Solid-state detectors

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Introduction

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Outline

Operation principles of silicon sensors

- Semiconductors
- p-n junction, diode characterization
- Signal induction
- Radiation damage

Physics applications and sensor technology

- Tracking and vertexing: segmented sensors
- Timing: LGADs
- Particle ID and 4D Tracking (at the Electron-Ion Collider and the PIONEER experiment)

Silicon detectors at future colliders

Other semiconductor materials and use cases

- *Ge, SiC, CdTe*

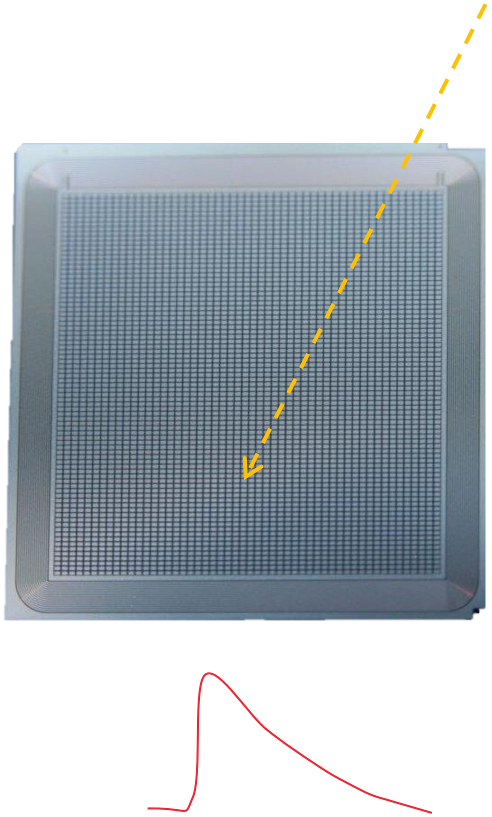
Somewhat focused on collider detectors – many or most points shown here can also be applied to smaller experiments ☺

"Solid-state detectors"?

Direct interaction with and detection of primary particle or photon as electric charge in a solid material

- ~~**Scintillators + photodetectors**~~
- ~~**Gas detectors**~~
- ~~**Polymers (bubble chambers etc)**~~
- ~~**Metals**~~
- ~~**Superconducting sensors or transition edge sensors**~~

➢ **Semiconducting material: most commonly, but not exclusively, silicon**

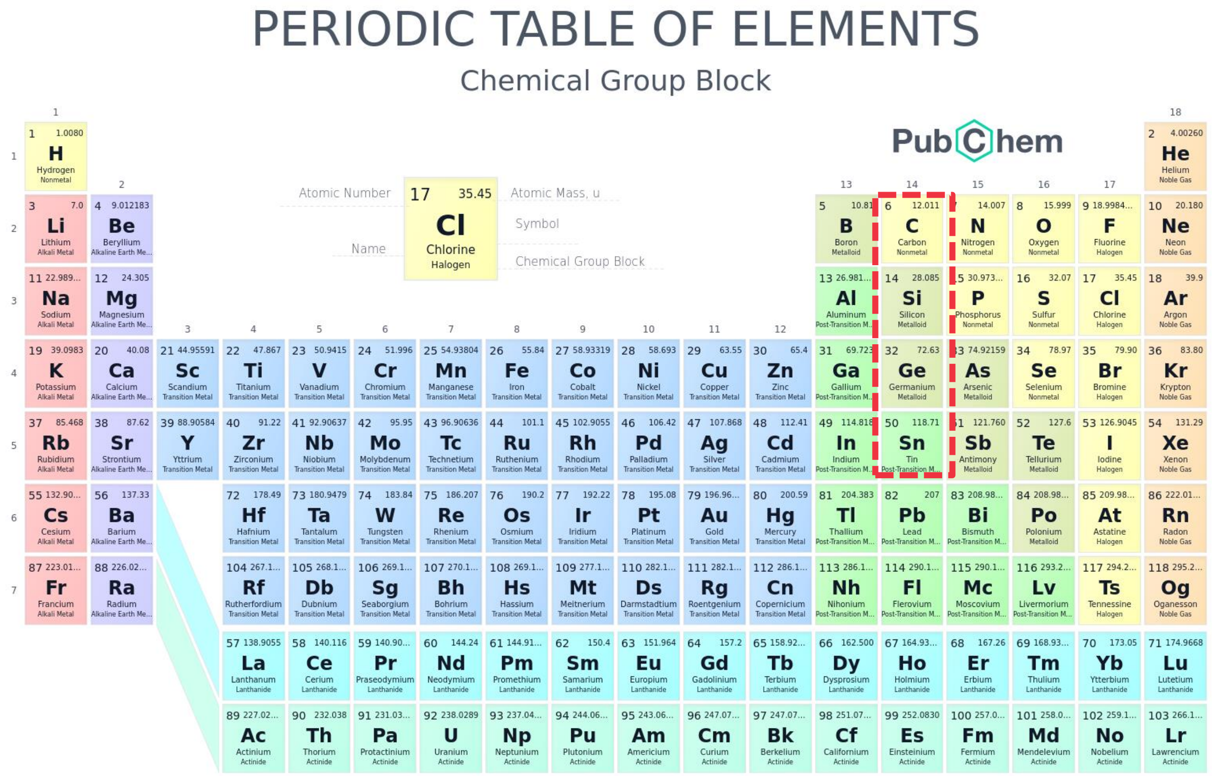


Semiconductor sensors

Semiconductors

Elemental semiconductors: prevalent in group IV with exactly 4 valence electrons

- C (diamond), Si, Ge



Component semiconductors

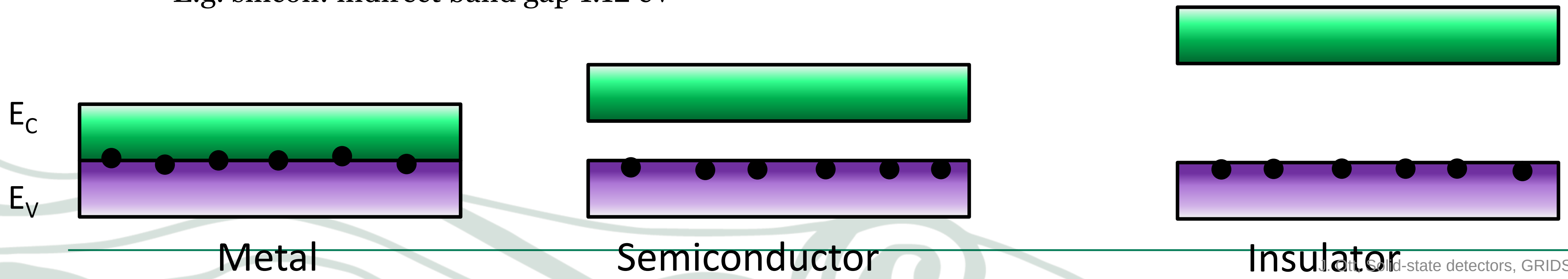
- III-V, II-VI
- GaAs, GaN, CdTe, …

- ***Why Si?***

Semiconductors

- In solids: atomic orbitals are joined over continuous structure of neighboring bonded atoms: **energy bands**
  - Determined by crystal structure or amorphous nature of the material
- Energy range *without allowed energy states* between valence and conduction band: **band gap**
- Excitement of **electron** to the conduction band leaves unoccupied vacancy in the valence band**: hole**

- **Semiconductor: defined 'band gap' of forbidden energy states between valence band and conduction band, E_G < ~5 eV**
  - Direct or indirect with respect to lattice vectors: radiative recombination, more relevant for photonics
  - E.g. silicon: indirect band gap 1.12 eV



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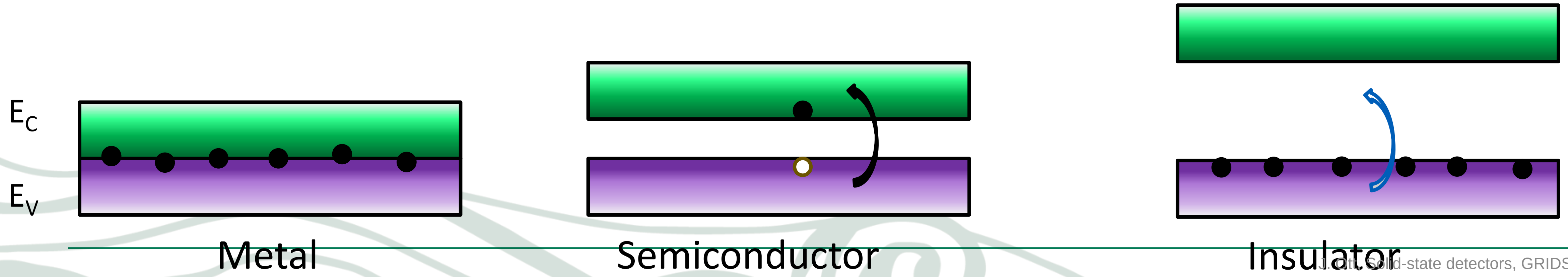
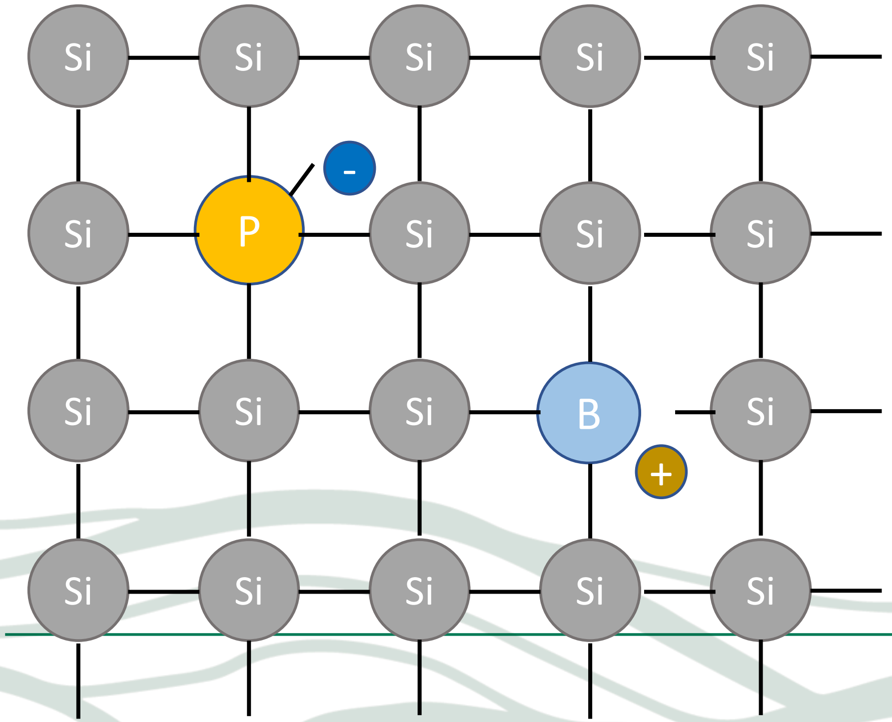
- **Transfer of energy > E_G to an electron: excited to conduction band, leaving behind a hole in the valence band**
- **Energy to produce 1 electron-hole pair with high-energy particles and photons: energy is dispersed in lattice phonons / heat – in practice, larger than band gap**
  - "work function"
  - E.g. silicon: 3.6 eV



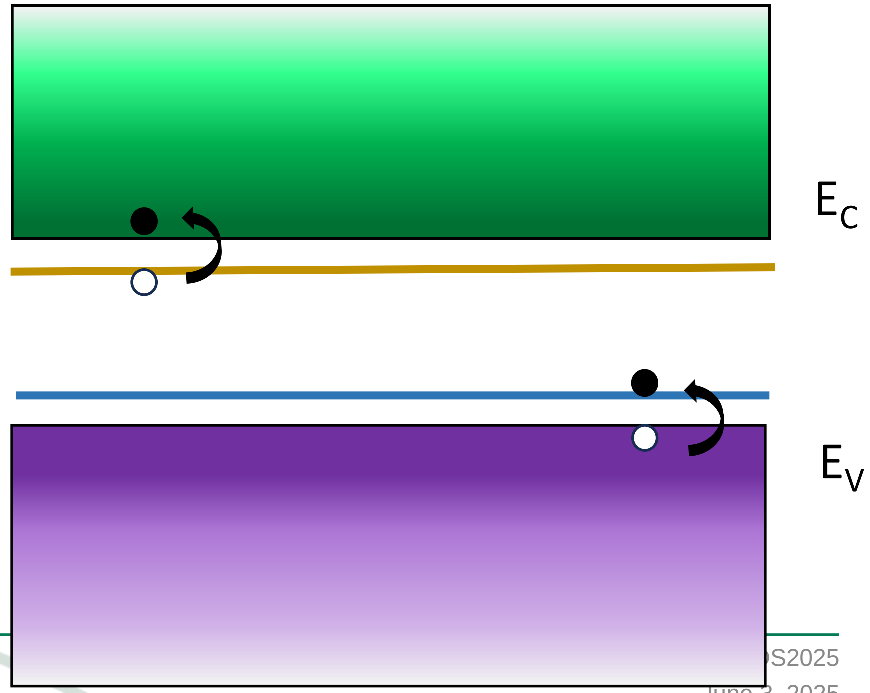
Doping of semiconductors

- Electrical properties of semiconductors are governed by impurities altering their band structure
- Aim at ultra-pure material: not sufficient in reality
- More convenient: adjust properties by controlled doping



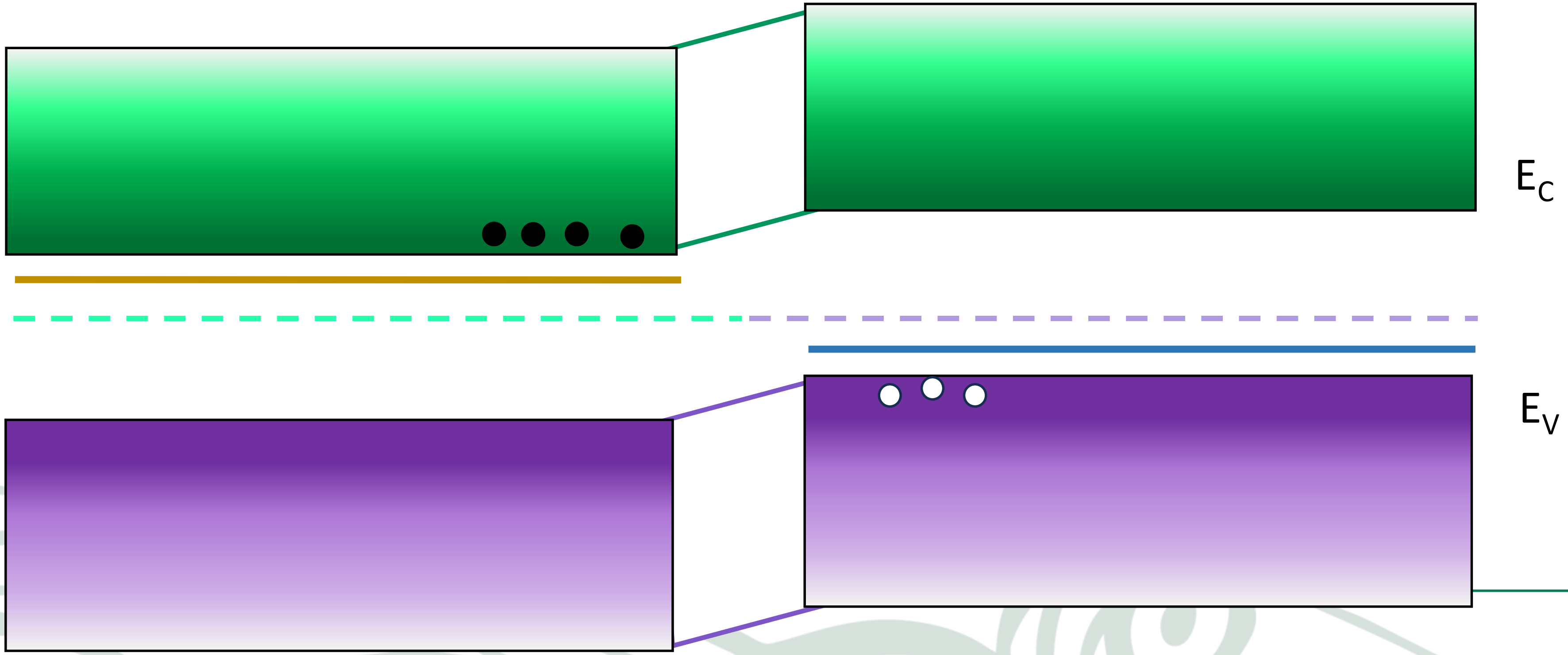
Donor: energy state close to conduction band

Acceptor: energy state close to valence band



p-n junction

- Typically, material is either n- or p-doped
  - This also shifts the Fermi level
- When layers are brought in contact to each other: **p-n junction**
  - Fermi levels align: **bending** of conduction and valence bands



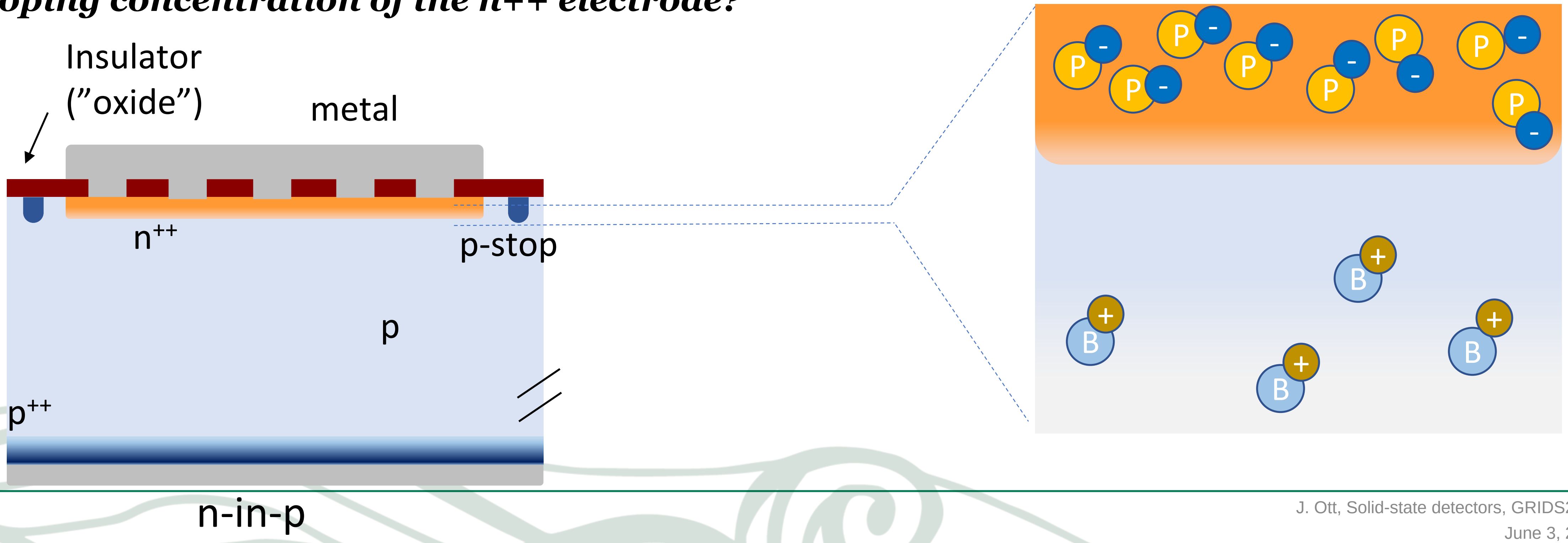
Potential barrier!

Silicon sensors: p-n junction

Example case (modern planar Si sensor): high-resistivity p-type bulk with Boron doping, n+(+) electrode implanted with Phosphorus

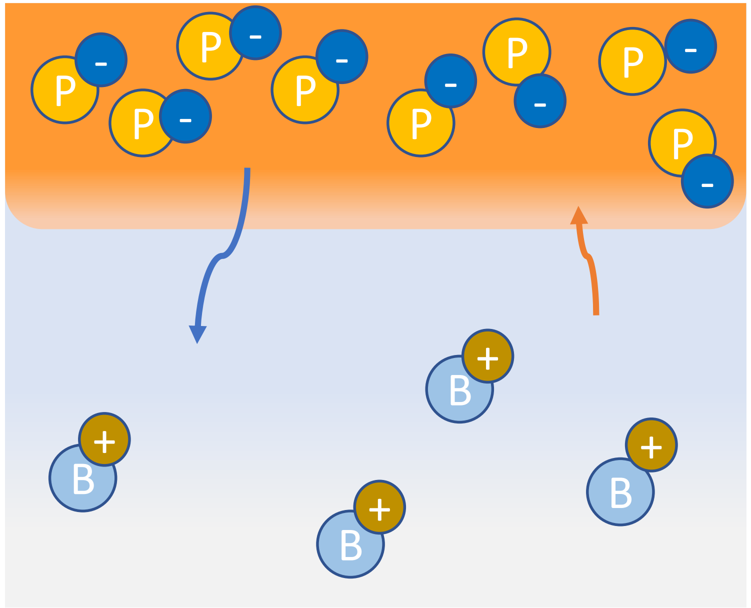
Doping concentration of the bulk in high-res Si: ~10^{12} cm^{-3}

Doping concentration of the n++ electrode?



Silicon sensors: p-n junction

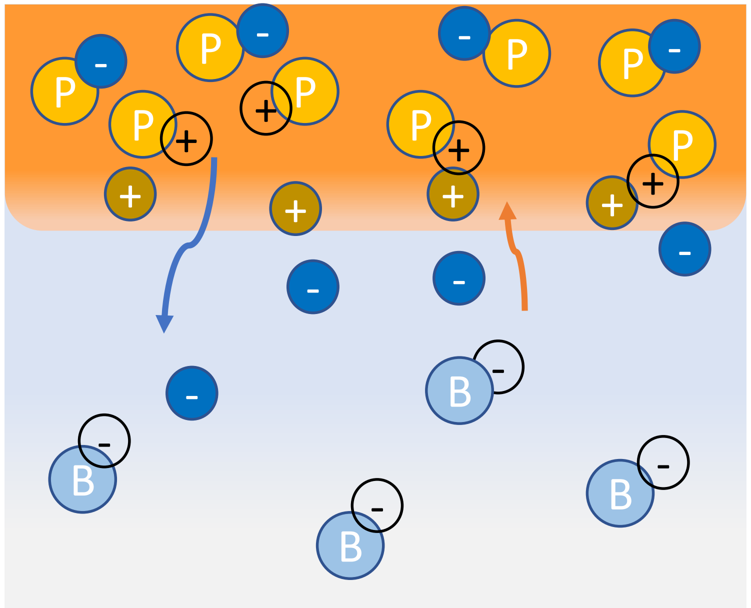
Additional electrons from P and holes from B diffuse at the immediate p-n interface and neutralize...



Silicon sensors: p-n junction

Additional electrons from P and holes from B diffuse at the immediate p-n interface and neutralize

→ leave behind a region with no free charge carriers, only fixed charge on dopant atoms



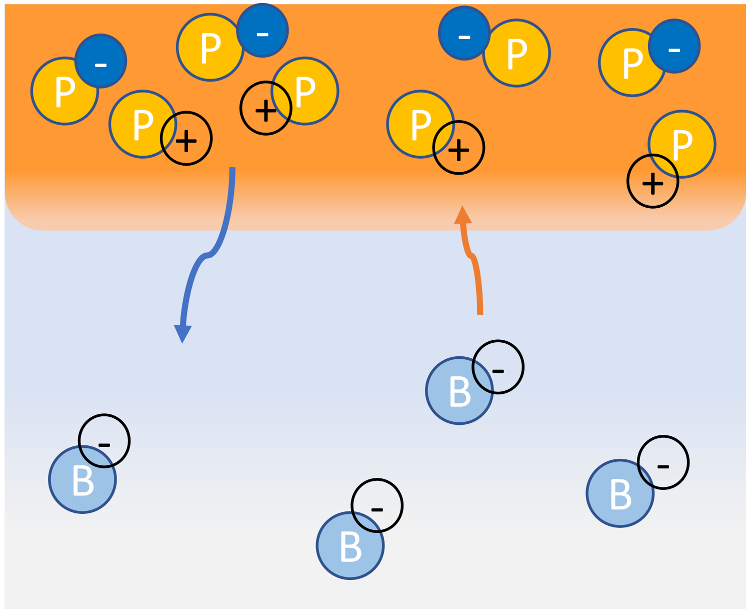
Silicon sensors: p-n junction

Additional electrons from P and holes from B diffuse at the immediate p-n interface and neutralize

→ leave behind a region with no free charge carriers, only fixed charge on dopant atoms

- "depletion region"
- "space charge region"

N.B.: now B is associated with fixed negative charge, P with positive!

