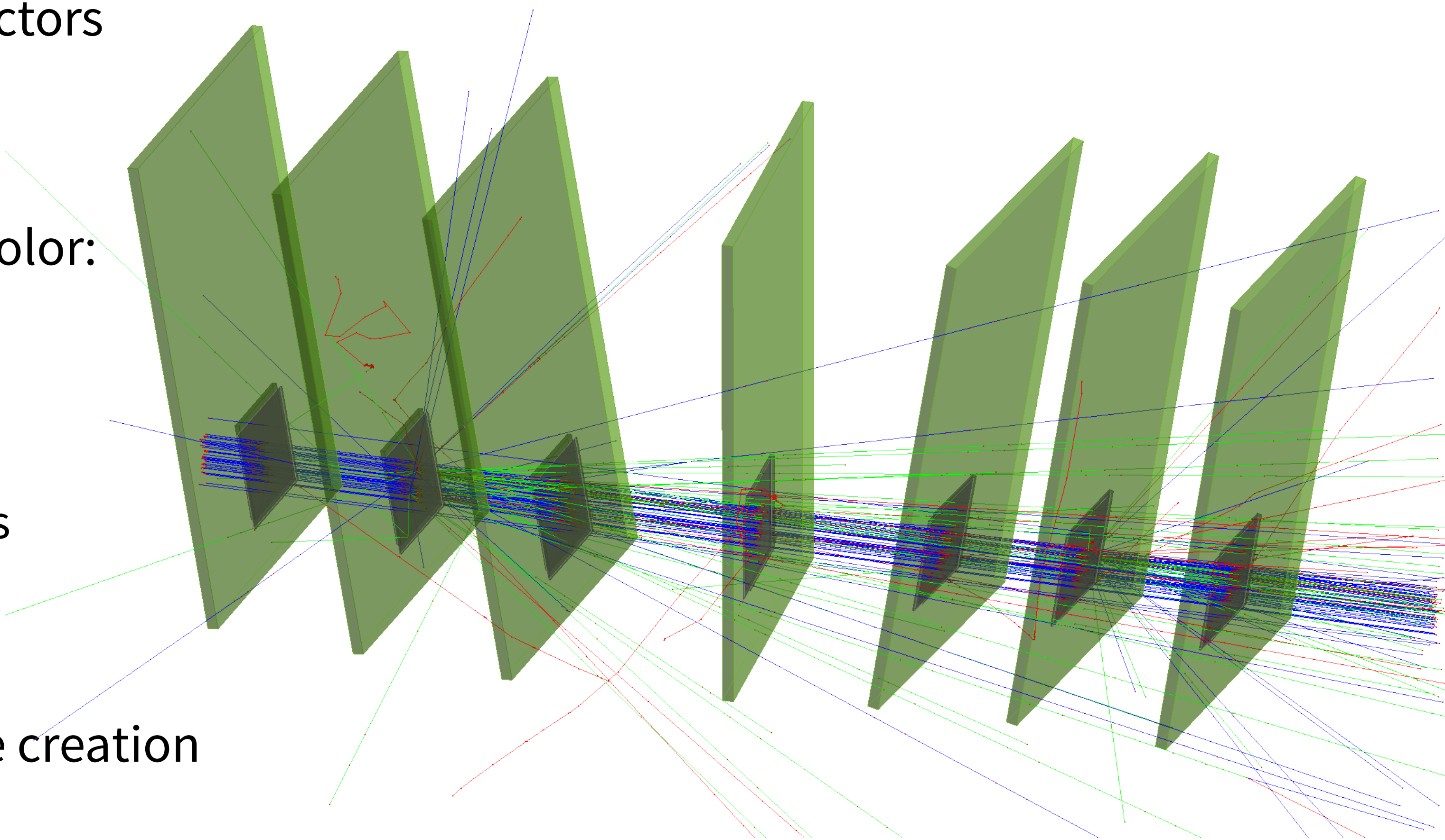
Following particles is done by stepping:

- Initializing of the track
- Polling of all processes (interactions) to see how far each one will occur next (free path)
- Determination of the minimum length, which is the length of the next step.
  This identifies also the winning process, the one which occurs at the end point of the step
- Calculating amount of energy lost along the length of the step
- Calling of the winning process to obtain results of the interaction
  including change in energy, momentum direction, new particles created, …
- Determination of volume the track enters
  next at the end of a step (if on boundary)

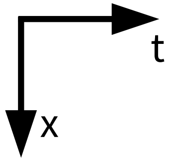


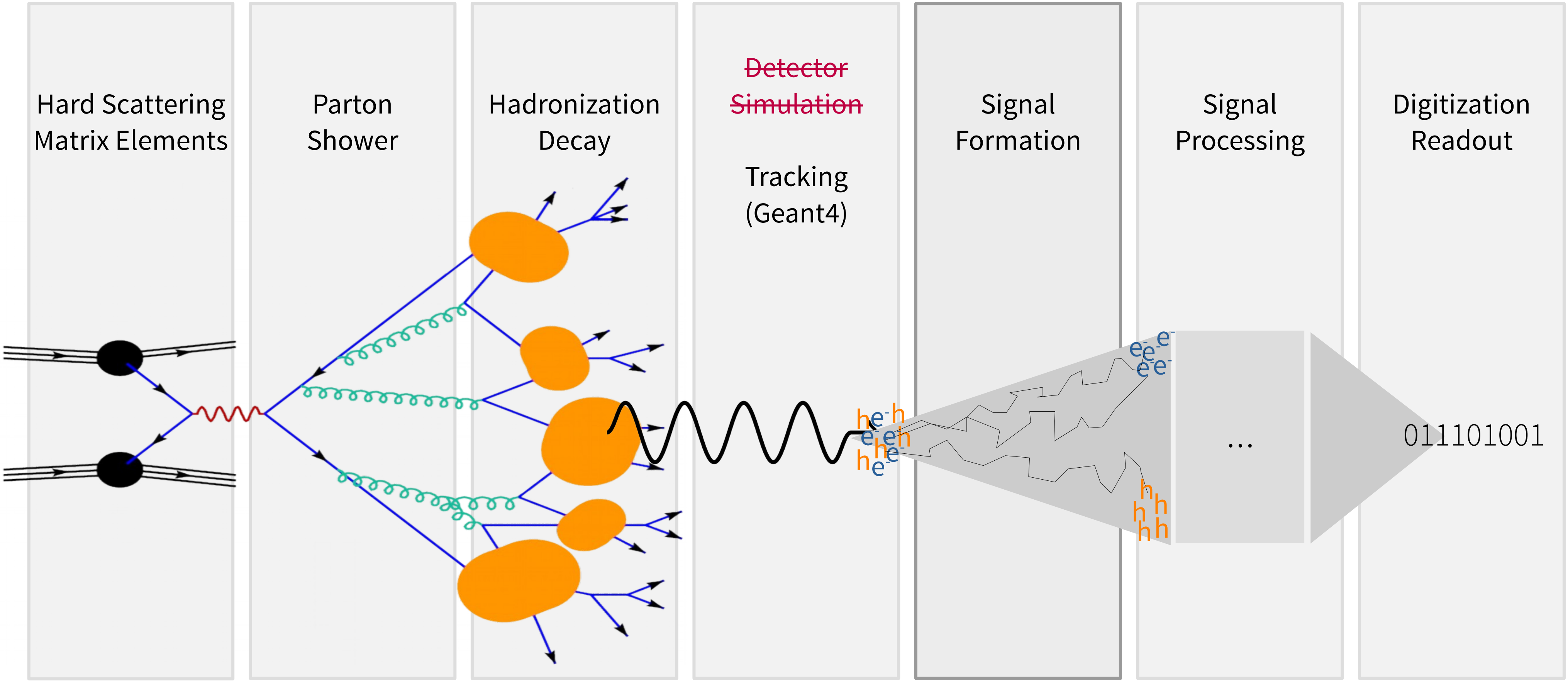
Example: Visualization of Geant4 Tracking