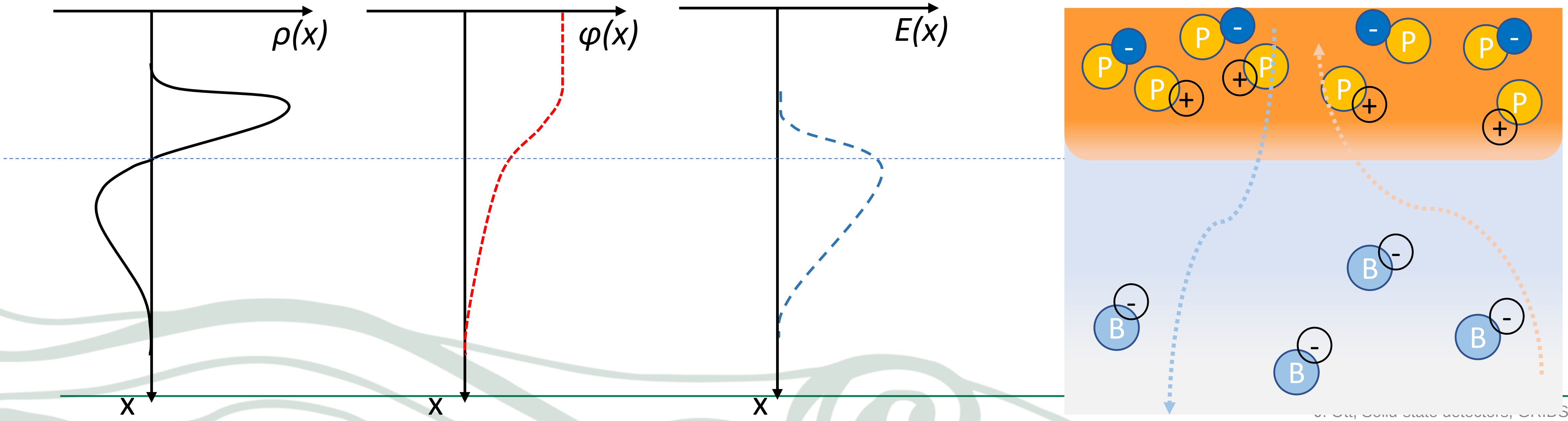


Silicon sensors: p-n junction

p-n junction ‘reverse-biases itself’ – potential barrier for diffusion of more free carriers

→ at equilibrium unless conditions are changed

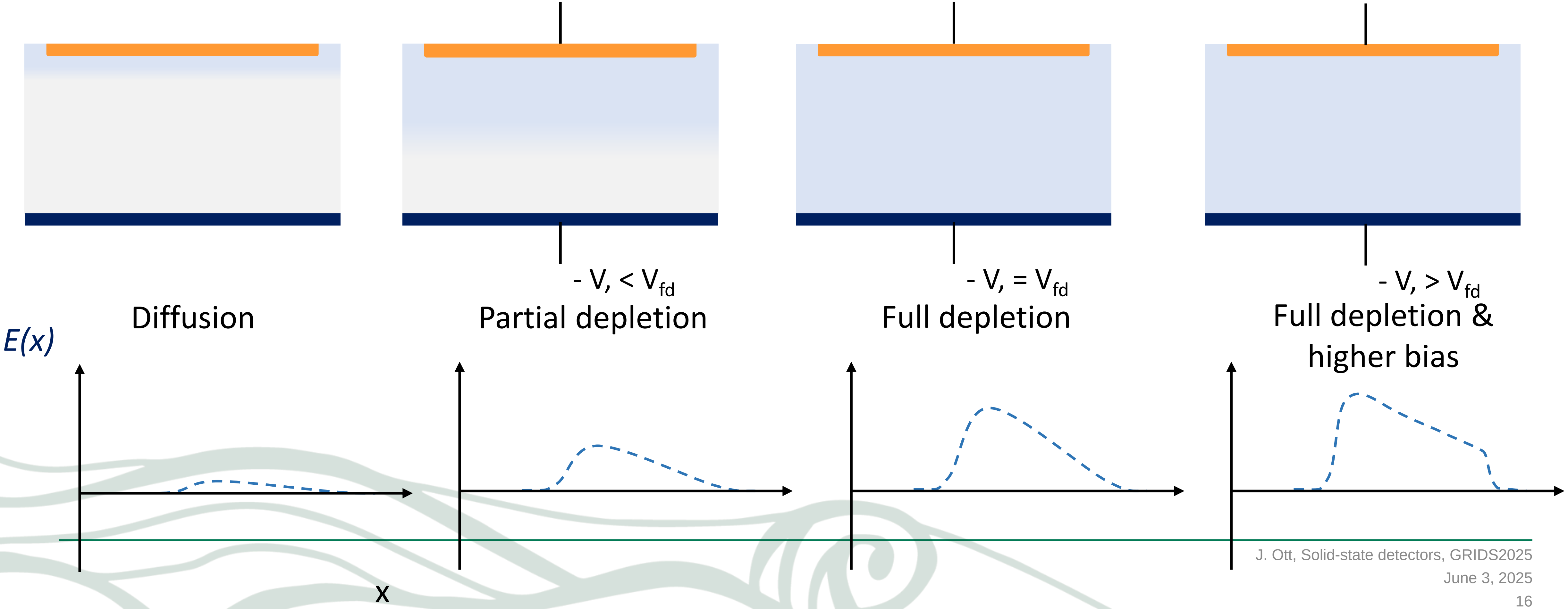
In high-quality silicon sensors, you likely observe signal even without external bias!



Silicon sensors: p-n junction

Widening the depletion zone until it extends through the full sensor by applying and external bias voltage!

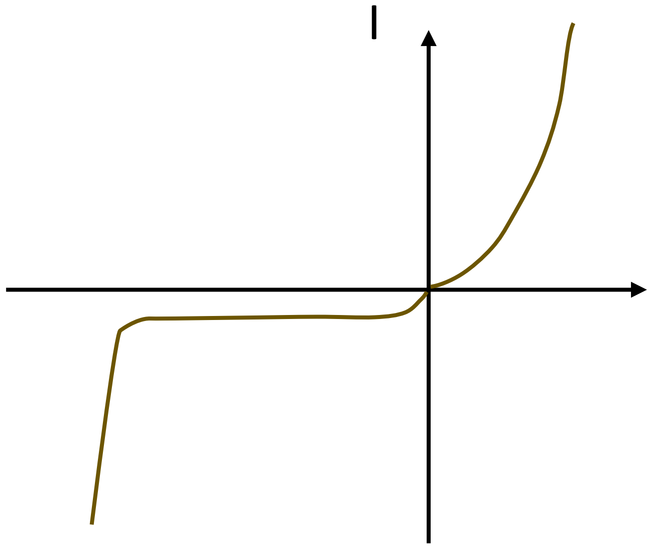
- Depleted sensor can be approximated as parallel-plate capacitor



Semiconductor sensors: contacts

The p-n junction forms a rectifying contact, diode: high current flows only in one direction (forward bias), in the other a potential barrier prevents flow of majority carriers and depletes the junction (reverse bias)

- Except for leakage current



Correspondingly, for a metal-semiconductor interface: **Schottky contact**

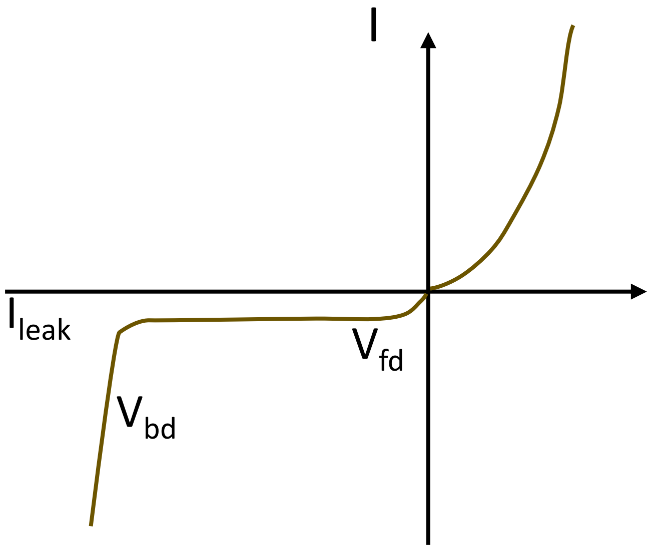
- More common for undoped compound semiconductors, also diamond

As opposed to an **Ohmic contact,** which is linearly conductive in both directions

➢ **Depends on work function of the metal and band energy levels of the semiconductor**

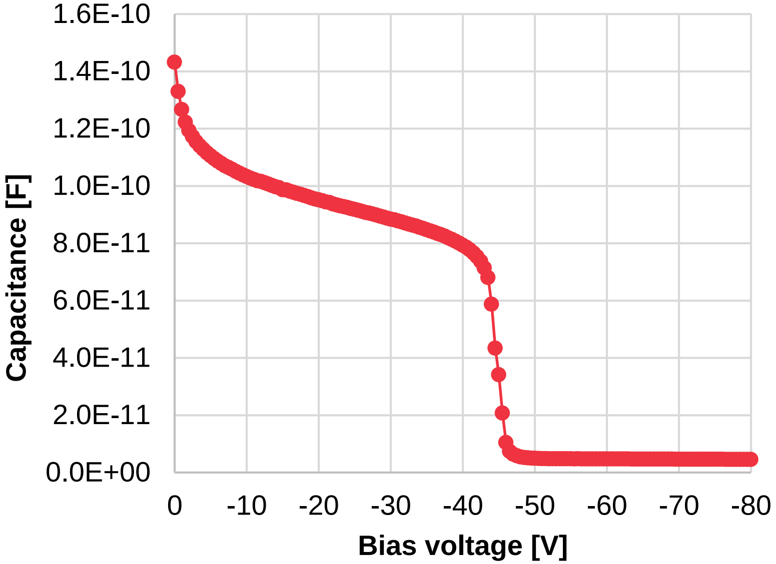
- Common contact metals: **Al**, TiW, In, Au, Pt

Device characterization



Current-voltage (I-V)

- (Polarity → operation voltage)
- (Full depletion voltage → minimum operation voltage)
- Leakage current → power consumption, signal-to-noise
- Breakdown voltage → maximum operation voltage
- Radiation damage



Capacitance-voltage (C-V)

- Full depletion voltage → minimum operation voltage
- Sensor capacitance → relevant for front-end electronics, noise
- (Radiation damage)

- ***Double feature in the C-V curve of a Si sensor: what could explain this?***

Signal generation

Interaction of radiation with matter

Charged particles

Continuous interaction along the path: *linear energy transfer*

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

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

Mechanisms:

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

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

Photons

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

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

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

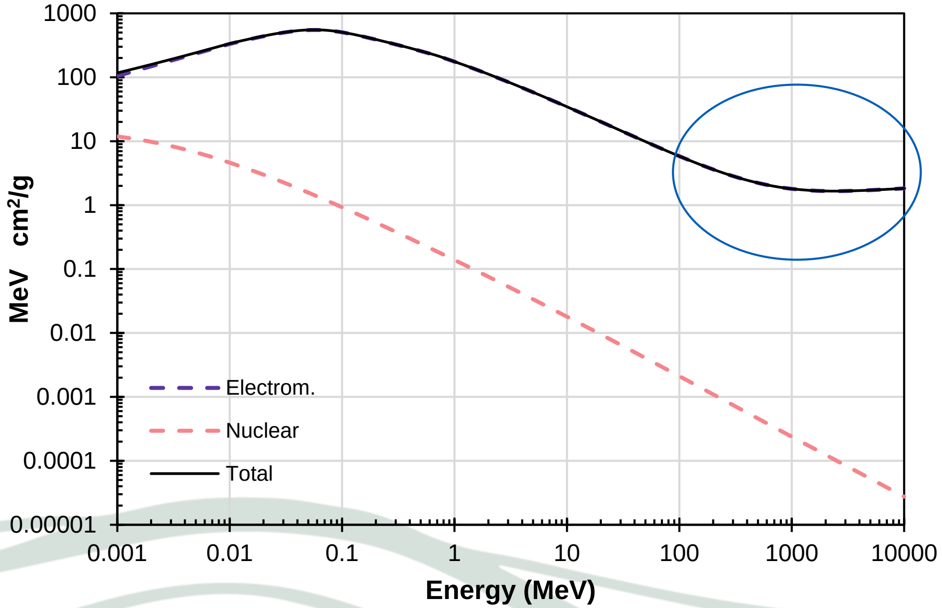
- Mechanisms:
- Elastic scattering
- Photoelectric effect
- Compton scattering = inelastic scattering
- Pair production
- (Photonuclear reactions)

Interaction of high-energy species in silicon

Energy scales: TeV c-o-m energies at the LHC - photon and particle energies in the GeV's
... vs laboratory: Co-60 gamma ray, 1.1 and 1.3 MeV, or Sr-90/Y-90 beta particle maximum energy, 0.6 – 2 MeV

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

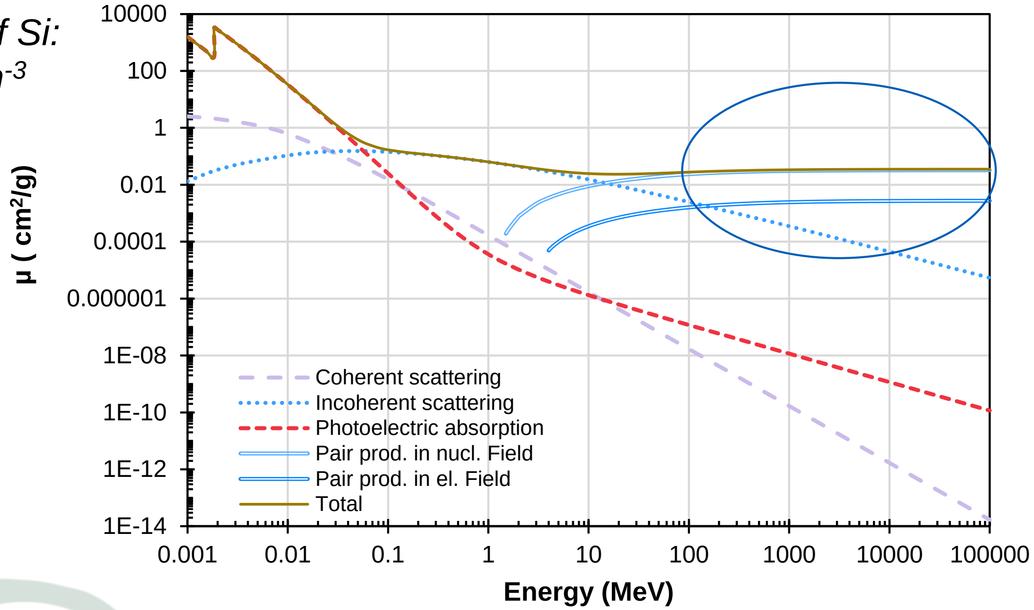
Proton stopping power in Si



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

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

Photon attenuation in Si



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

Signal induction

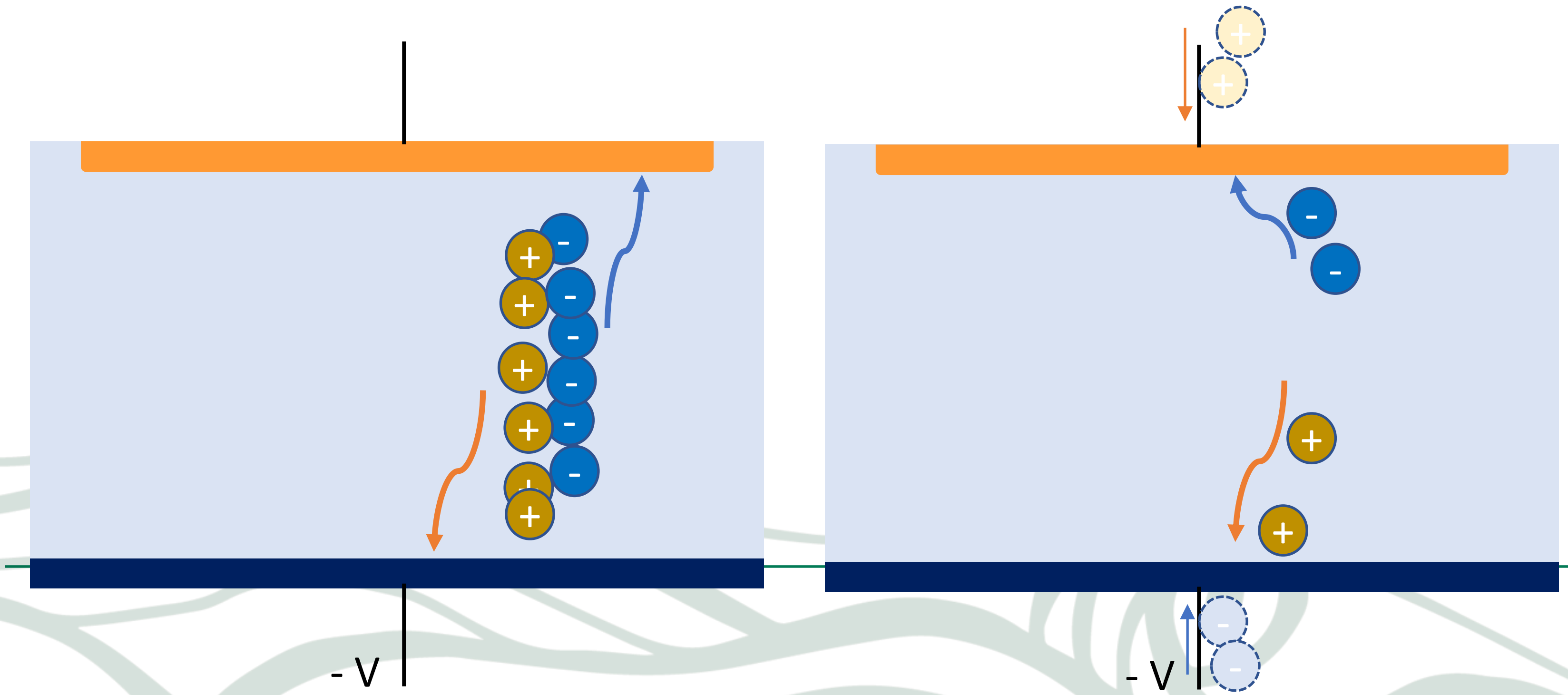
A traversing particle generates electron-hole pairs, which are attracted to and drift to the electrode of the opposite polarity

- Photon: otherwise similar, but point-like energy deposit for a single photon, with exponential absorption of the beam as function of depth (statistically)

Shockley-Ramo theorem: signal is generated as **induced current on the electrode by the drift of charge carries in the electric field:** charge and energy are conserved – mirror charge is drawn from the circuit as the carrier approaches the electrode

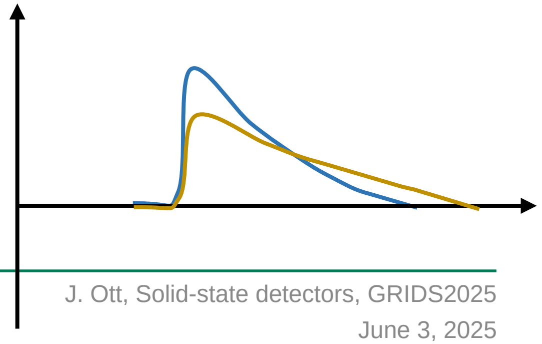
➢ **The signal rise time begins instantaneously, signal *ends* when the carriers have reached the electrode**

➢ **Drift time / carrier mobility can be different – material-dependent**



$$\boldsymbol{v} = \mu_{e,h}\boldsymbol{E}$$

$$i = q\boldsymbol{v} \cdot \boldsymbol{E_w}$$



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

Energy loss (cf. Bethe-Bloch!) = charge carrier generation is described by a Landau distribution: mean and most probable value are not identical.

$$i = q\boldsymbol{v} \cdot \boldsymbol{E_w}$$

Experimental values for Si: ca. 80 (105) e/h pairs per µm → **in a 300 µm Si sensor, ca. 24 000 e/h pairs**

How fast do they drift?

- Depends on electric field = bias voltage. Drift velocity saturation at about 10^7 cm/s, or about 100 µm/nsec

Why p-type Si?

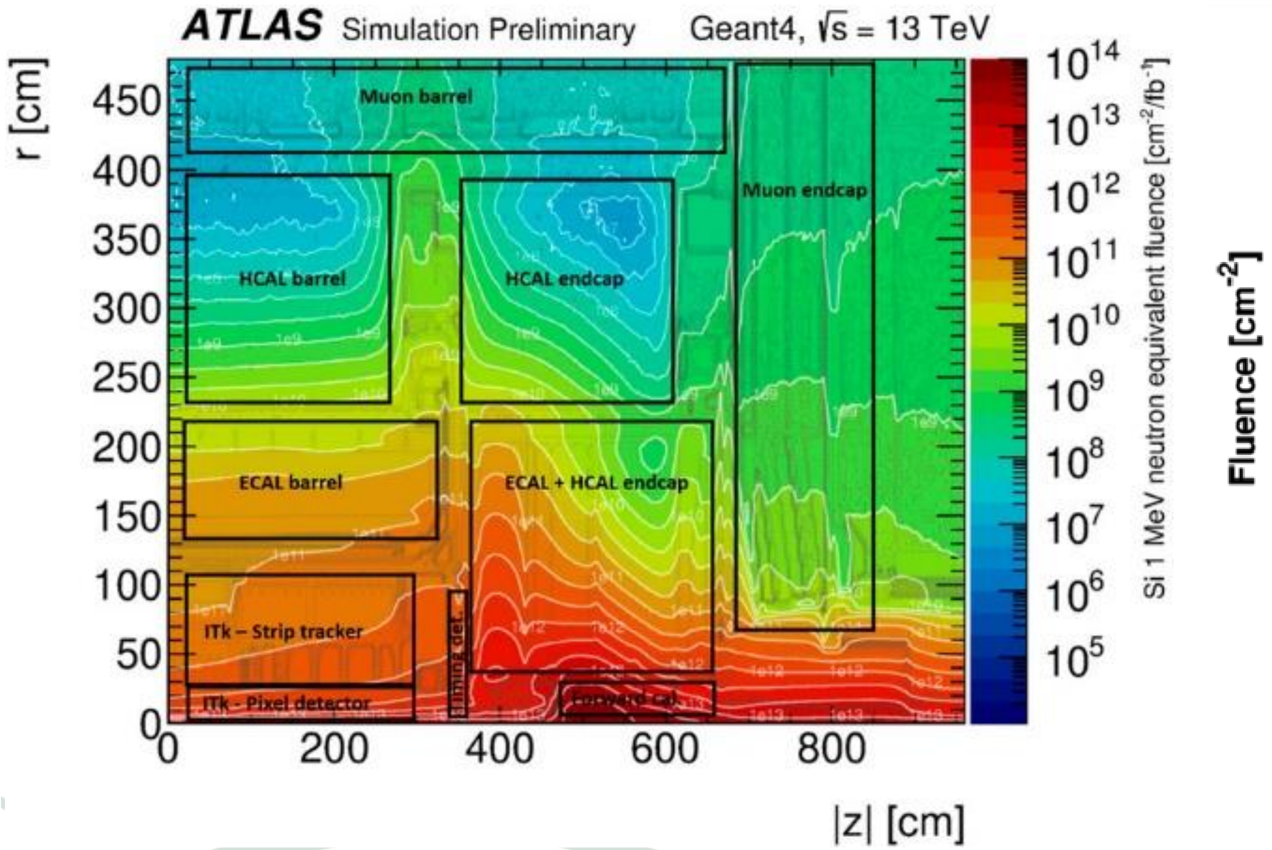
Earlier, not available as high-purity and high-resistivity substrate compared to n-type Si: nowadays high resistivities are available; active sensor may be grown by chemical vapor epitaxy

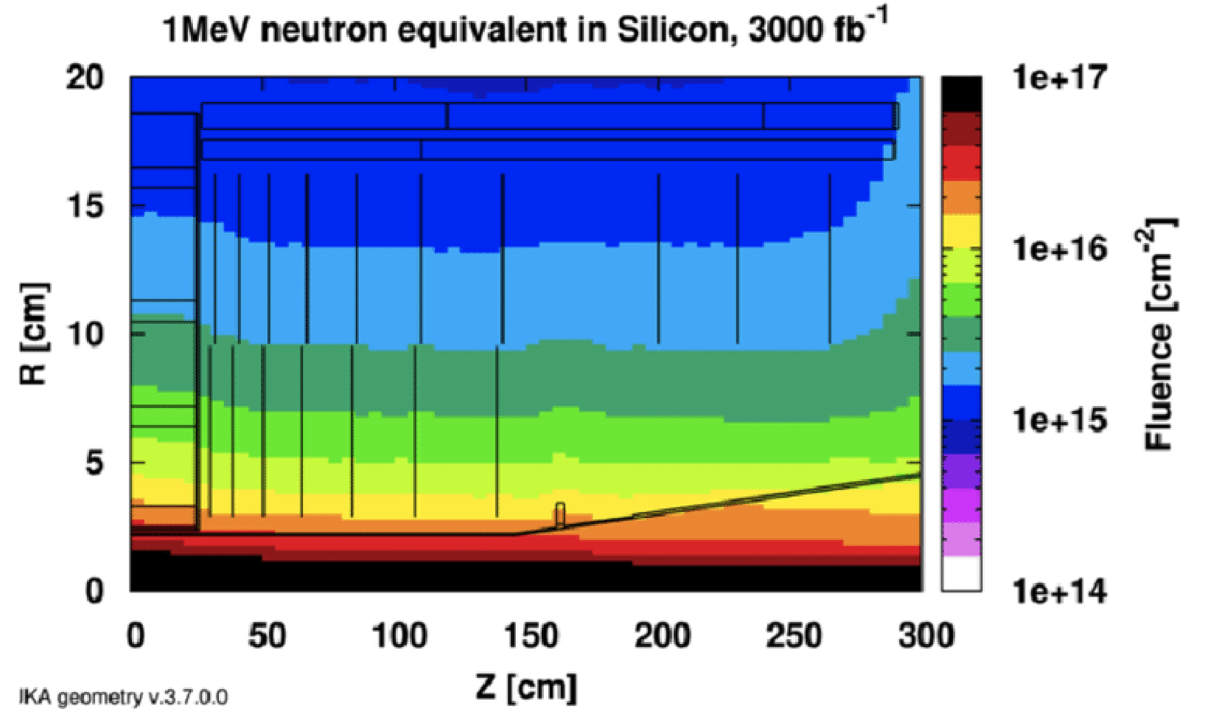
Higher radiation hardness in some aspect*