- Seven silicon detectors in a Pion beam
- Particle types by color:
  - Blue: Pions
  - Red: Electrons
  - Green: Gammas
- Scattering, secondary particle creation



Monte Carlo from Start to End





Hard Scattering Matrix Elements

Parton Shower

Hadronization Decay

~~Detector Simulation~~

Tracking (Geant4)

Signal Formation

Signal Processing

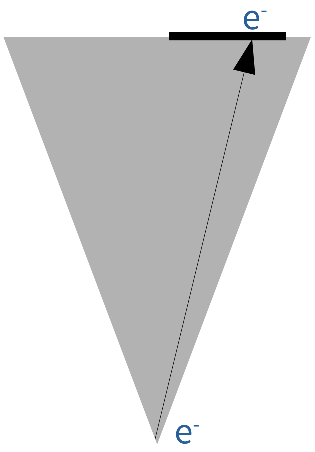
Digitization Readout

O(1) – Projecting Charge Carriers

- With linear electric field, calculate approximate total drift time via analytical approximation of mobility integral
- For each (group of) charge carrier,
  - Calculate total drift time
  - Calculate total diffusion offset for this time
  - Put charge carrier on sensor surface, with offset drawn from Gaussian distribution of width σ_x

$$t = \int \frac{1}{v} ds \approx \frac{1}{\mu_0} \left[\frac{\ln(E(s))}{k} + \frac{s}{E_c} \right]_a^b$$

$$E(s) = ks + E_0$$



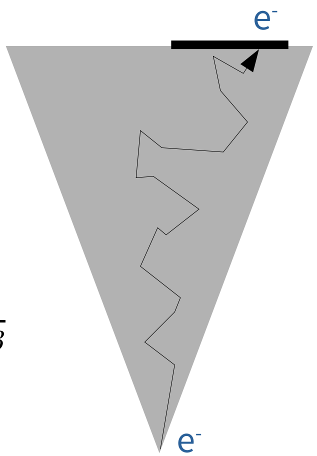
- Very fast simulation, few calculations
- Only works for linear electric field approximations (reasonable for many thick planar sensors) and without magnetic field

O(N) – Integration of Equations of Motion

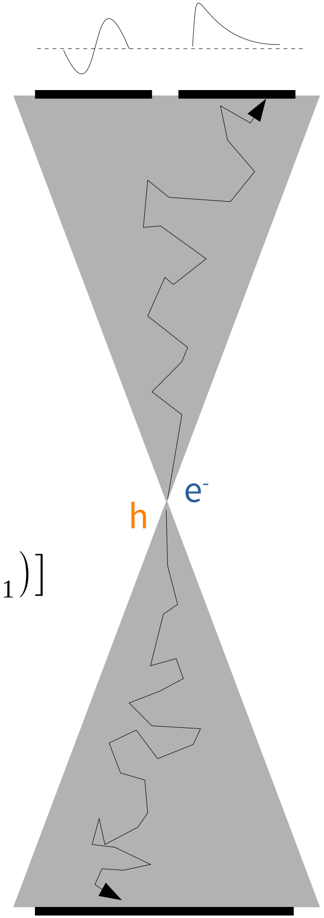
- Successive integration of charge carrier motion
- Take each (group of) charge carrier
  - Calculate mobility μ from local electric (and magnetic) field (e.g. using Jacoboni/Canali parametrization)
  - Calculate velocity
  - Make step, add diffusion offset from Gaussian distribution
  - Repeat N times until sensor surface is reached
- Using 4th order Runge-Kutta-Fehlberg method
  - Adaptive step size according to position uncertainty (embedded 5th order)
  - Method allows description of drift in complex field configurations

$$\mu = \frac{v_m}{E_c} \frac{1}{\left(1 + \left(E / E_c\right)^{\beta}\right)^{1/\beta}}$$