Electrode which forms the p-n junction with the bulk (= where the depletion starts, and electric field peaks) attracts electrons

- Higher mobility, less trapping in silicon – faster signal with higher collection efficiency
- Weighting field at the segmented electrode favors electron drift

Radiation damage





Towards the high-luminosity LHC

Radiation damage

- **Dislocation of atoms from their lattice sites**

- **Introduction of charge at surfaces and interfaces**

Nuclear interactions: non-ionizing energy loss

Total Ionizing Dose

➢ **Introduction of new defects in the solid**
  - Neutral and charged defects
  - Defect clusters

➢ **More charge carriers through addition of energy levels**

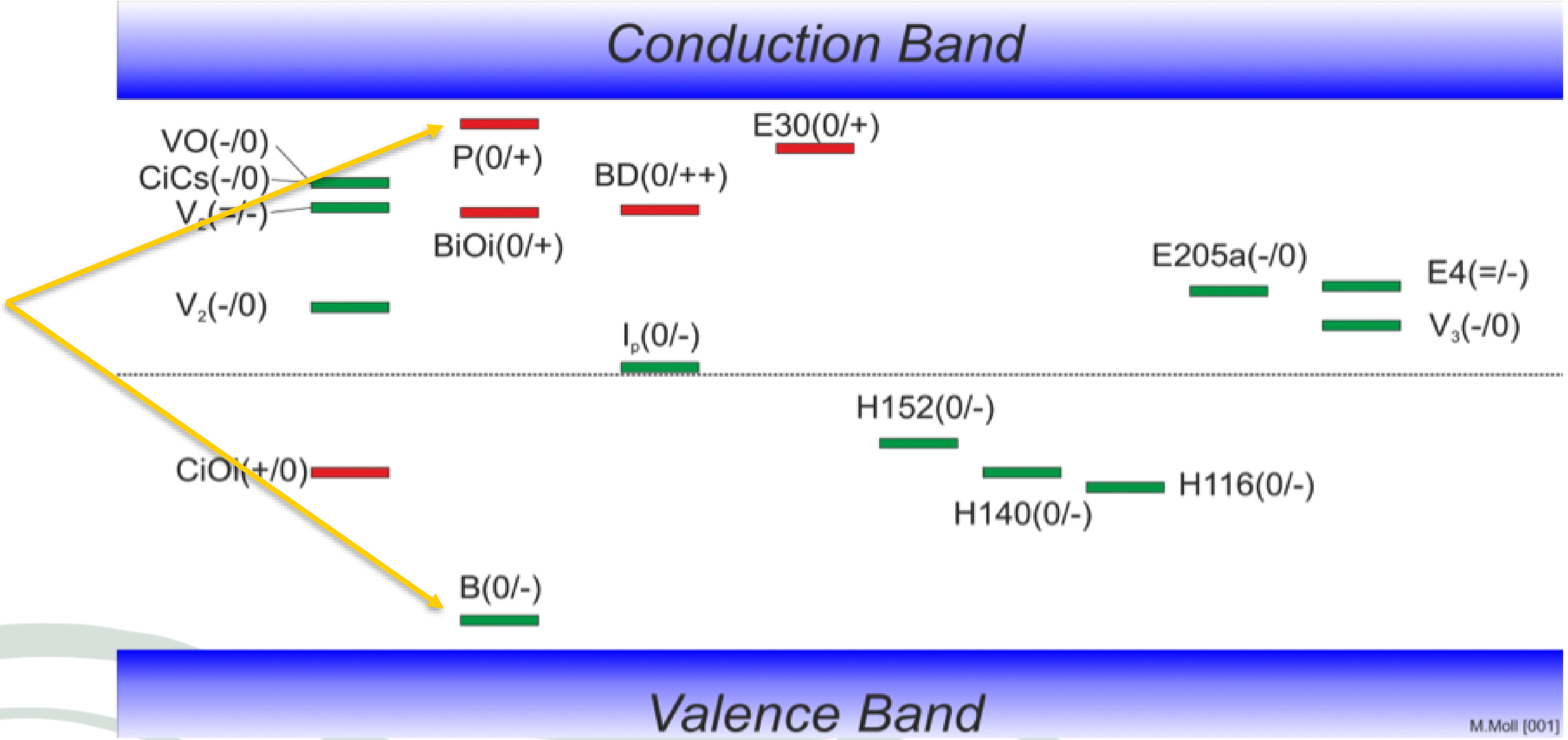
➢ **Trapping and recombination of charge carriers = signal**

➢ **Modification of existing (intentional) impurities**

Radiation damage

Effect of radiation-induced defects depends on their charge, and their energy level within the band gap

Dopants



***V**acancy*

***i**nterstitial*

***C**arbon, **O**xygen, ...*

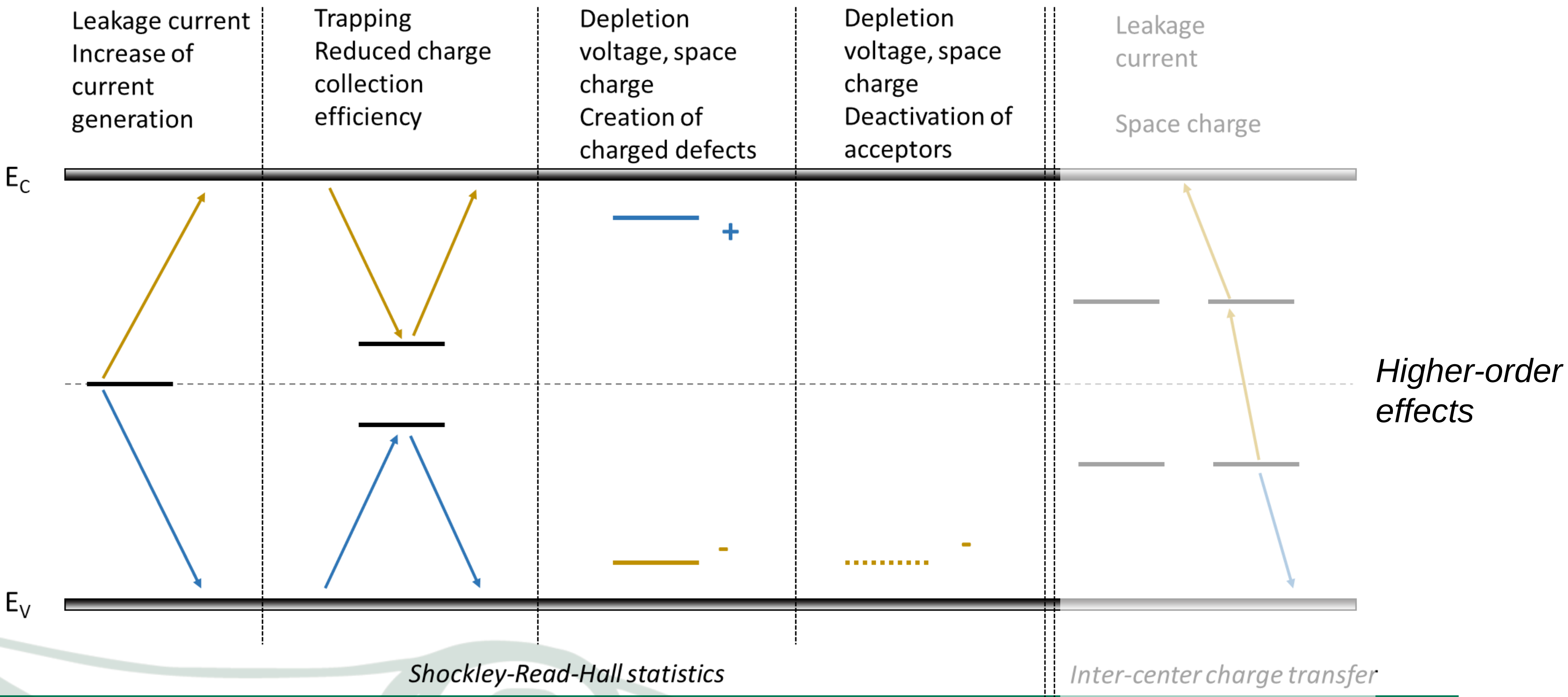
Silicon detectors for the LHC Phase-II upgrade and beyond. RD50 status report - Mandurrino, Marco - arXiv:1910.06045

Radiation damage

Effect of radiation-induced defects depends on their charge, and their energy level within the band gap

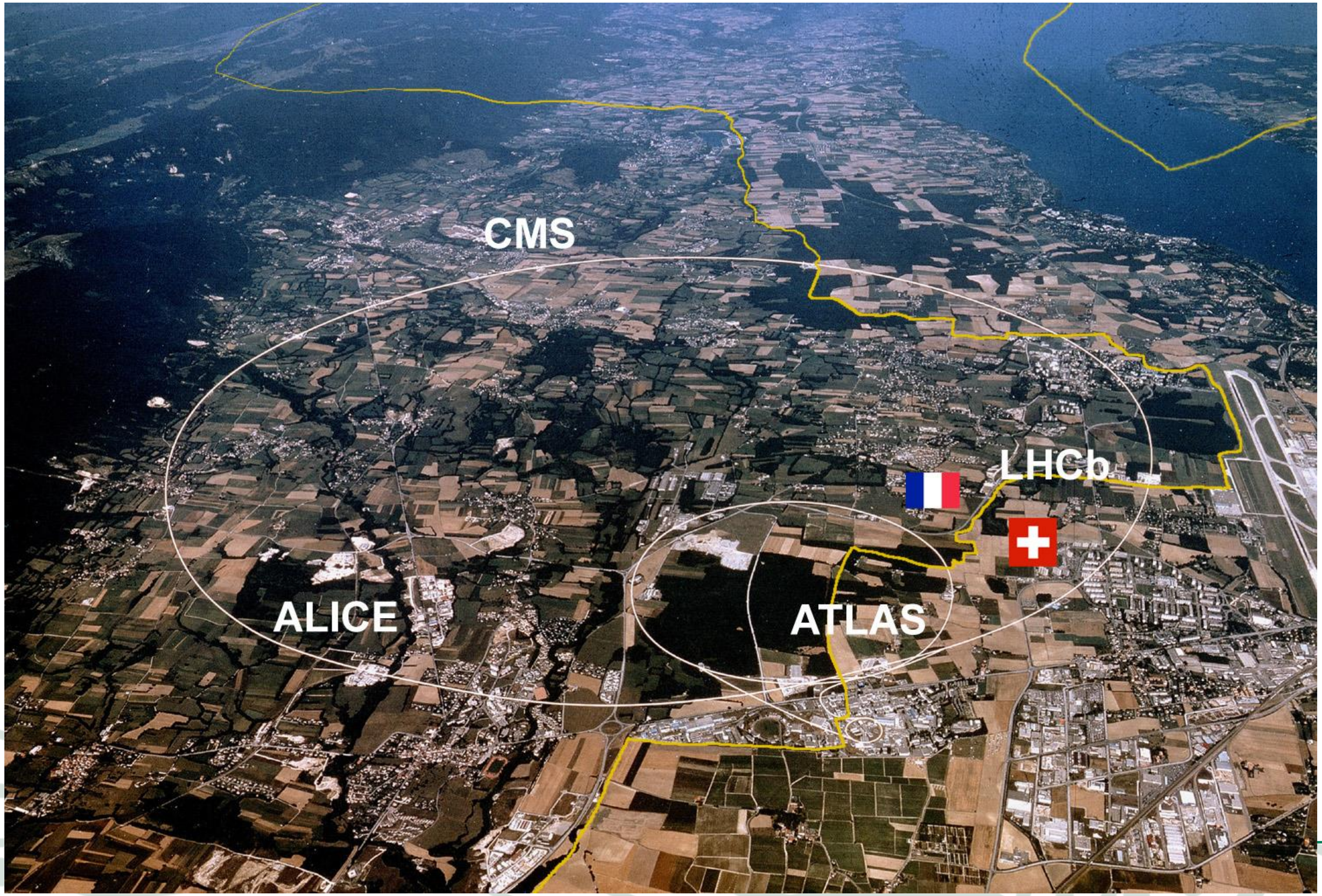
- Mid-gap energy levels lead to increased current generation
- Deep levels trap signal charges

- ‘Shallow’ defects increase, compensate, or deactivate doping



Tracking detectors

The Large Hadron Collider

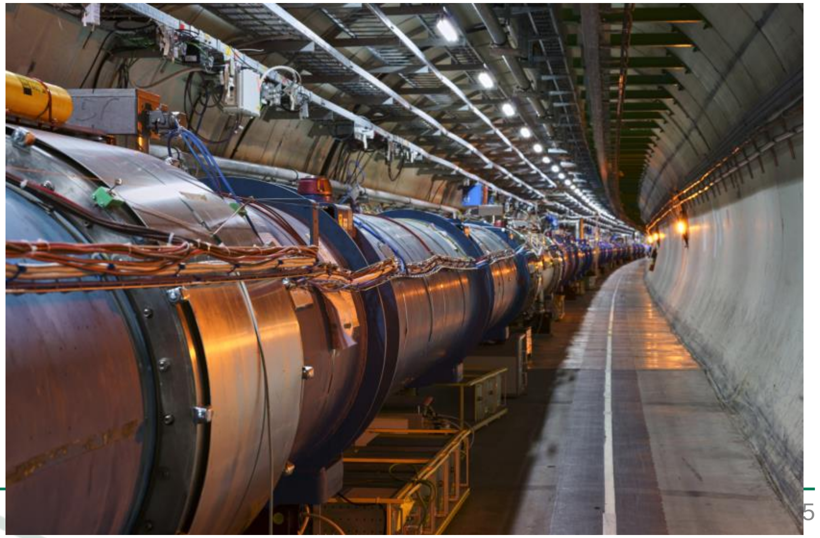


Circumference: 27 km

Primarily proton-proton (p-p) collisions: center-of-mass energy 13 TeV

Luminosity: 2×10^{34} $cm^{-2}s^{-1}$

Collision frequency: 40 MHz = **25 ns**



Physics at collider experiments

Precision measurements of the Standard Model of particle physics

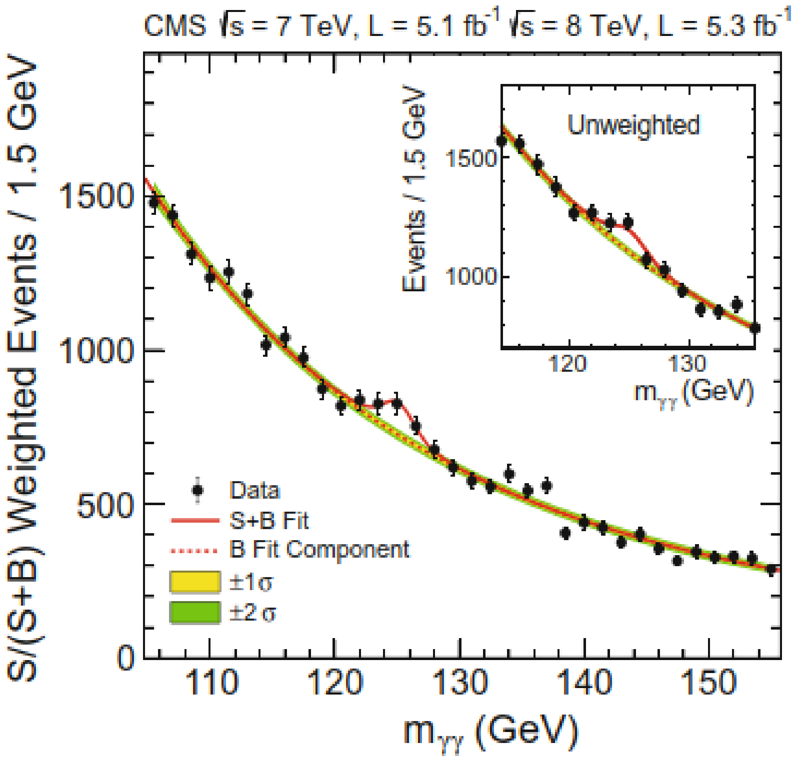
- **Top quark, W/Z bosons**
- **Higgs boson(s)**

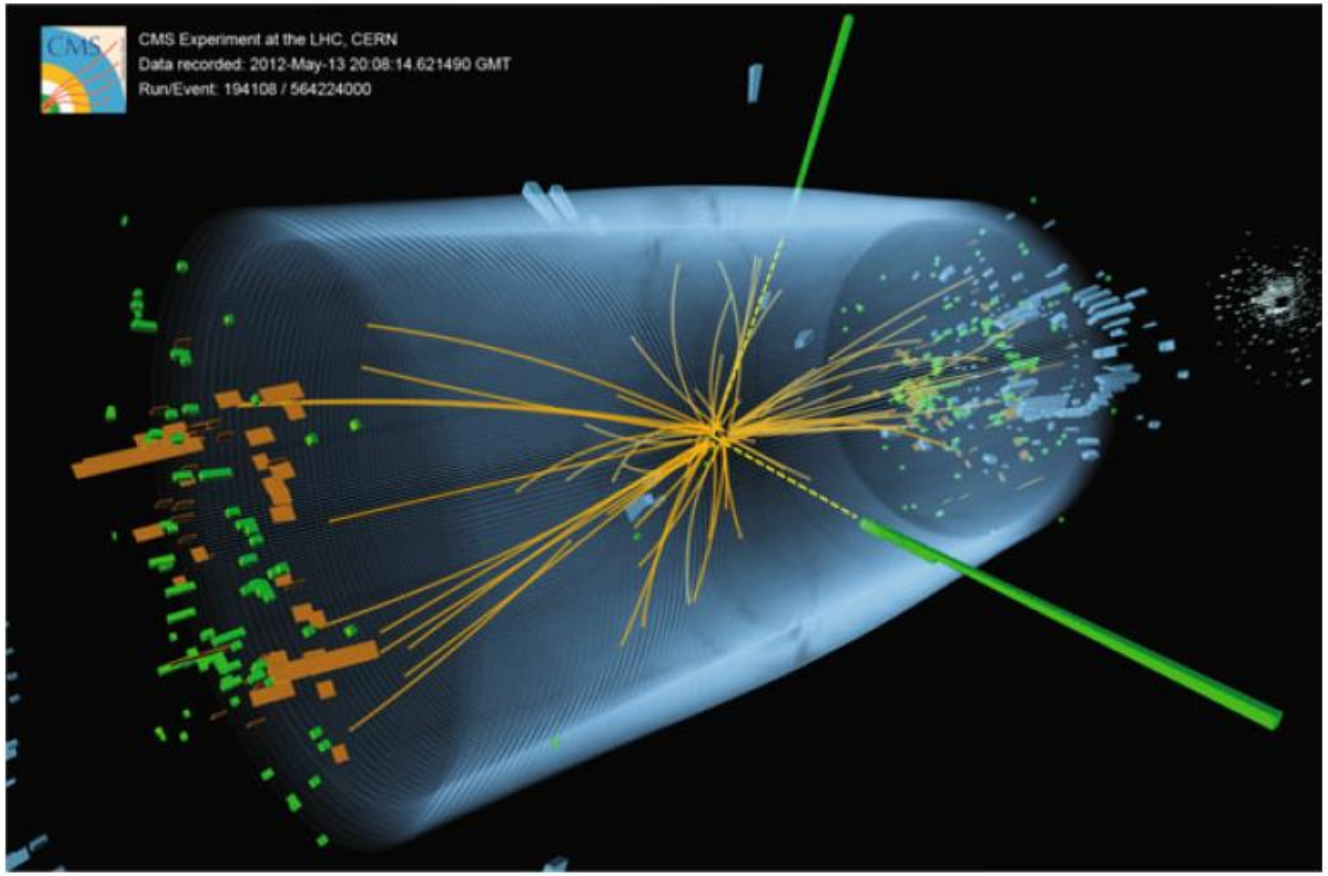
Search for physics Beyond the Standard Model

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

Heavy ion physics

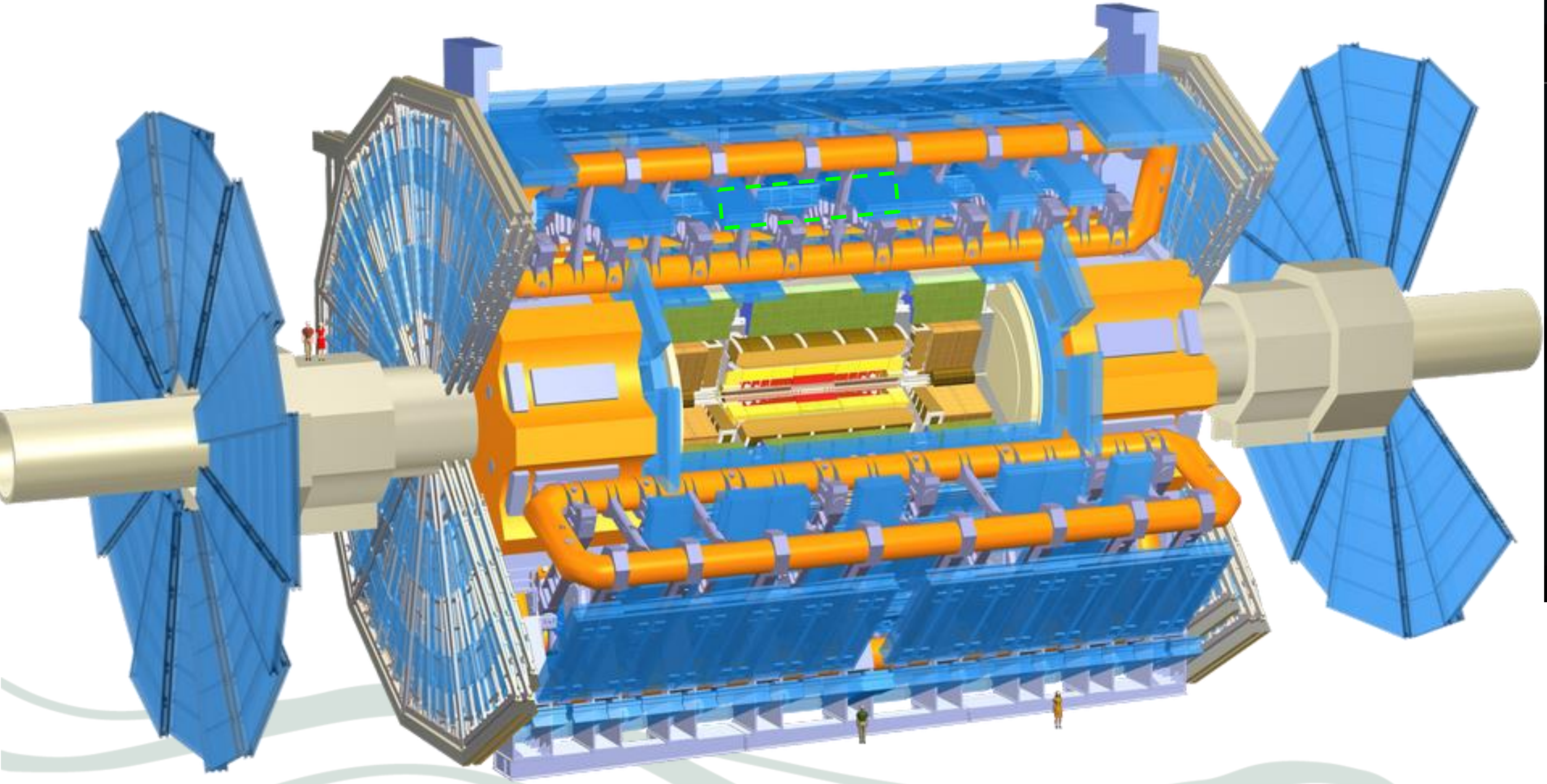
- **Extremely dense medium**

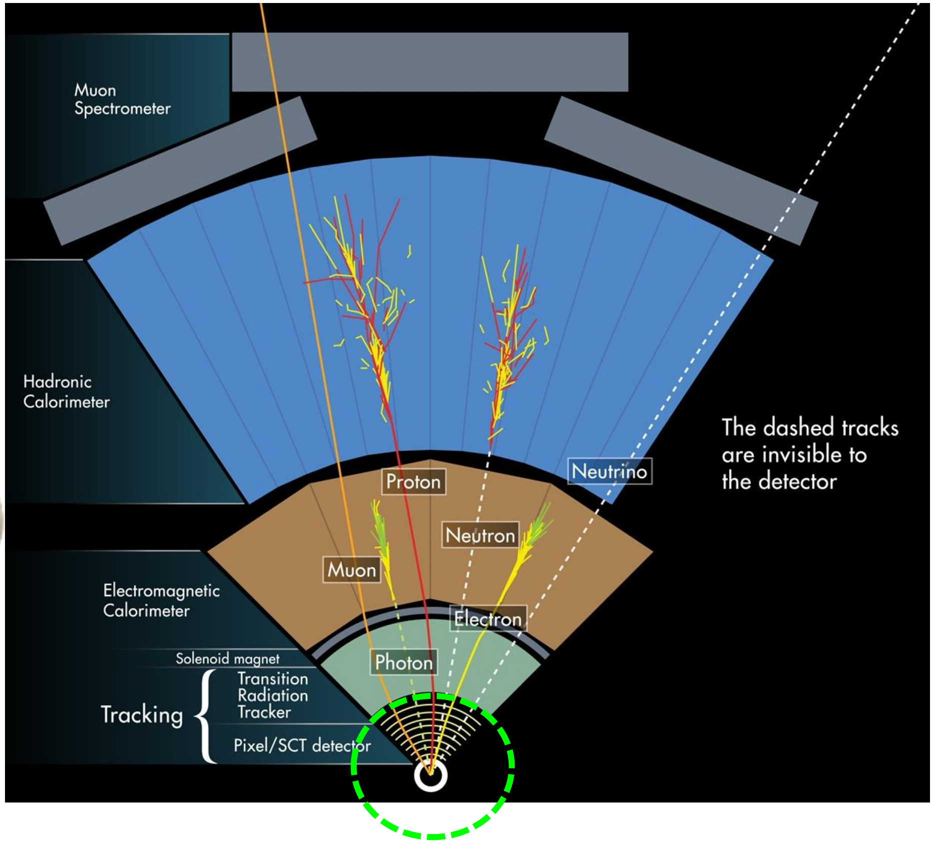

CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
Data
S+B Fit
B Fit Component
±1σ
±2 σ
mγγ (GeV)


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

The ATLAS Experiment

Multiple layers of specialized detector technology: tracking, calorimetry, spectrometers

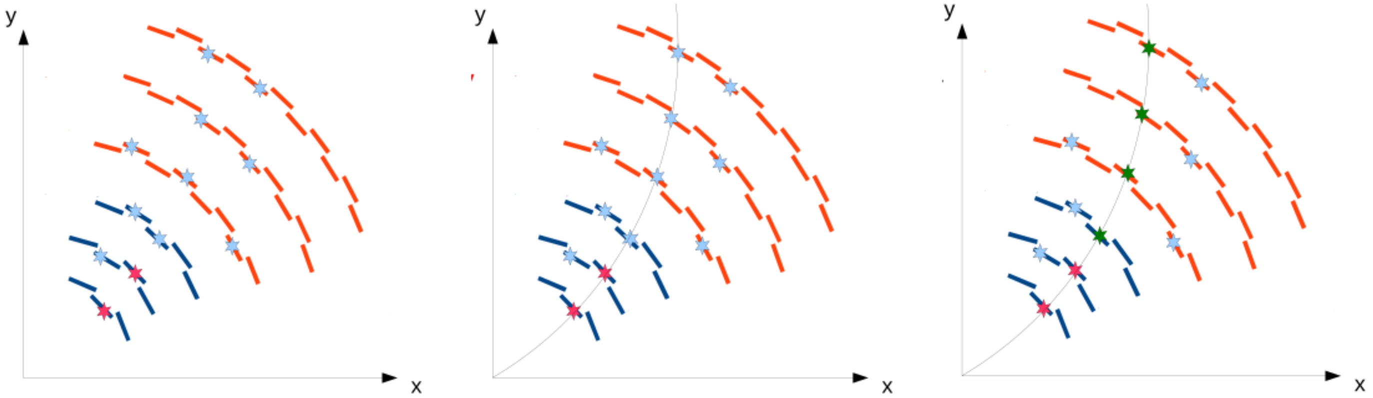




Particle tracking

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

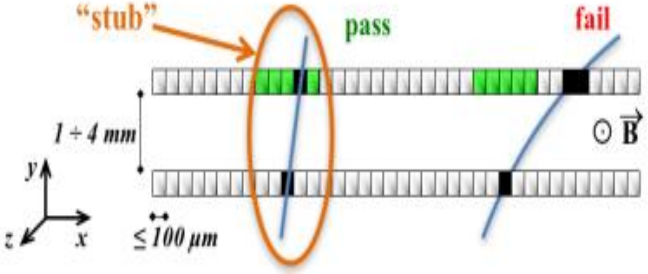
- Multiple layers
- Thin sensors
- Light material
- Capable of detecting small signal
- High spatial resolution = fine segmentation



$$F_L = \frac{dp}{dt} = qv \times B$$

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

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



Interactions of different species

Photons: minute probability of scattering

Neutral hadrons: small probability of non-ionizing interaction

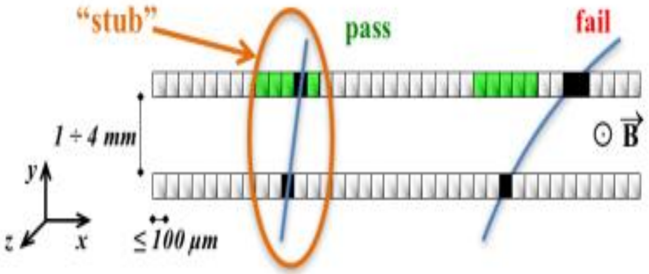
- ➢ Not detected in the tracker on the level of individual particles, but notable for the sensor in the long run...

Neutrino: no interaction, not detected

Electron, muon: track of minimum-ionization

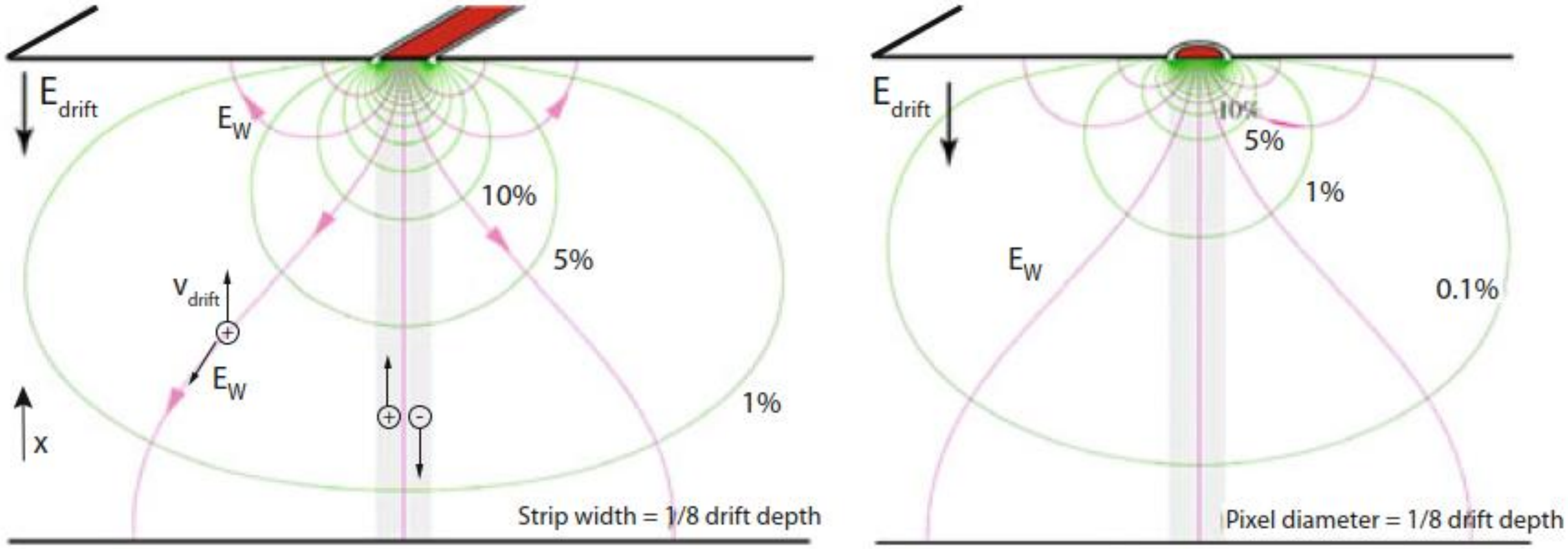
Charged hadrons: track of minimum-ionization

Segmented sensors



Precise spatial resolution is needed for tracking

- Typically one electrode is segmented into strips or pixels, that are all read out through their own channel
-



$$\boldsymbol{v} = \mu_{e,h}\boldsymbol{E}$$

$$i = q\boldsymbol{v} \cdot \boldsymbol{E_w}$$

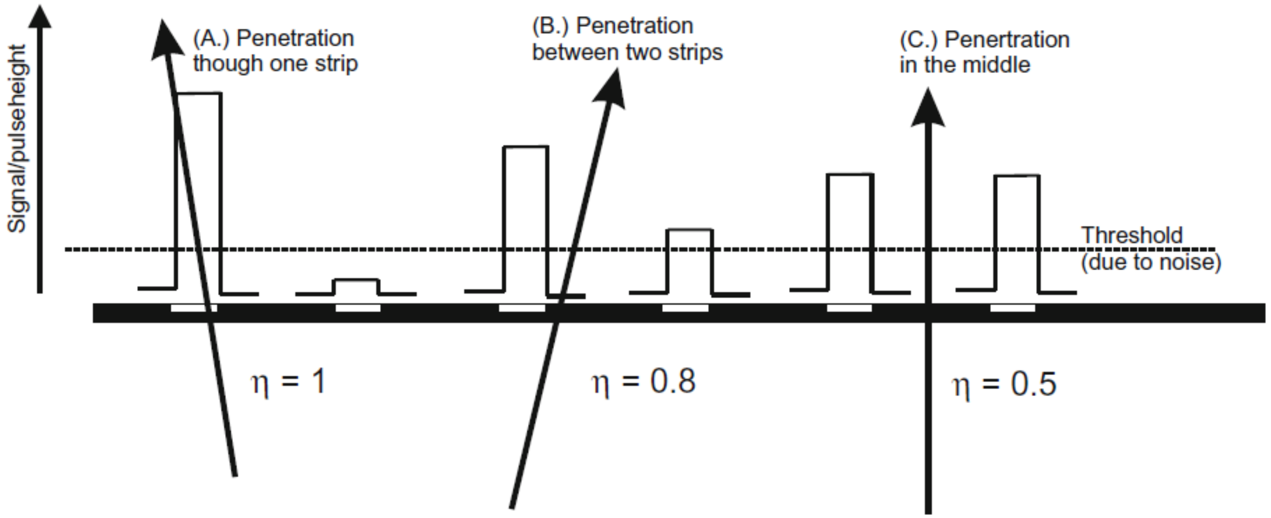
F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, 2nd Edition, Springer 2017

Position reconstruction

Clustering: summing of signals in adjacent pixels

Center-of-gravity: reconstruction of position by weighting their signal amplitudes

Geometric position resolution: pitch/$\sqrt{12}$

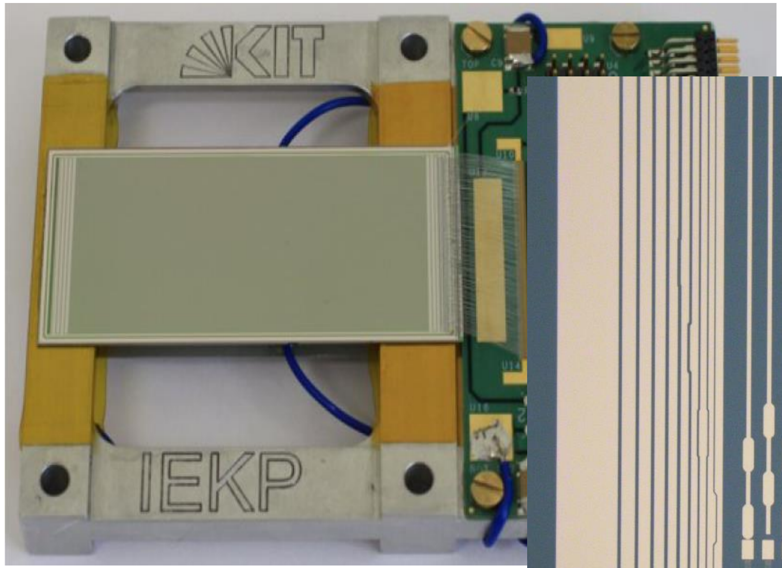


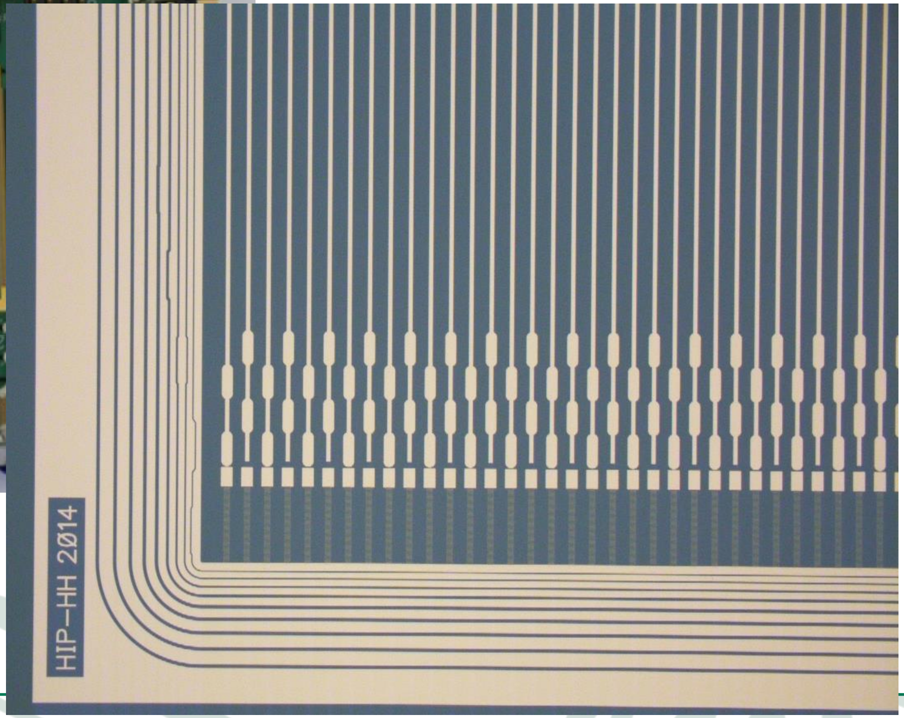
F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, 2nd Edition, Springer 2017

Planar segmented sensors

Resolution in 2D: strips

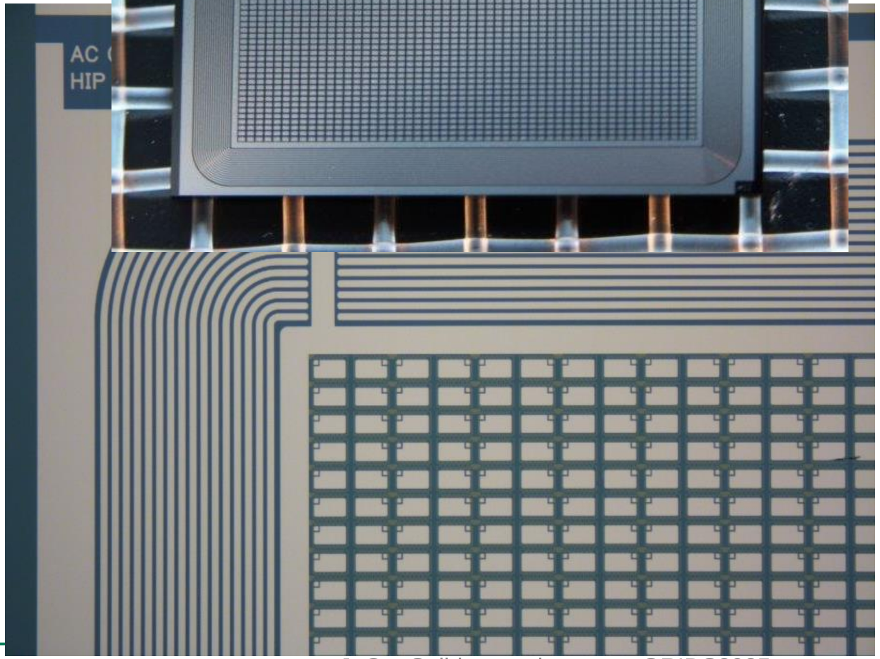
Read out via wirebonds

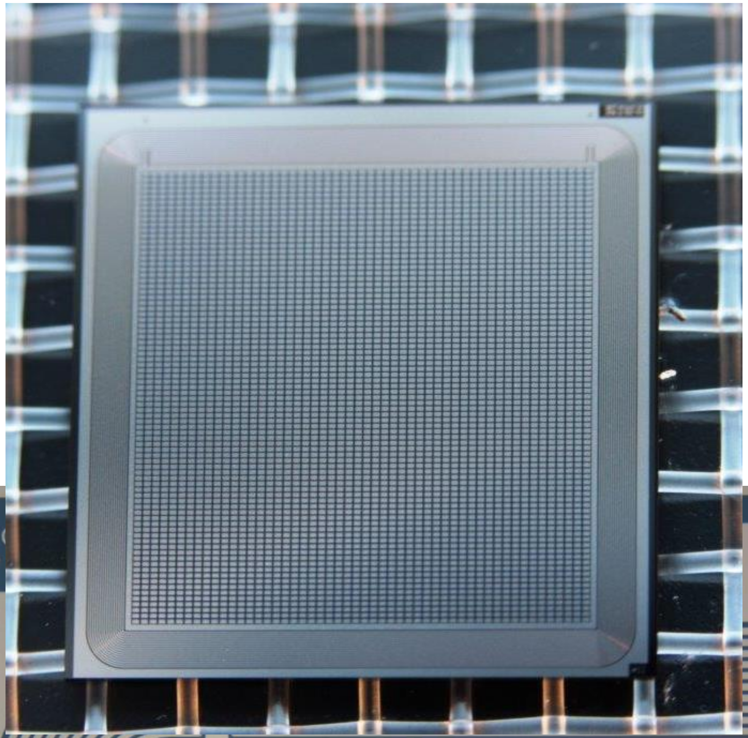




Resolution in 3D: pixels

Interconnection via bump bonding

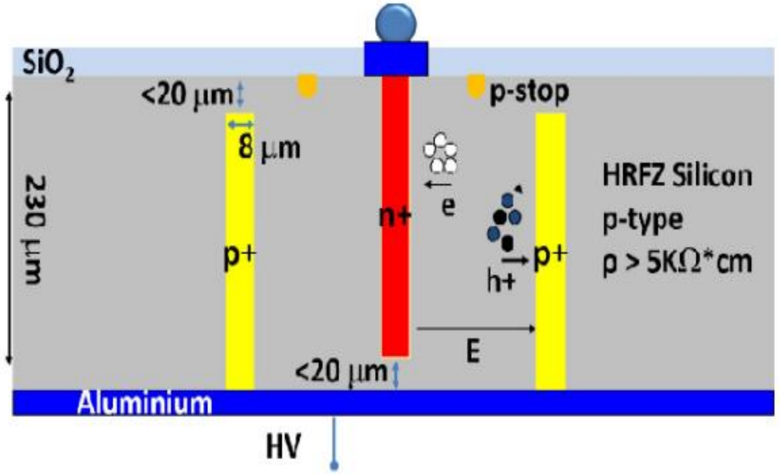




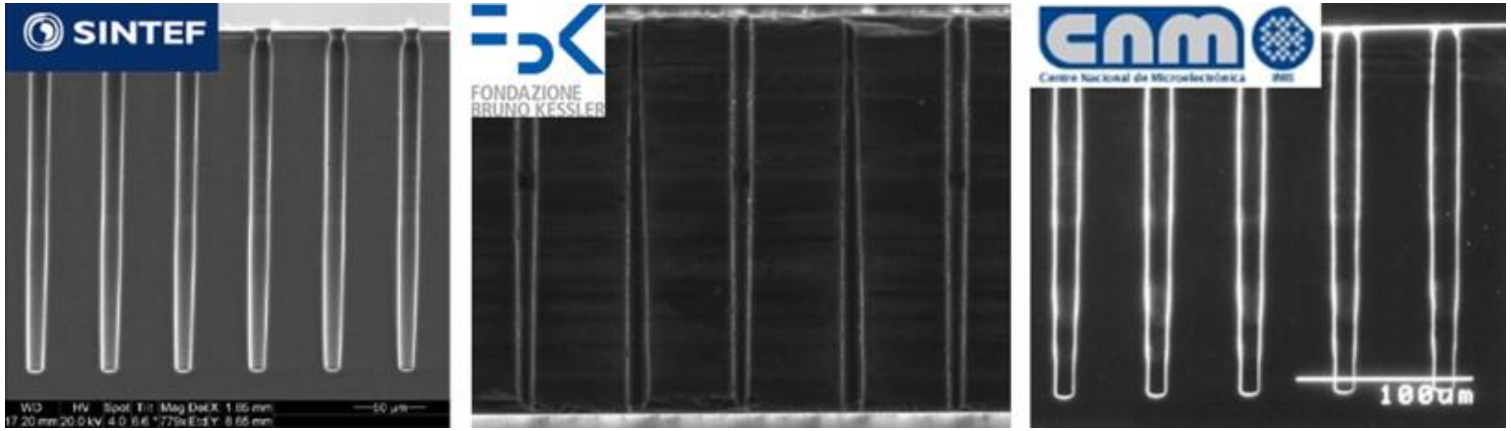
3D sensors

p- and n-electrodes not implemented as patterned sheets on the surfaces of the silicon surface, but as channels through the bulk
→ lower drift distance for charge carriers!
→ faster drift – good timing resolution

Efficiency before radiation dose is lower than for planar Si sensors, but radiation tolerance is better: 3D sensors to be used in innermost layers of CMS and ATLAS Tracker upgrades



E. Curras 2019



C. Da Via 2012

The High-Luminosity LHC

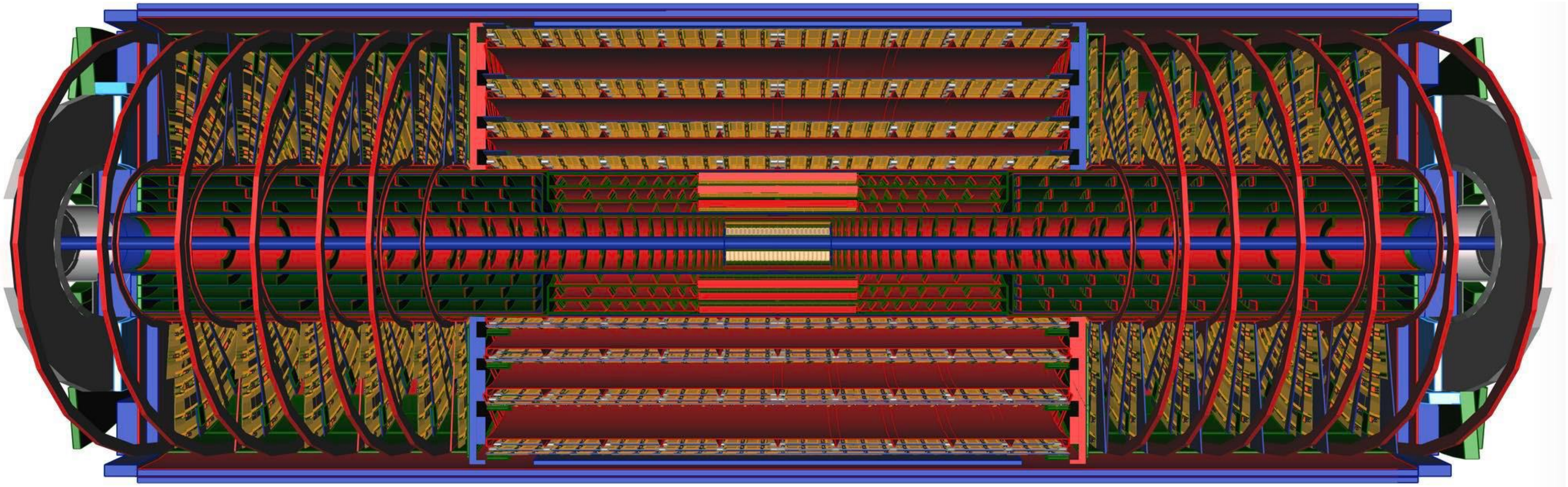
- Long shutdown in years 2024-~~2026~~ **2029**: installation of Phase II upgrades and transition to High-Luminosity LHC
- Collision center-of-mass energy 14 TeV