$$\sigma_x = \sqrt{\frac{2 k_b T}{e} \mu t}$$

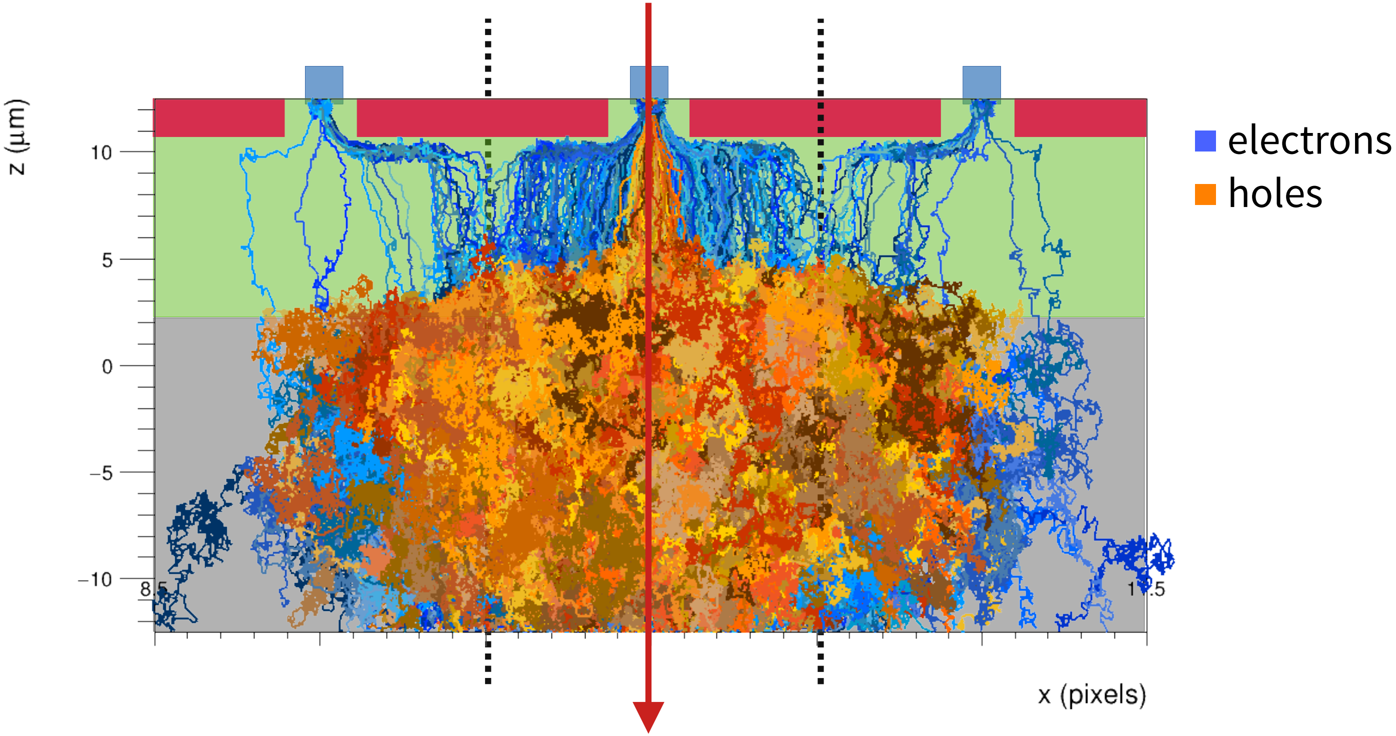


O(2xNxM) – Induced Signal at Electrodes



- Successive integration of motion, calculating induced charge per step
- Take each (group of) charge carrier
  - Calculate mobility & velocity from local fields
  - Make step, add diffusion offset from Gaussian distribution
  - Get induced charge from weighting potential difference for M neighbors
  - Repeat N times until sensor surface is reached
- Allows time-resolved simulation
  - Requires weighting potential, might not be trivial to obtain
- Time consuming:
  - Calculation for all neighboring electrodes for every step
  - Requires propagating both electrons and holes (x2)

$$Q_n^{ind.} = \int_{t_{n-1}}^{t_n} I_n^{ind.} dt = q[\phi(X_n) - \phi(x_{n-1})]$$


z (µm)
10
5
0
−5
−10
8.5
11.5
x (pixels)
electrons
holes


DESY.