- Luminosity up to 7×10^{34} $cm^{-2}s^{-1}$ (LHC: 2×10^{34} $cm^{-2}s^{-1}$)
- Up to 200 p-p collisions per bunch crossing (”pile-up”)
- Fluence, i.e. radiation dose, to the innermost silicon detector layers: 2×10^{16} n_{eq} cm^{-2}

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

ATLAS ITk

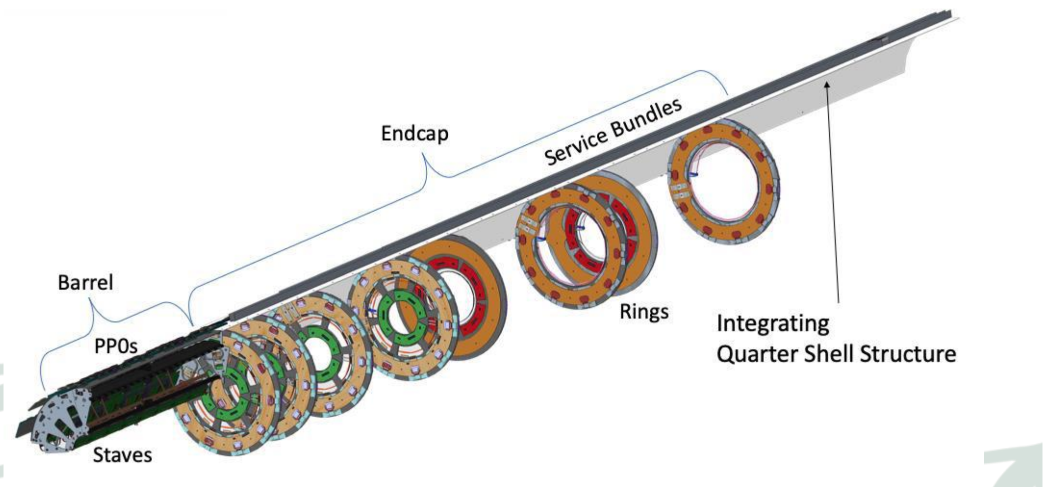
Phase-2 Upgrade for the ATLAS Experiment towards the HL-LHC features a new Inner Tracker detector: all-silicon, inner tracker with pixel sensors, outer region with strips

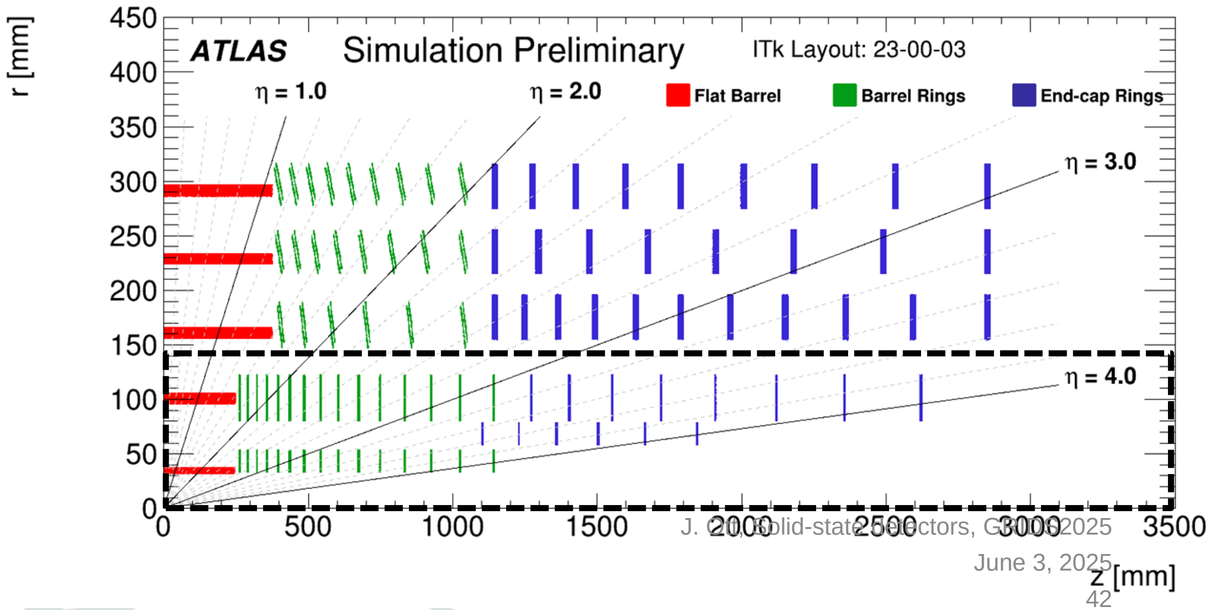


ATLAS ITk Pixel detector

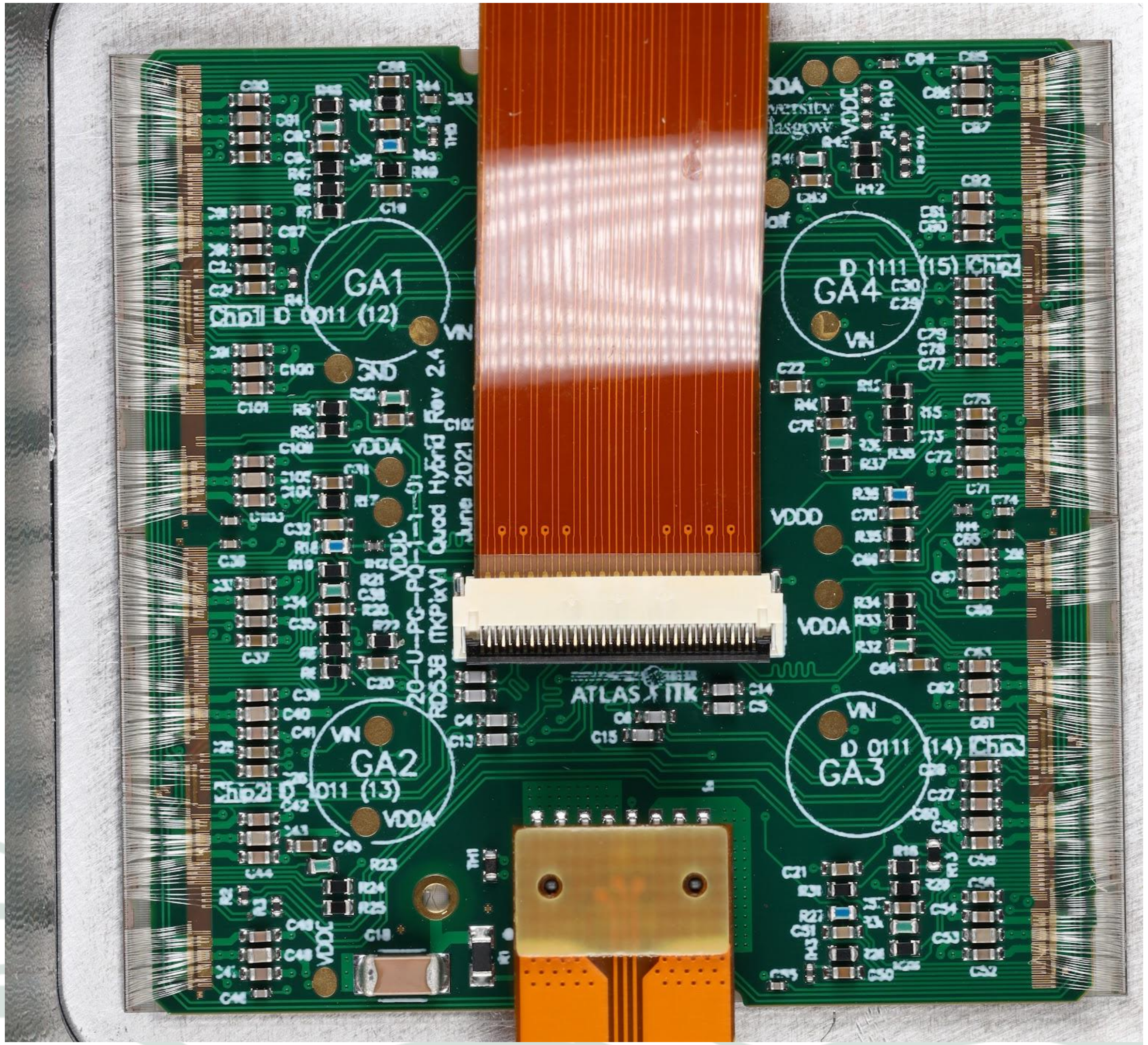
The US has committed to provide a standalone inner unit of the pixel tracker – the Inner System

- Modules, electronics, mechanics, cooling, services, data transmission, …
- Interfacing with international ITk project

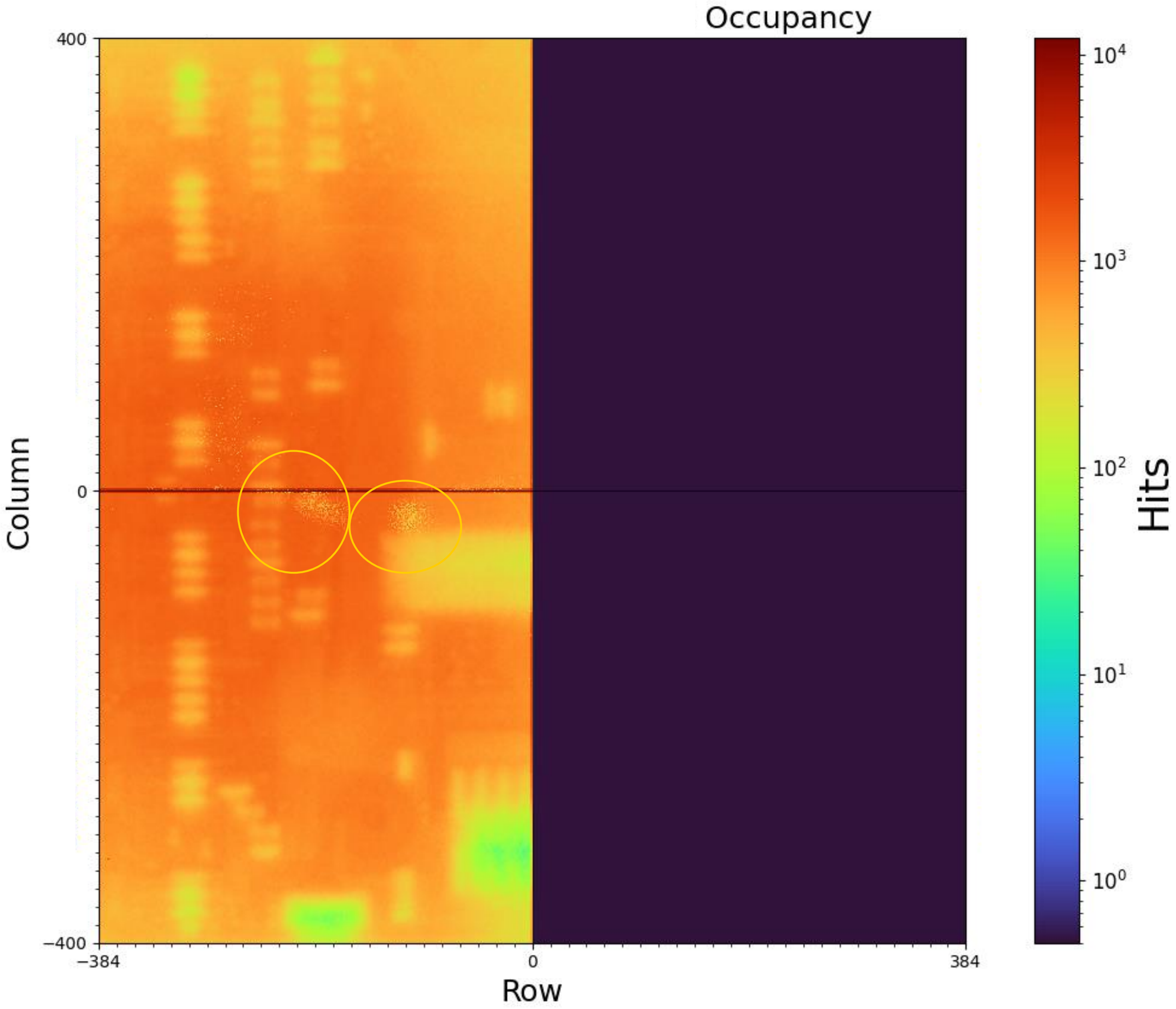




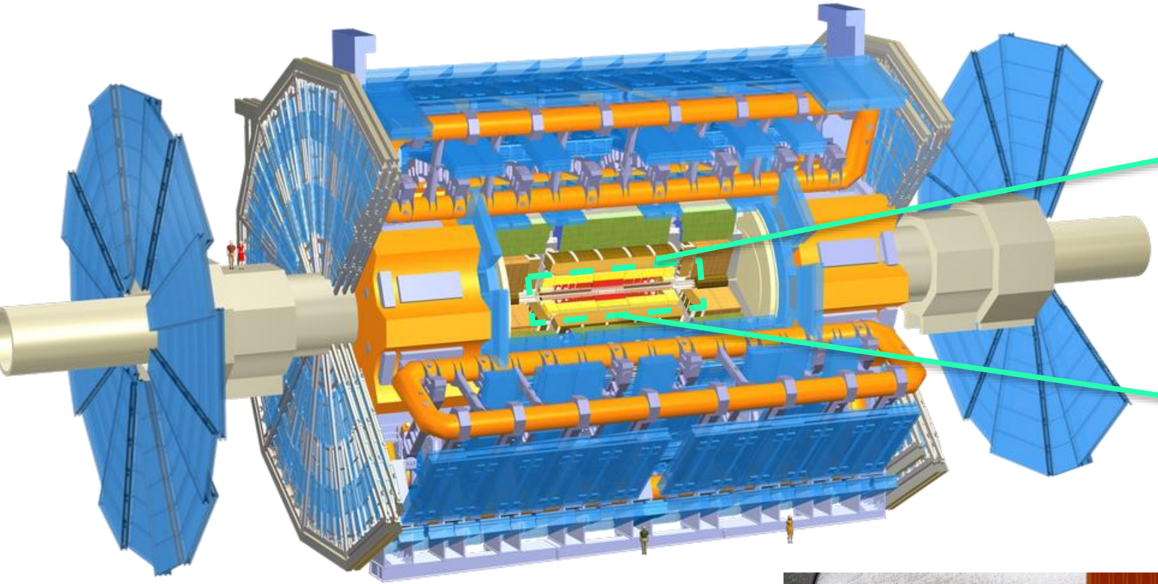
Pixel module testing

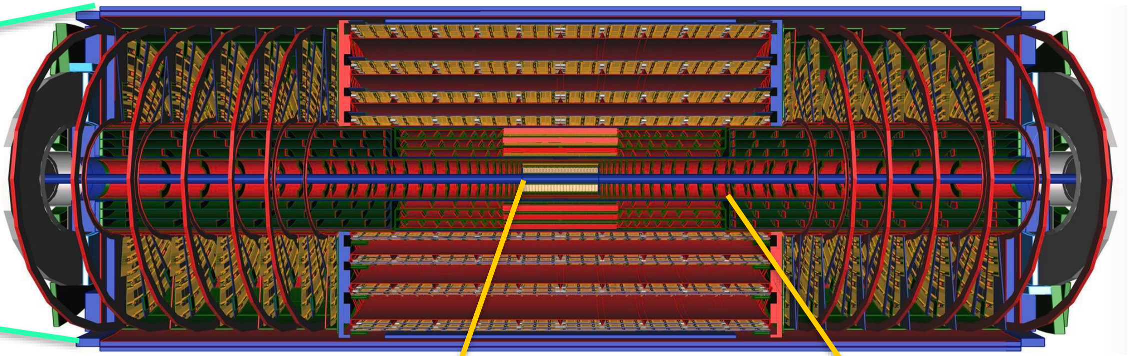


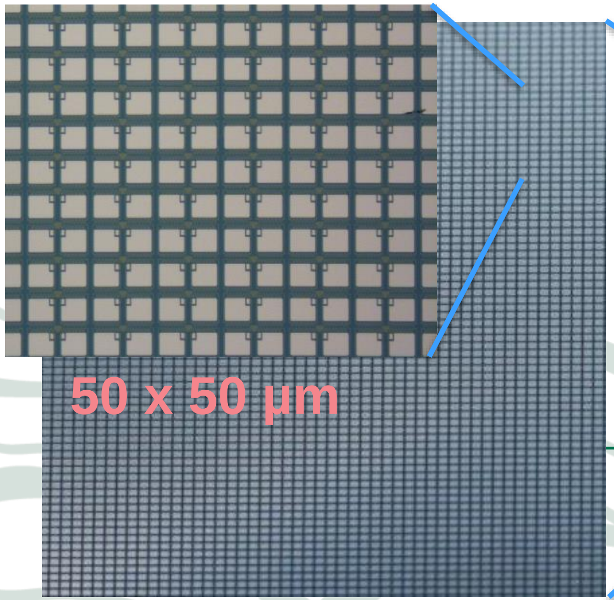
Areas with disconnected bumps identified with Sr-90 source scan

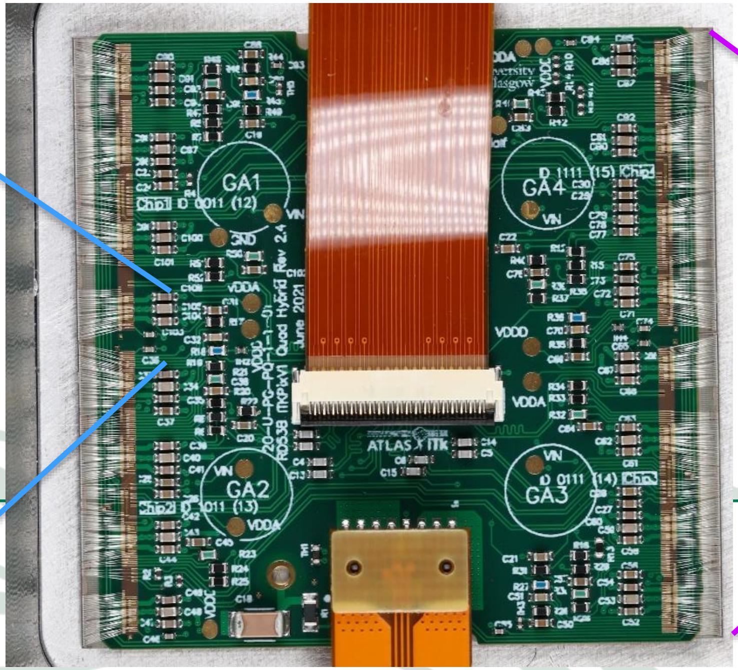


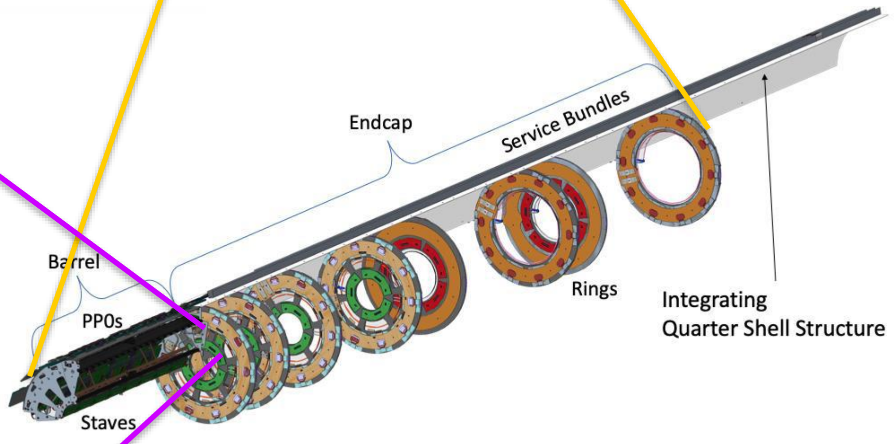
Example: ATLAS Inner Tracker pixels







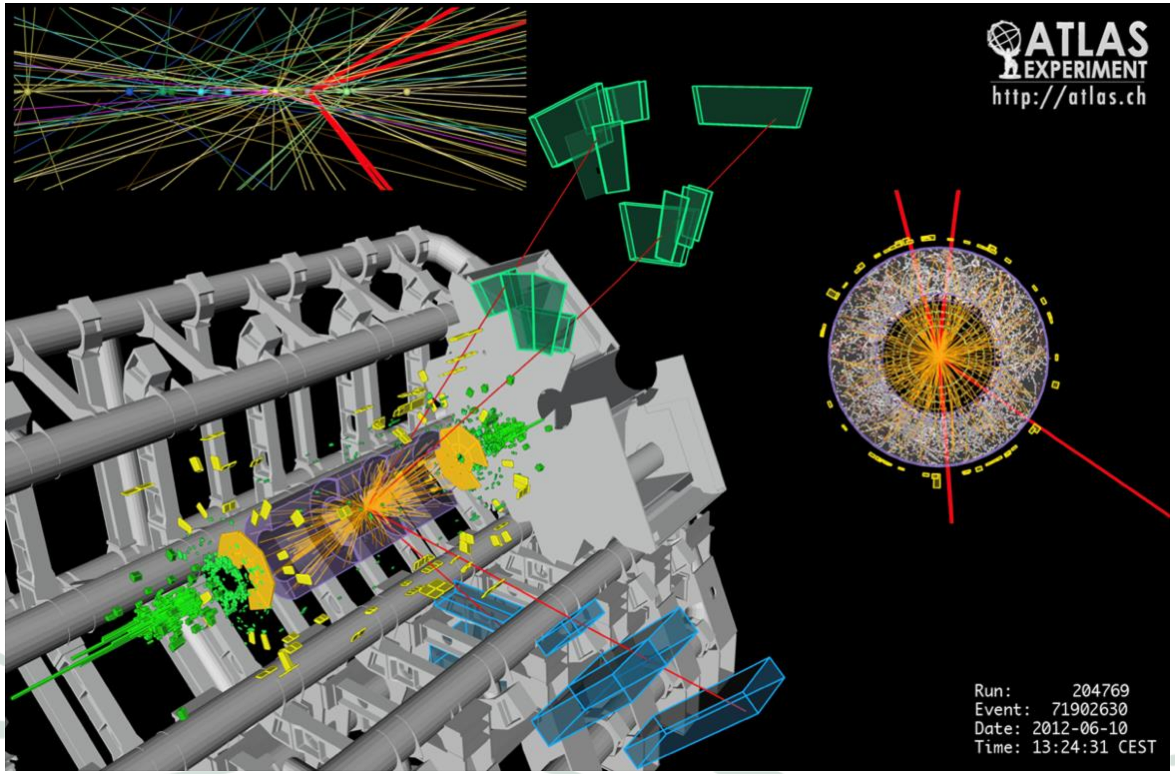


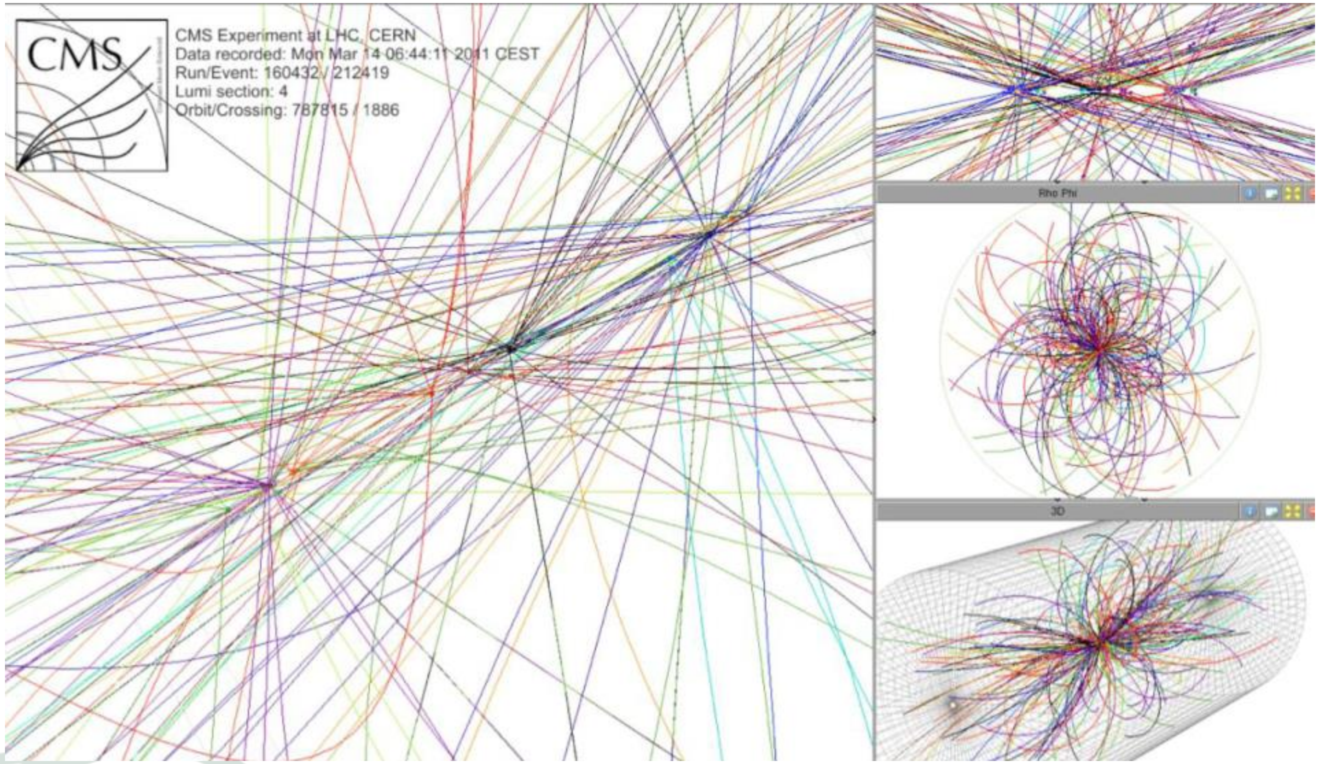


Particle tracking and vertexing

Several collisions per bunch crossing:

→vertexing: point / associate a track to the original interaction point



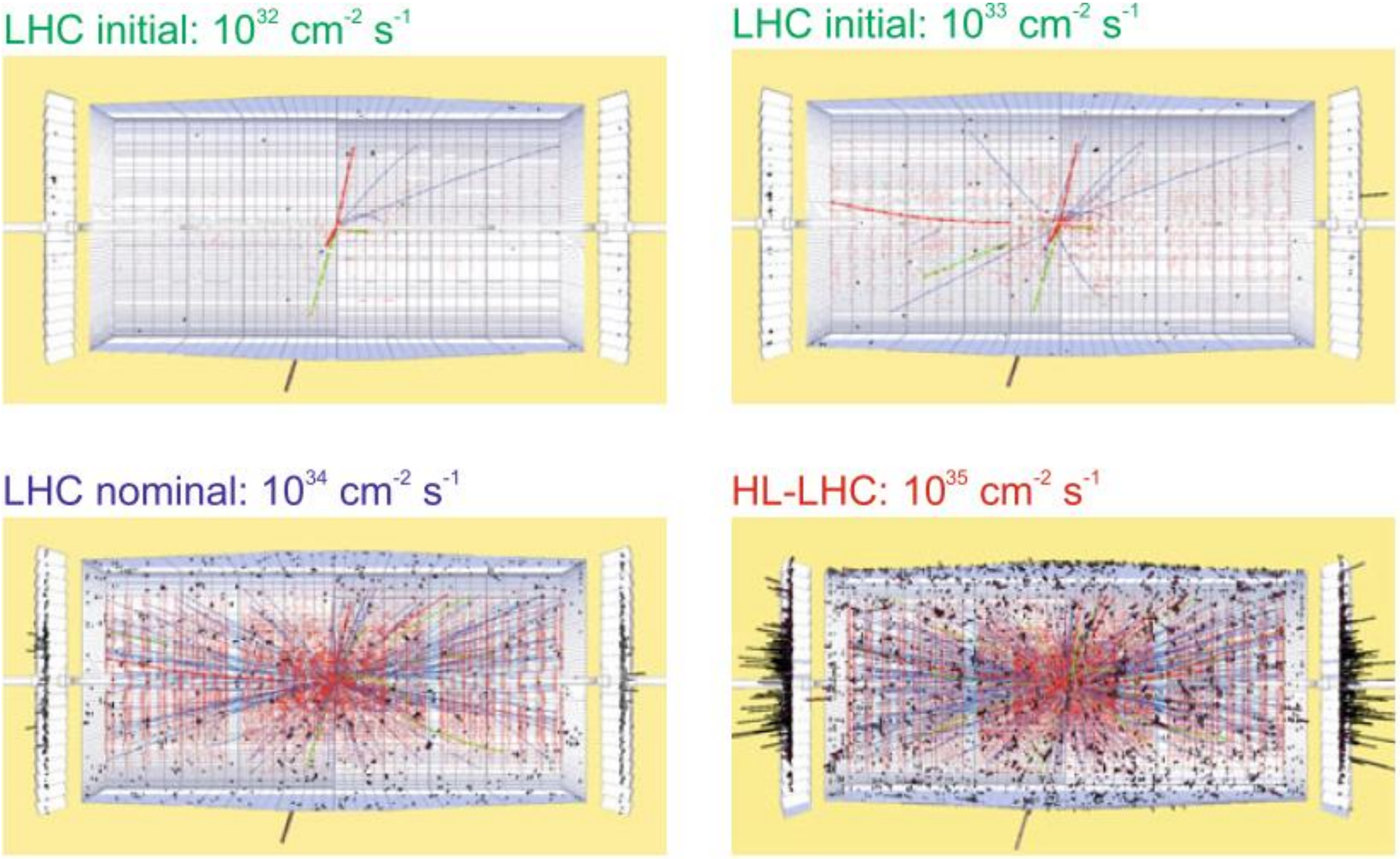


Timing

Precision timing

At the HL-LHC, the number of interactions per bunch crossing, i.e. *pile-up* increases from ~50 to ~200

Timing resolution of 30-60 ps is needed to associated tracks to primary vertex (and improves many analyses performances)



Precision timing

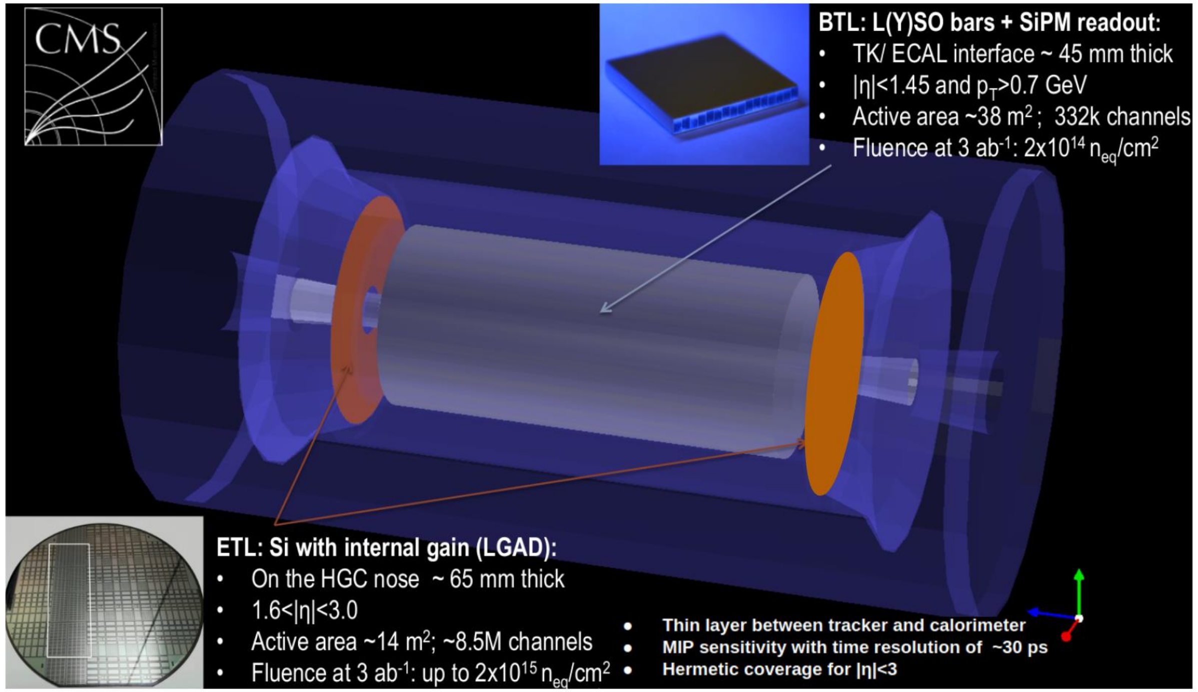
CMS and ATLAS experiments will install dedicated MIP timing detector layers in the Phase-2 upgrades, between tracking systems and calorimeters

CMS

- Barrel and endcap region with different technologies: barrel scintillators + SiPM, endcap with fast silicon detectors – **LGAD**s

ATLAS

- Timing detectors only in the endcap region, with **LGAD**s



CMS MTD Technical Design report

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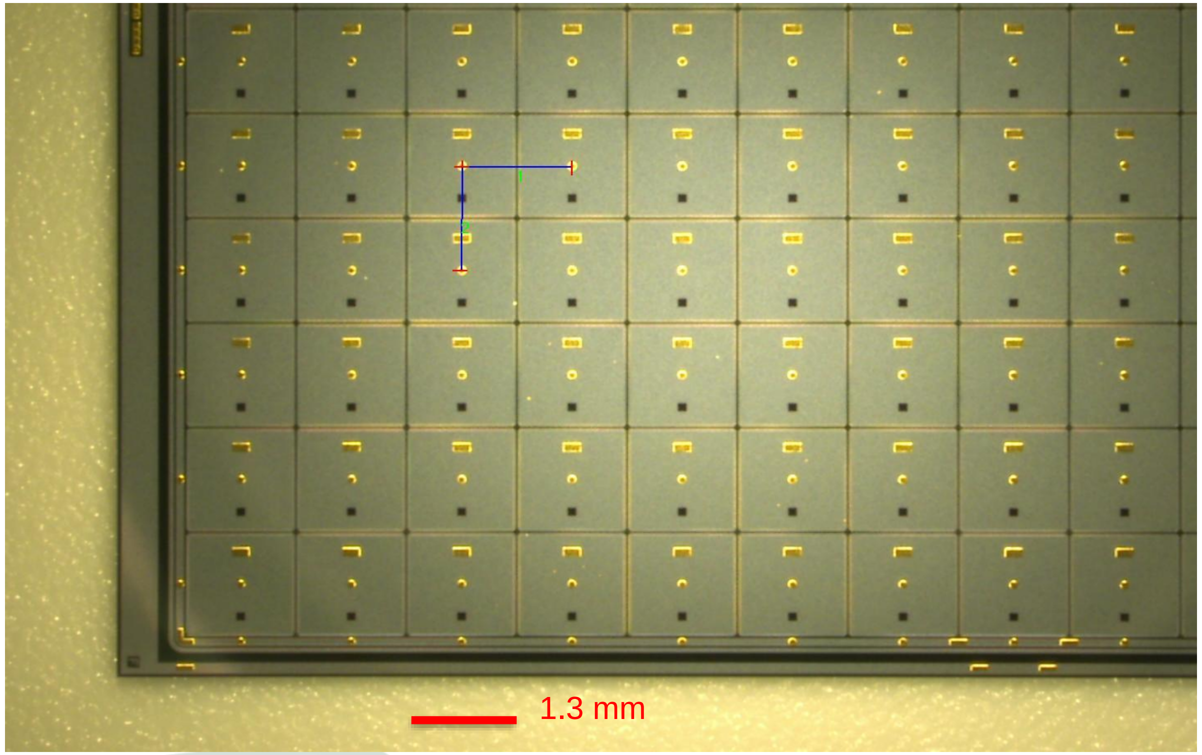


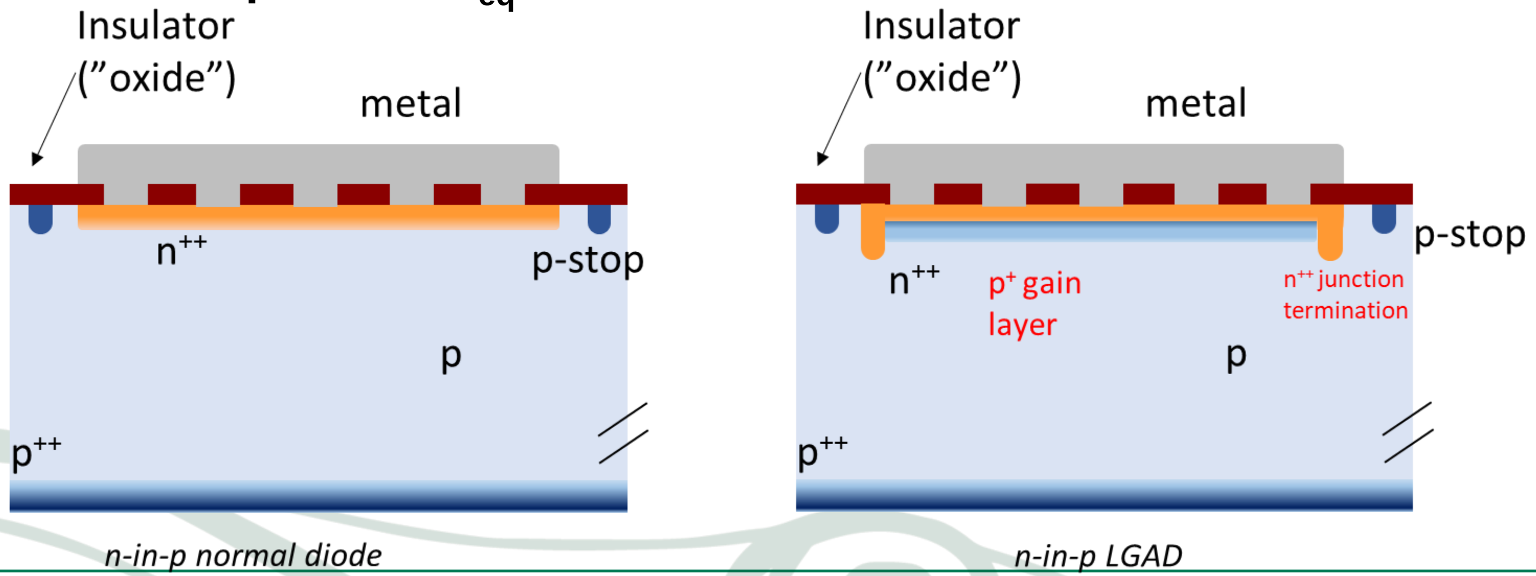
15x15 pad prototype LGAD sensor for HGTD

Low-gain avalanche diodes

Thin sensors, typical active thickness 50 µm – shorter drift time, higher electric field, less Landau fluctuations!

- Mechanical support wafer 150-400 µm!

Low to moderate gain (5-50) provided by p^+ multiplication layer
Timing resolution down to ca. 20 ps
Good radiation hardness up to 10^{15} n_{eq}/cm^2



H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, CERN-LHCC-2018-023, 2018

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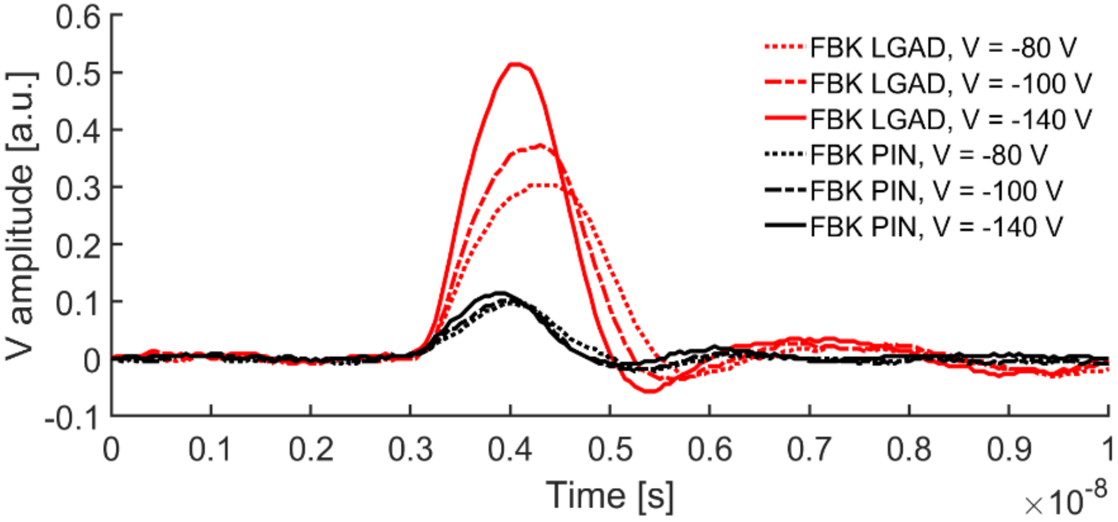

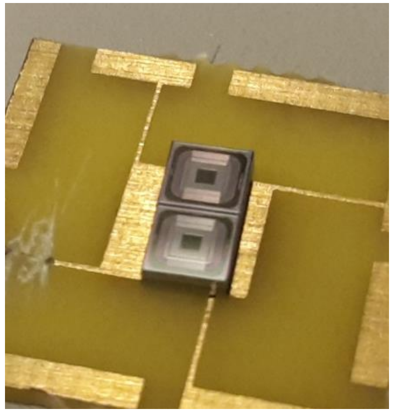

Gain determination with LGAD-diode pairs in laser TCT

H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
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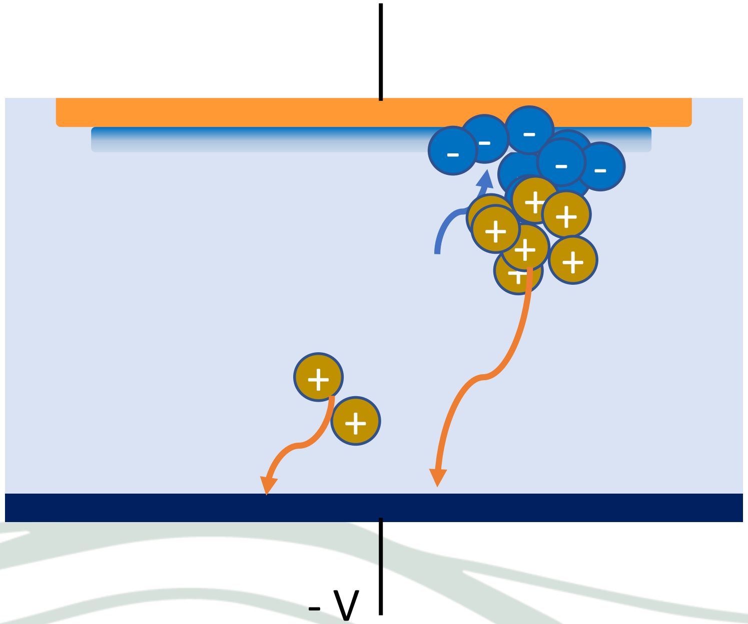
Low-gain avalanche diodes

- **Gain layer with moderate doping concentration (lower than n^{++} or p^{++} contacts) results in localized, higher electric field**
- **Electrons reach enough kinetic energy to ionize other atoms in the Si lattice – multiplication, ‘avalanche’**



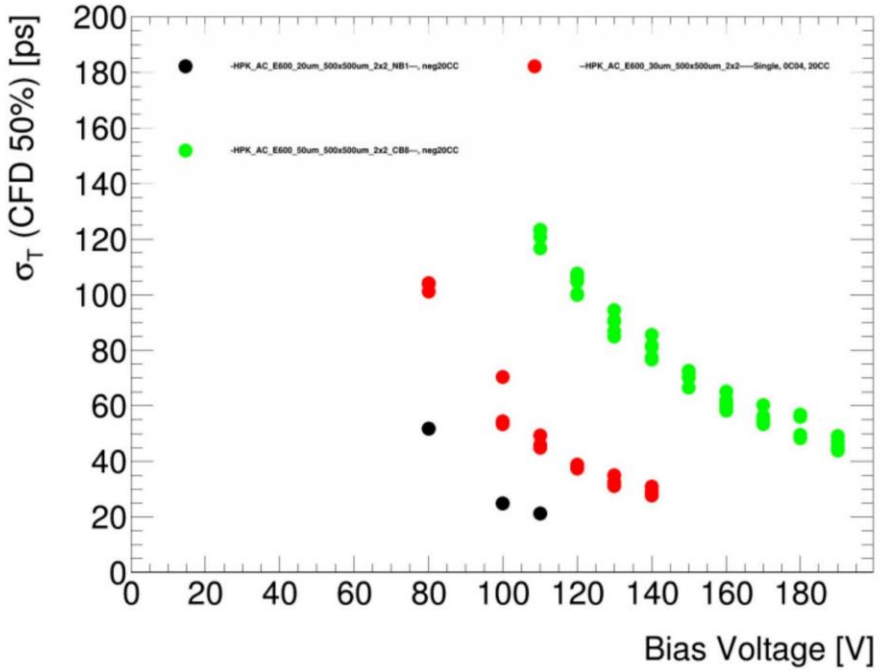
1. Electrons drift to the segmented electrode and pass by the gain layer
2. Holes drift to backplane
3. Electrons generate new e-h pairs at the gain layer
4. New electrons only drift a few µm to the front electrode: are typically obscured by rise time of the electronics
5. **New holes drift through the bulk to the backplane**

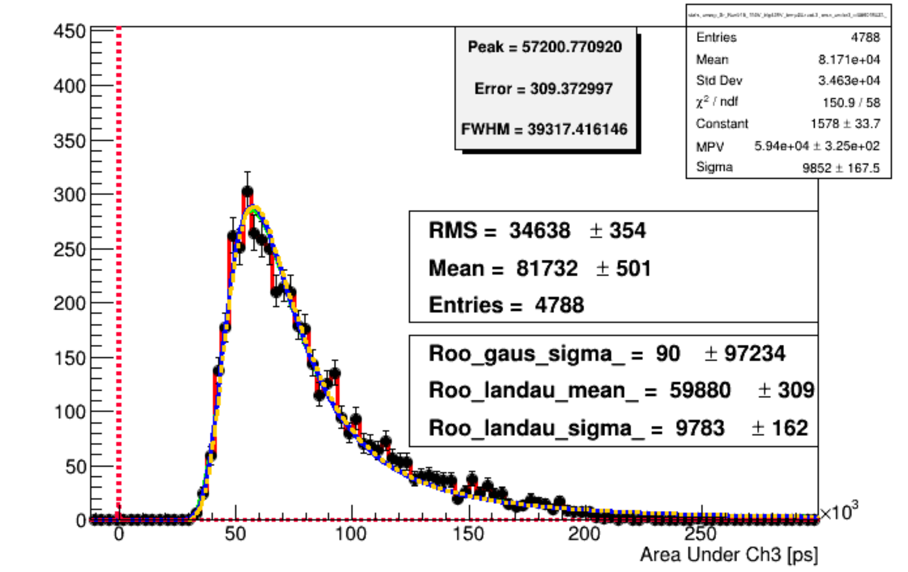
Timing resolution

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{time\ walk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2$$

Timing resolution consists of several contributions

- Landau fluctuations of charge deposition: reduce by thinner sensor
- Time walk
- Jitter (sensor & electronics)
- TDC



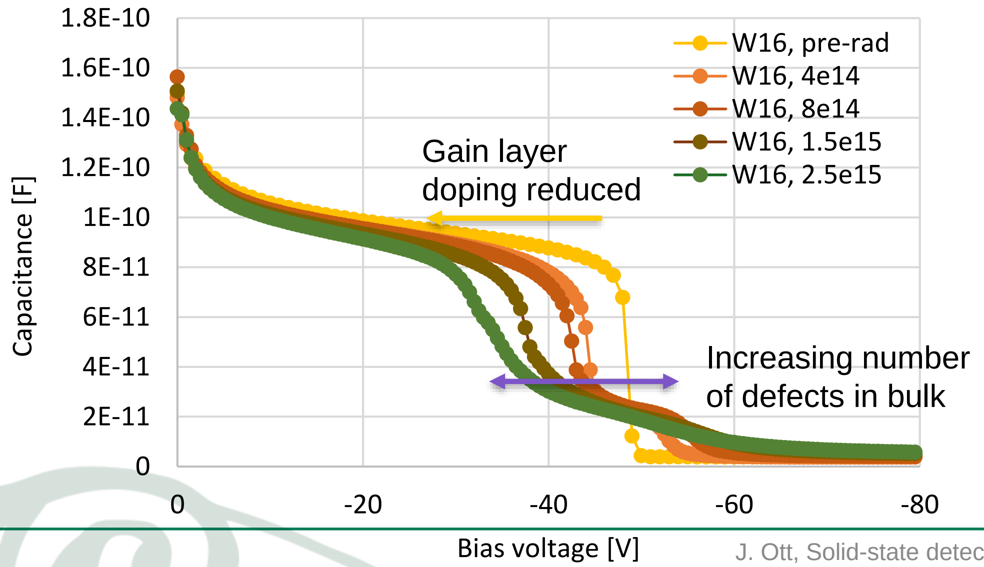


Radiation damage in LGADs

LGADs (regardless of what structural variant) suffer from degradation of the gain due to deactivation of acceptors

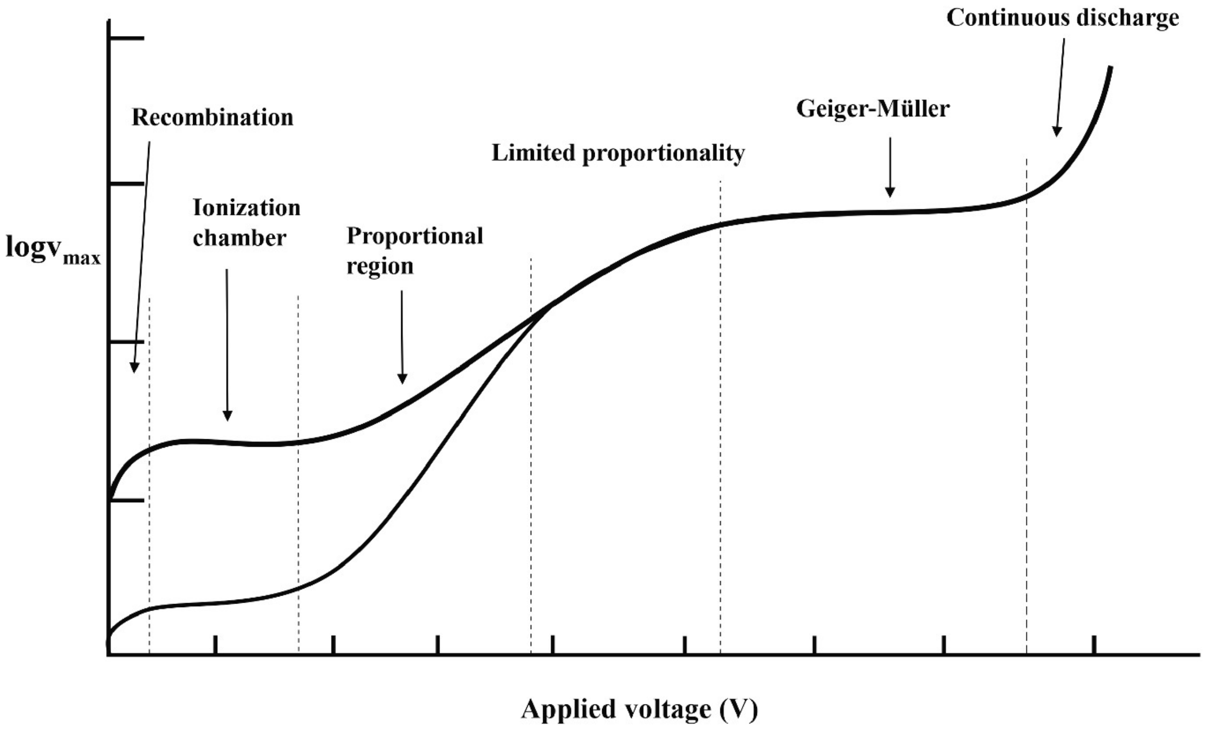
Can be addressed to some extent by gain layer and defect engineering:

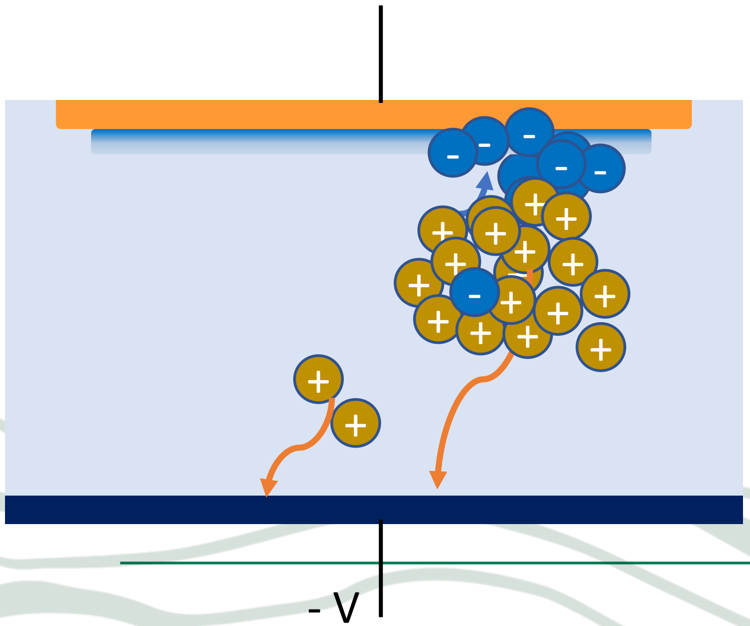
- Different dopant: e.g. Ga instead of B
  - Not successful
- **Carbon co-doping**
  - **Successful at reducing gain layer deactivation**
- Partially activated boron
  - More recent; very mixed results for different vendors



LGAD vs SiPM

- Avalanche breakdown: multiplication of charge carriers as kinetic energy of electrons is sufficiently high
- Breakdown voltage (of the diode): exponential increase in current across p-n junction
- Breakdown voltage (of device): current flow around guard rings or over surface, renders device inoperable





1. Electrons and/or holes drift through the gain layer
2. Charge carriers ionize atoms, form new e-h pairs at the gain layer, ...
3. New charge carriers continue impact ionization
4. **High concentration of charge affects electric field across the device, 'screens' charge carriers from external field**
5. **Multiplication reaches saturation level**

4D Tracking in upcoming experiments

Electron-Ion Collider ePIC Detector

Electron-Ion Collider

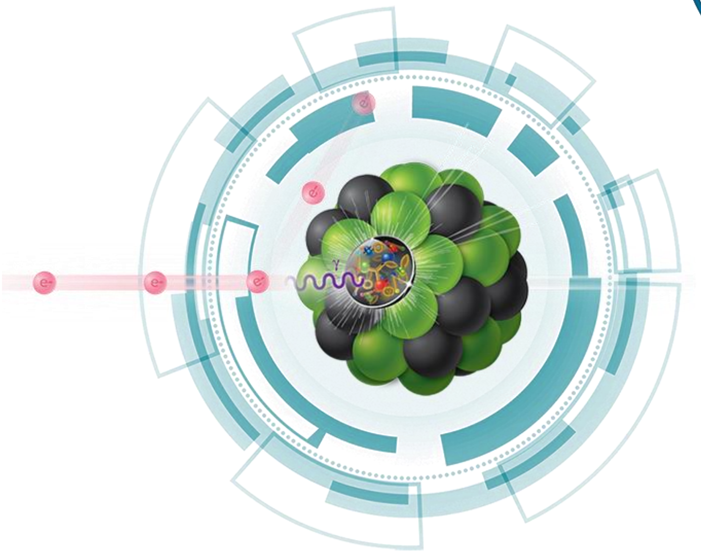
- Nucleon and nuclei structure, mass and spin; QCD at extreme densities; ‘imaging’ of nuclei
- Jointly hosted by Brookhaven and Jefferson National Laboratories
  - ➢ **Detector 1 at the EIC: ePIC**

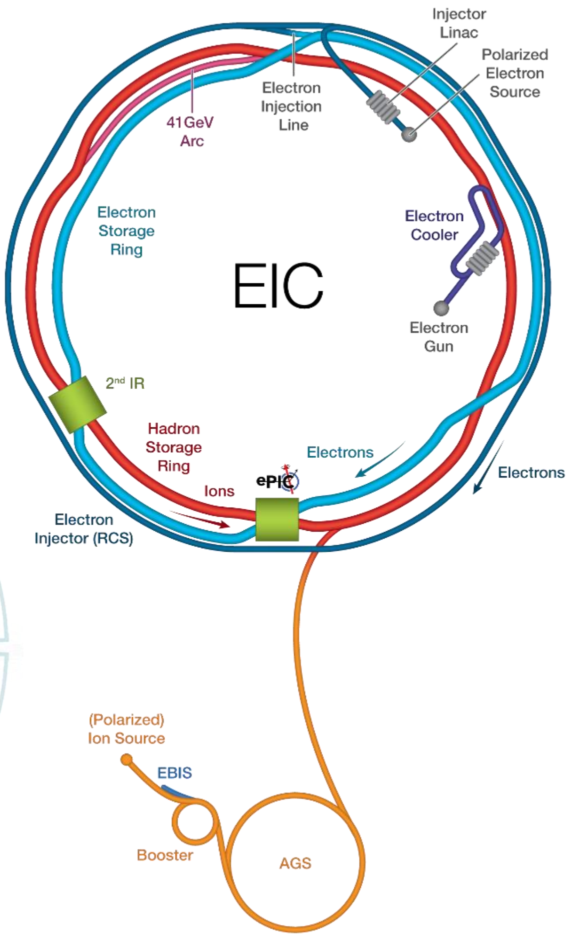
Operations scheduled to begin 2032-2034

Center-of-mass energy: 20 –140 GeV

- electrons: 2.5 –18 GeV
- protons: 40 –275 GeV (ions: Z/A * E_p)

Luminosity: $2x10^{34}$ $cm^{-2}s^{-1}$



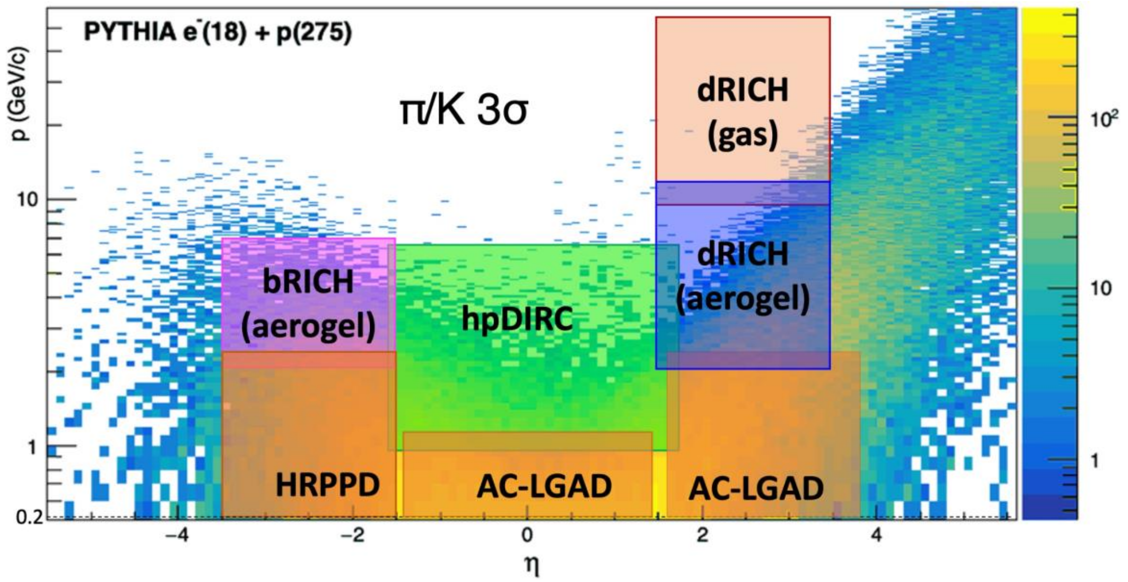


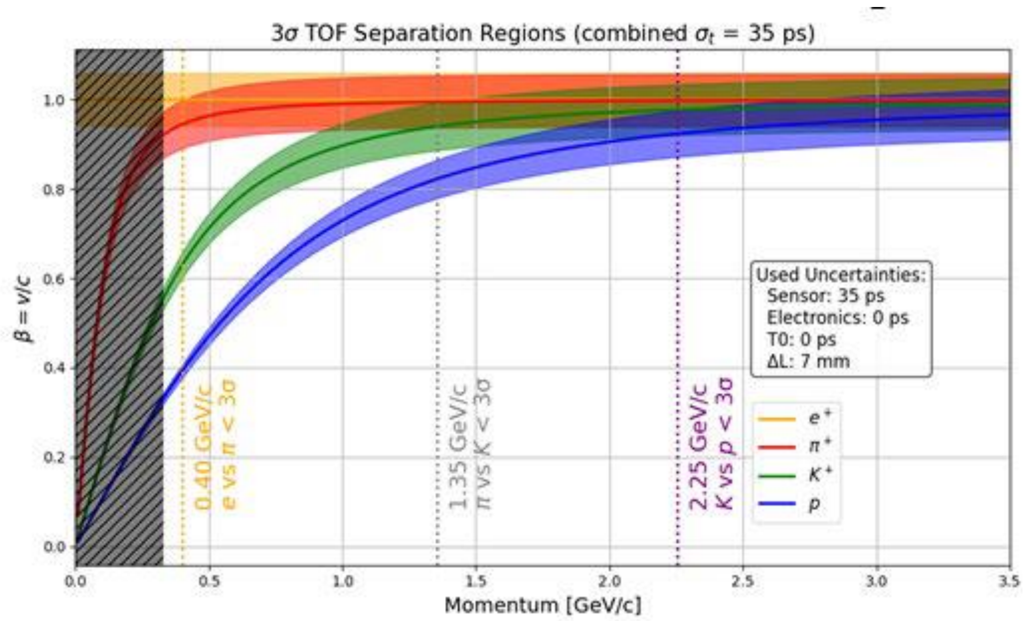
Particle ID

Distinction of different charged particle species becomes more important at lower momenta and for flavour physics

ePIC detector features several Particle ID systems, mostly based on Cherenkov light detection

- **Time-of-flight particle ID layer: silicon AC-LGADs**
- **T0 timestamp?**





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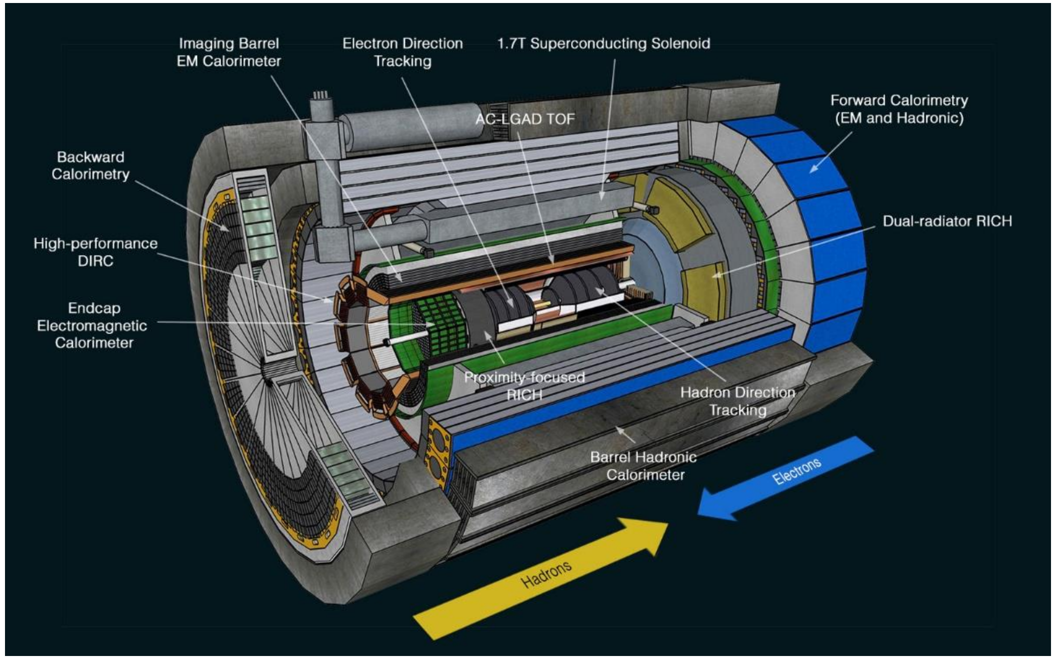
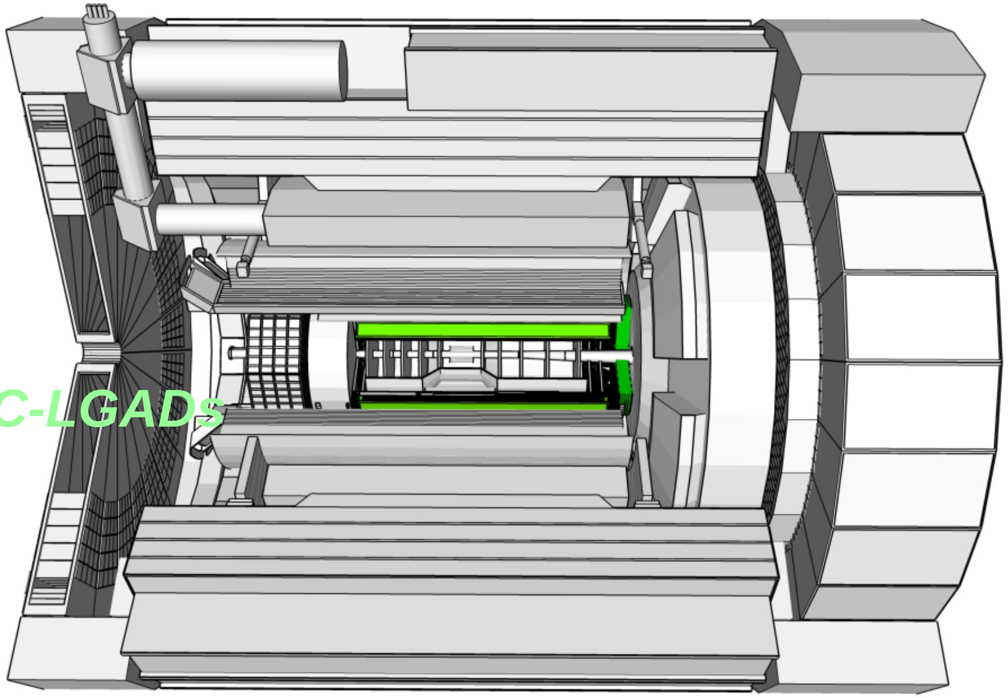




TOF-PID in ePIC

Several detectors for particle ID in inner or outer barrel layers, hadronic endcap, electron endcap

- Momentum and rapidity range cannot be covered by a single technology
- Leveraging variants of Cherenkov detectors
- AC-LGADs replaced by picosecond photodetectors in electron (backward) endcap
- Excellent performance in distinction of charged particle species at low momenta < 3 GeV

Radiation hardness of timing detectors not very challenging - more important:

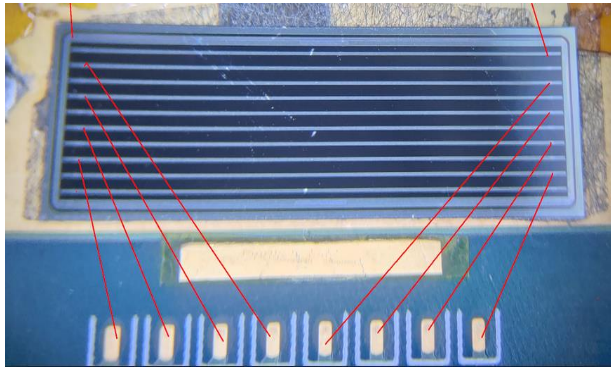
- **Combination of precise temporal and spatial resolution: 25 ps and 30 µm / hit**
- Low material budget

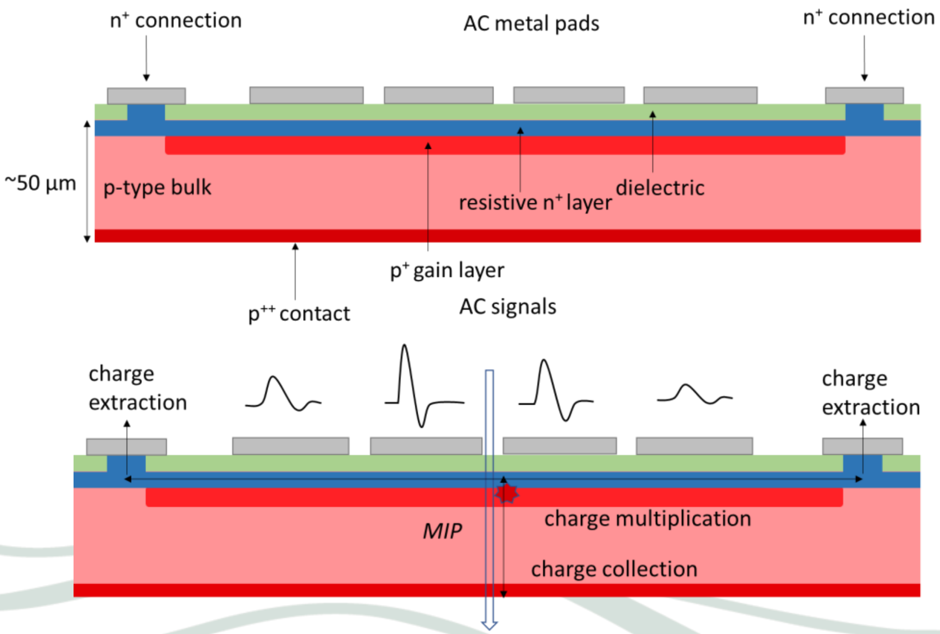
Current sensor design baseline:

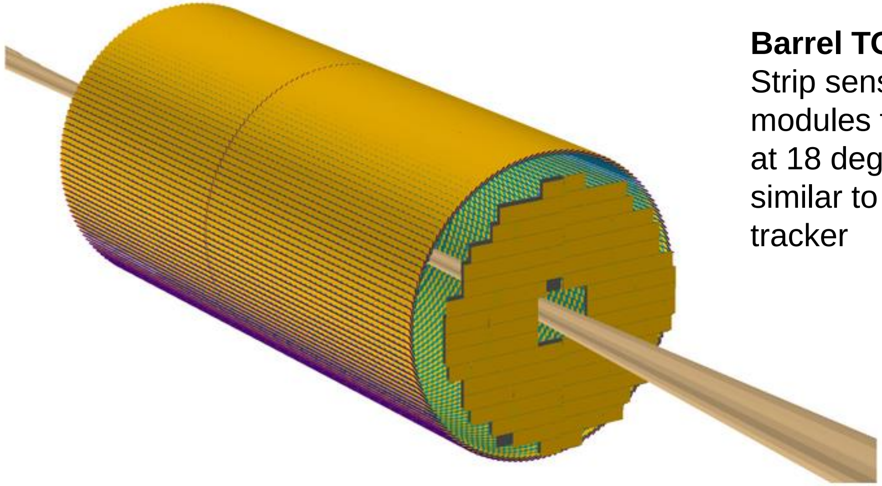
- Barrel: **strips, 500 µm pitch and 1 cm length**
- Hadronic endcap (and Roman Pots): **pads, 500 x 500 µm**

AC-LGADs

- Higher fill factor than standard LGADs
- Charge sharing over resistive n^+ layer

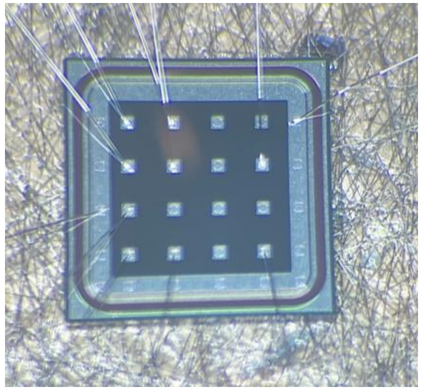






Barrel TOF
Strip sensor modules tilted at 18 deg, similar to STAR tracker

Forward TOF
Similar to CMS ETL



PIONEER experiment

PIONEER Experiment

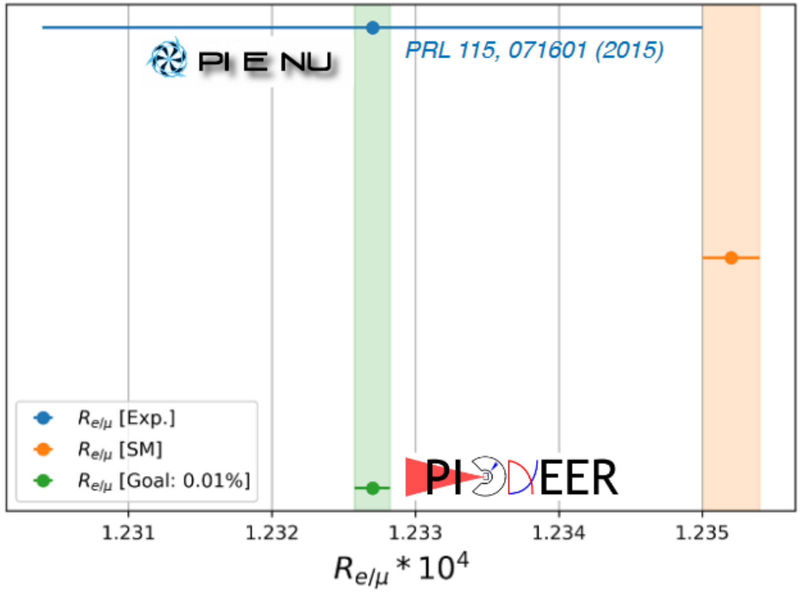
New pion decay experiment approved at PSI, data taking to be started in 2028

Phase 1

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+ \nu(\gamma))}{\Gamma(\pi^+ \to \mu^+ \nu(\gamma))}$$

Lepton flavor universality → charged lepton flavor universality violation?
SM prediction ca. 15x more precise than experiment!

Heavy neutrinos; light New Physics



Phase 2

$$\pi^+ \to \pi^0 e^+ \nu(\gamma)$$

CKM unitarity
$|V_{ud}|$

https://arxiv.org/abs/2203.01981

4D (5D) tracking: PIONEER experiment

Precision measurement of lepton flavour universality through the charged pion decay branching ratio:

$$R_{e/\mu} = \frac{\Gamma(\pi\rightarrow e\nu(\gamma))}{\Gamma(\pi\rightarrow \mu\nu(\gamma))}$$

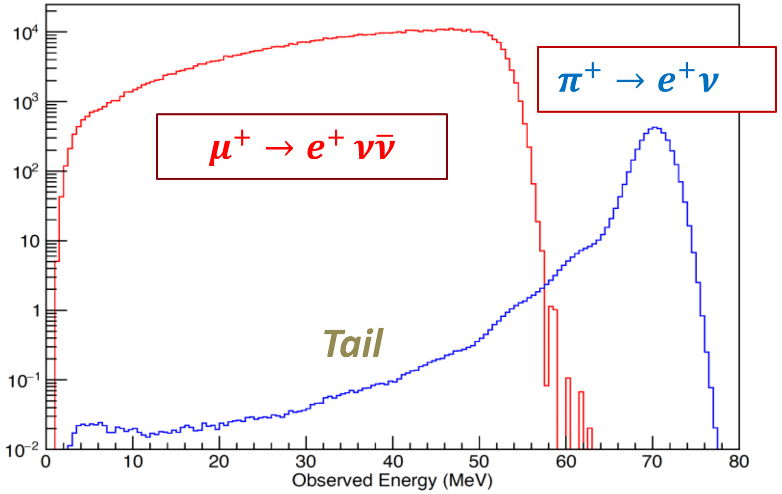
$\pi^+ \rightarrow e^+\nu(\gamma)$ $\mathbf{1.23 \times 10^{-4}}$

$E_e = 69.8$ MeV

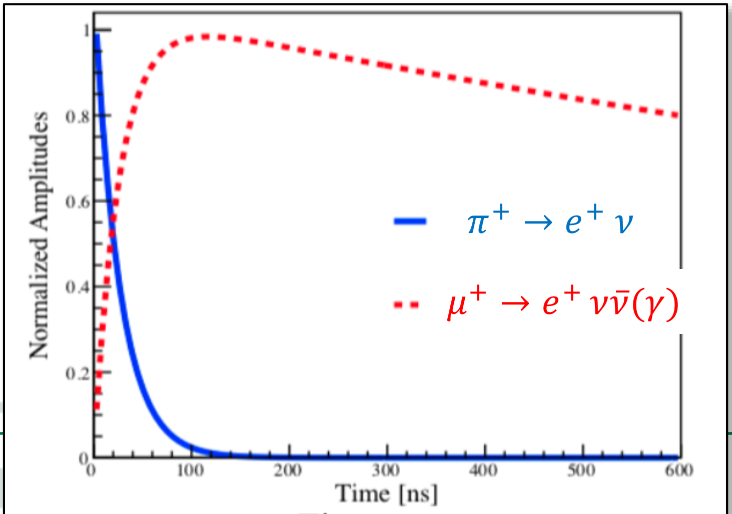
$\pi^+ \rightarrow \mu^+ \nu(\gamma)$ $\mathbf{99.99\%}$

$\mu^+ \rightarrow e^+ \nu\bar{\nu}(\gamma)$ $\mathbf{100\ \%}$

$E_e = 0.5\text{-}52.8$ MeV

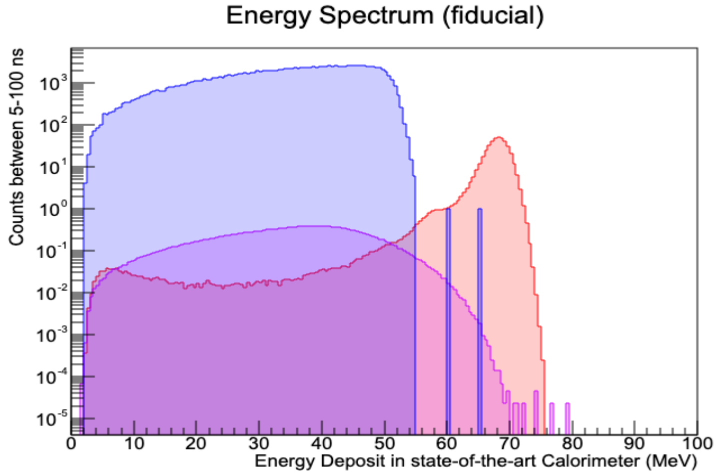


e⁺ energy deposition in calorimeter



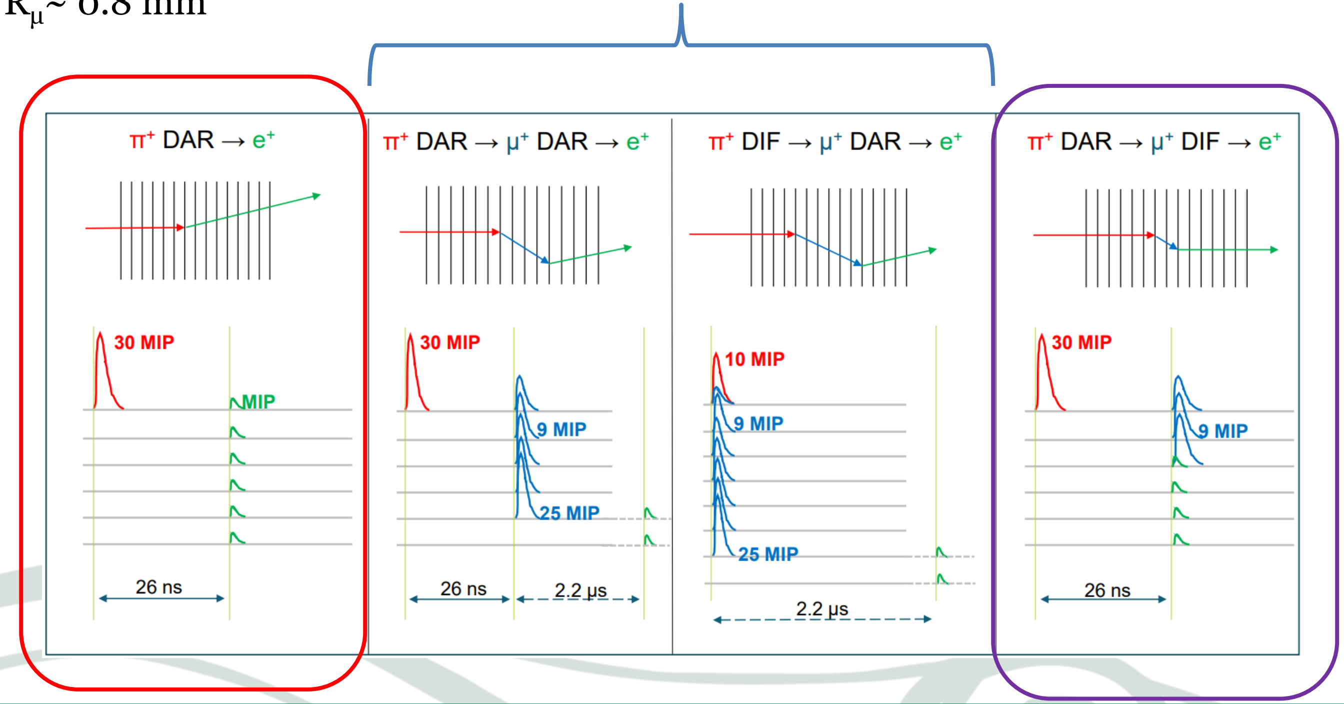
Time spectrum

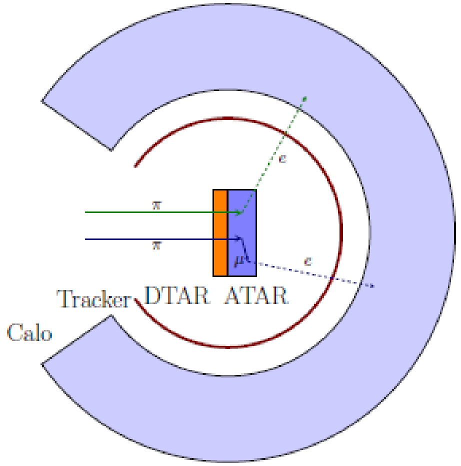
PIONEER: separating muons and positrons



It will be crucial to separate the low-energy tail of $\pi \to e$ events from $\pi \to \mu \to e$ decays in-flight and at-rest

$R_\pi \sim 4$ mm, $R_\mu \sim 0.8$ mm





The Active Target detector

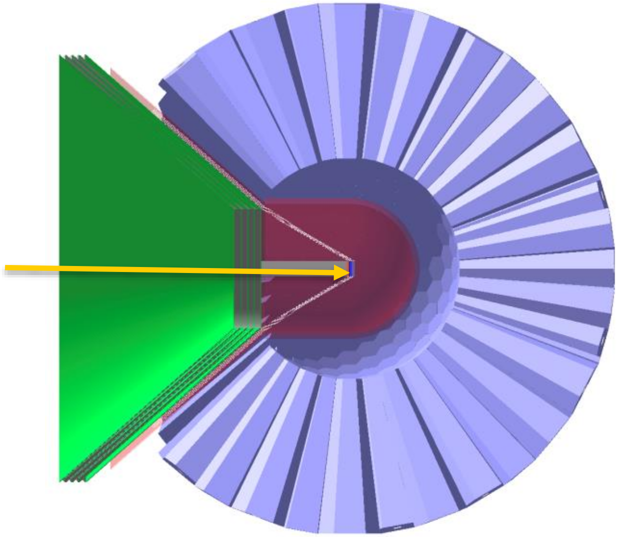
5-D tracker can provide rich information (x, y, z, t, E)

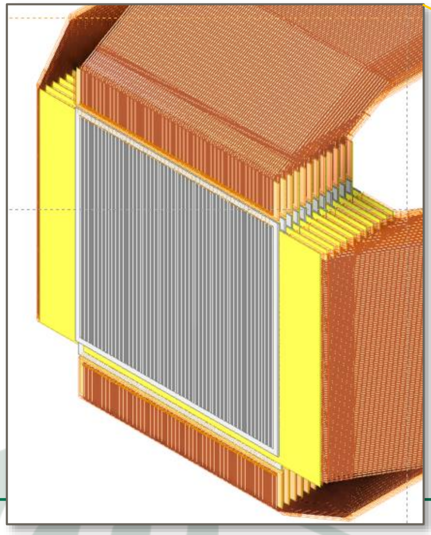
Baseline Technology: low-gain avalanche diodes

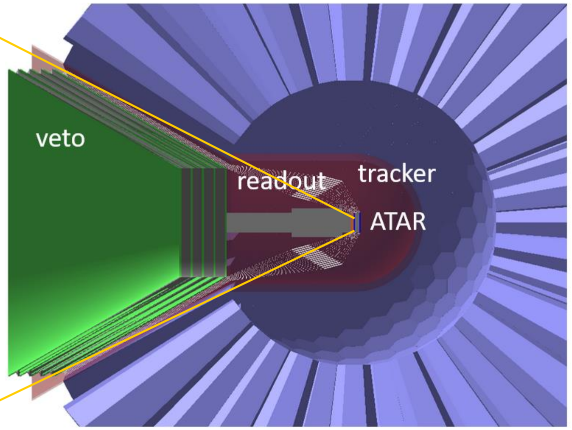
- *No-gain option has been / is being explored: requires very low-noise front-end*
- AC-LGADs
- TI-LGADs

Dimensions:

- 20 x 20 x 5.76 mm
- 48 sensor layers
- **120 µm thickness**, 200 µm strips







t: Δt ~ 200 ps, pulse pair 2 ns

E: ~ 100 dynamic range, $\sigma_E < 10\ \%$

stack: fully active, “no: dead material

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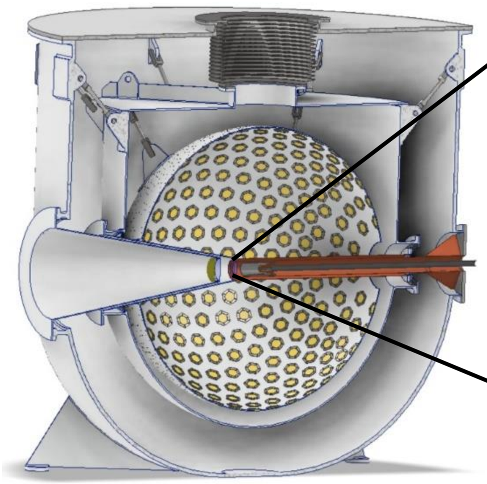

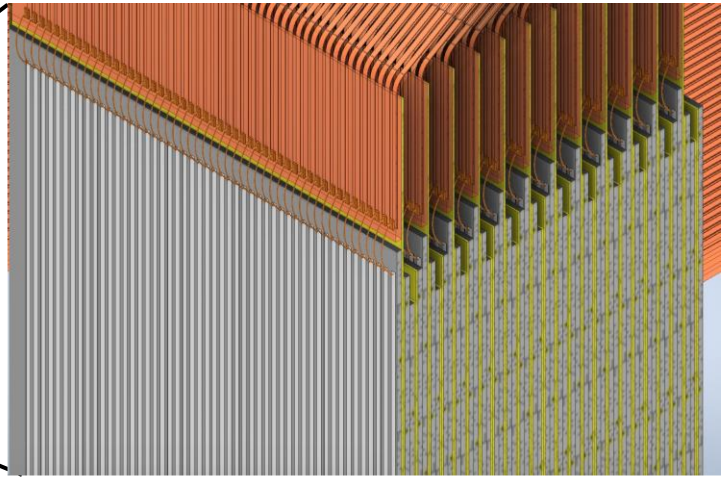

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Silicon detectors for future colliders

Key developments in silicon sensors for the (HL-)LHC

- **Radiation hardness**
  - P-type sensors – using electron drift to pixels
- **Sensor design**
  - Smaller pitch, e.g. pixels: 50x50 or 25x100 µm

- **Fast timing: LGADs in HL-LHC upgrades**

- **3D sensors incorporated in pixel detector upgrades inner layers – also strong potential for timing**

Silicon detectors in future particle physics experiments

Efficient tracking (in 4D)

Precise timing resolution
- Silicon sensors with gain
- 3D detectors

Improved spatial resolution
- Small pixels
- Charge sharing
- 3D detectors

Operation at extreme fluences
- Radiation tolerance of material
- Sensor design (incl. thickness)

Efficient manufacturing and operation
- Low mass
- Large area, low cost, low power consumption
- Address challenging interconnection technology

Extreme conditions in future colliders

HL-LHC

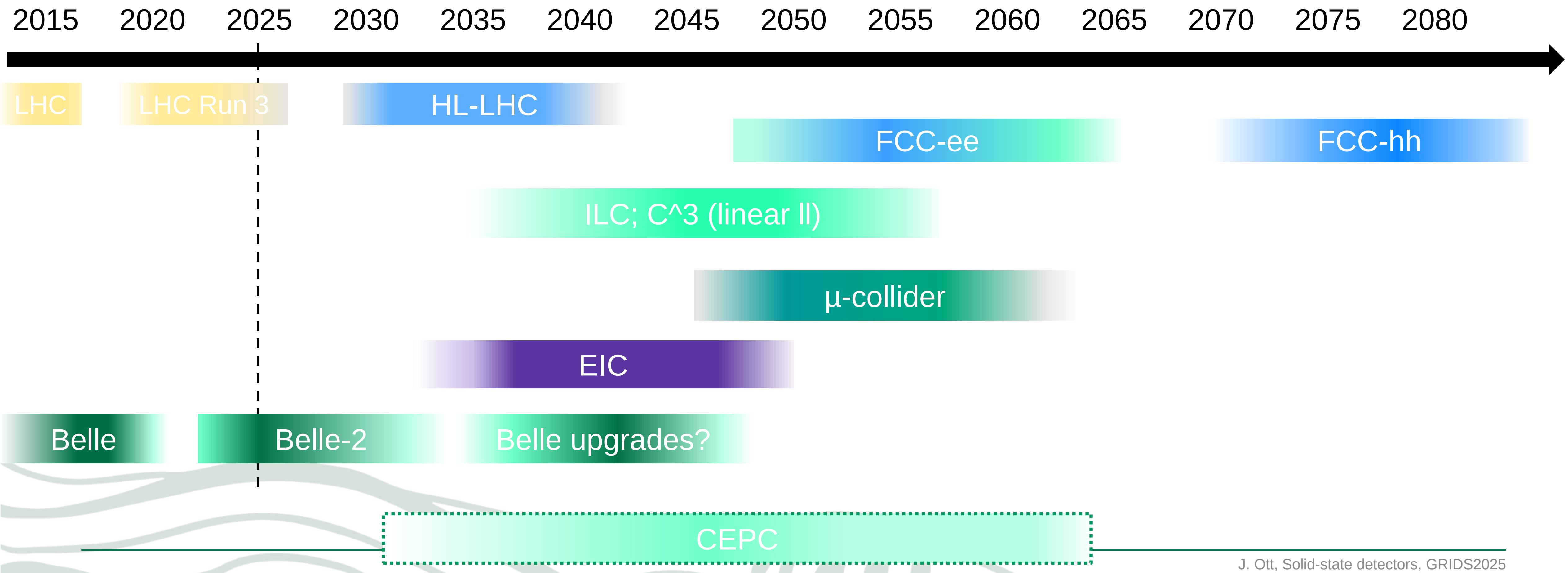
- Max. fluence on silicon detectors ~$3x10^{16}$ n_{eq}/cm^2
- Pileup ~200, for mitigation: timing resolution < 50 ps

Future colliders

- Fluence on inner layers up to $7x10^{17}$ n_{eq}/cm^2 (FCC-hh)
- Similar pileup conditions to HL-LHC

- Desired resolution: 1-3 µm (lepton colliders)
- Material budget: down to 1% X_0

Landscape of colliders



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

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

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

- Further: muon collider, FCC-hh

- ➢ **All near-future colliders are lepton or lepton-hadron colliders, at the Intensity Frontier**
  - ➢ No q-q, g-g interactions in the collisions, no QCD background – ‘clean’ collisions

- ➢ **Near-term trends for silicon tracking and timing detectors are turning to some extent!**

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

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

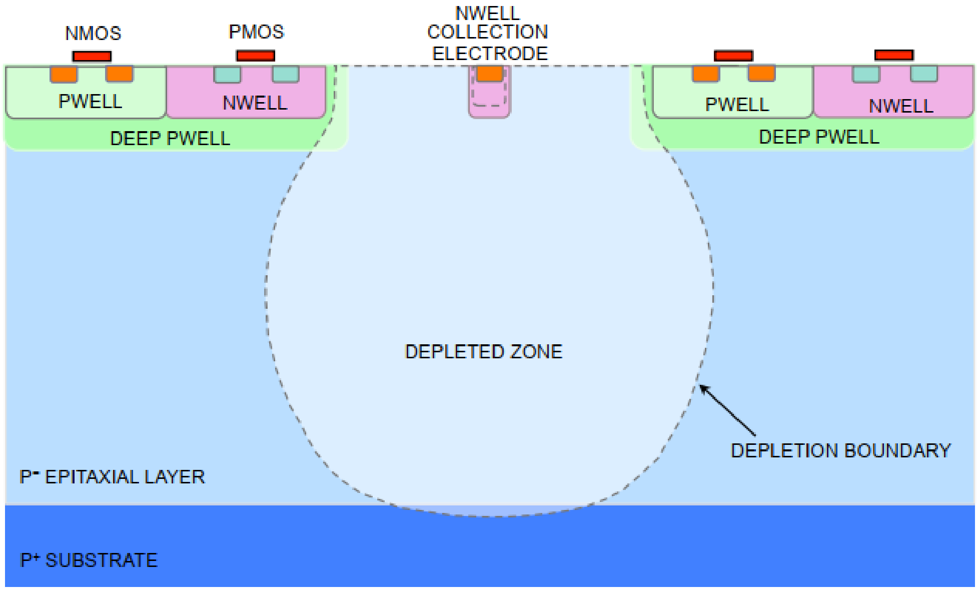
- **Radiation levels significantly lower**
- **Fewer vertices and tracks, little to no pileup – timing less essential**
- **Tracking resolution needs to improve: reduce material budget to minimize scattering**
- **Large area and low cost, low power consumption increasingly important**

Monolithic CMOS detectors

Active CMOS / MAPS

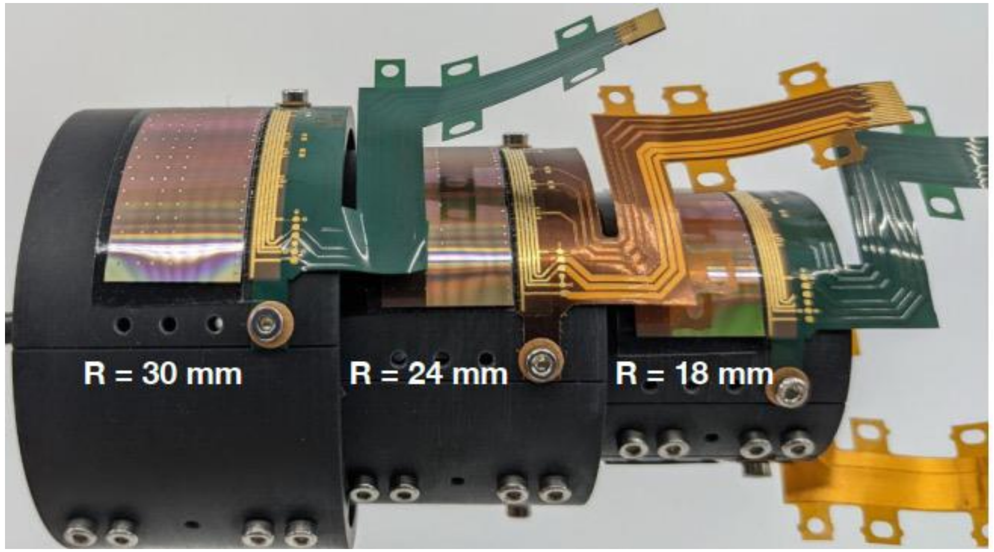
- Small pixels, better spatial resolution, do not require elaborate interconnection
- Commercial large vendor processes
- **<u>Showstopper for p-p colliders so far: radiation levels</u>**

➢ ***Eventually MAPS with gain layer?***



“Massless” detectors

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



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

Fast timing

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

3D integration
Integration into CMOS process

Not only in silicon trackers!

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

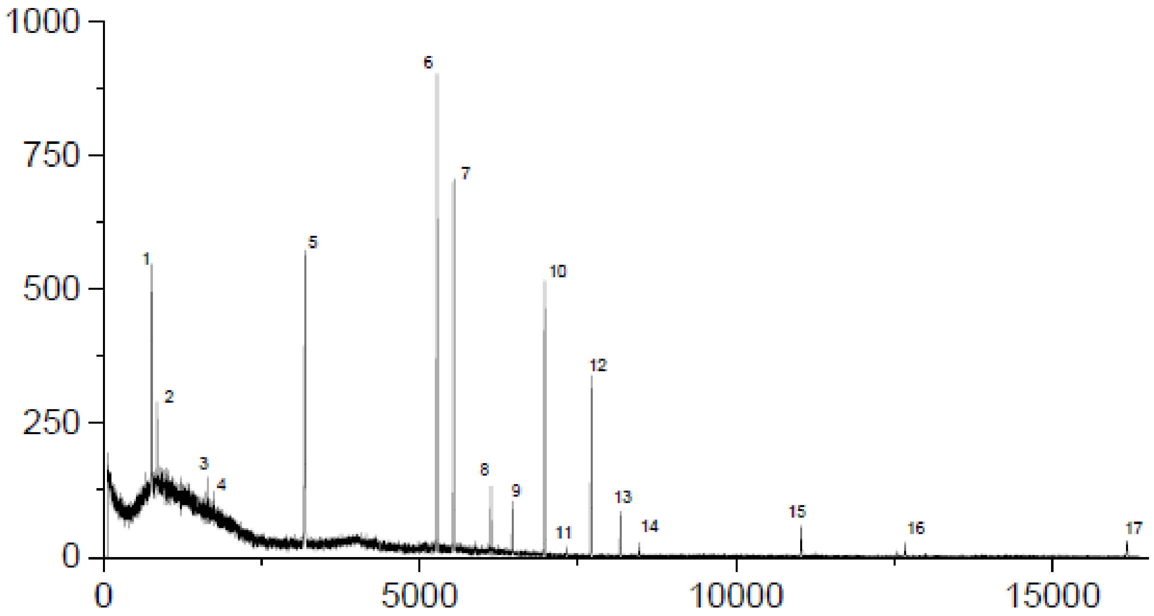
➢ **Detectors with gain: not only high-energy physics: nuclear physics, photon science, medical imaging (e.g. positronium decay PET)**

Other materials and applications

Other semiconductor materials

Germanium

- Band gap 0.67 eV
- Higher noise, is operated at cryogenic temperatures (liquid N2)
- High-purity Ge (HPGe) single crystals can be fabricated
- High efficiency and excellent energy resolution



Prior to calibration: ADC channel

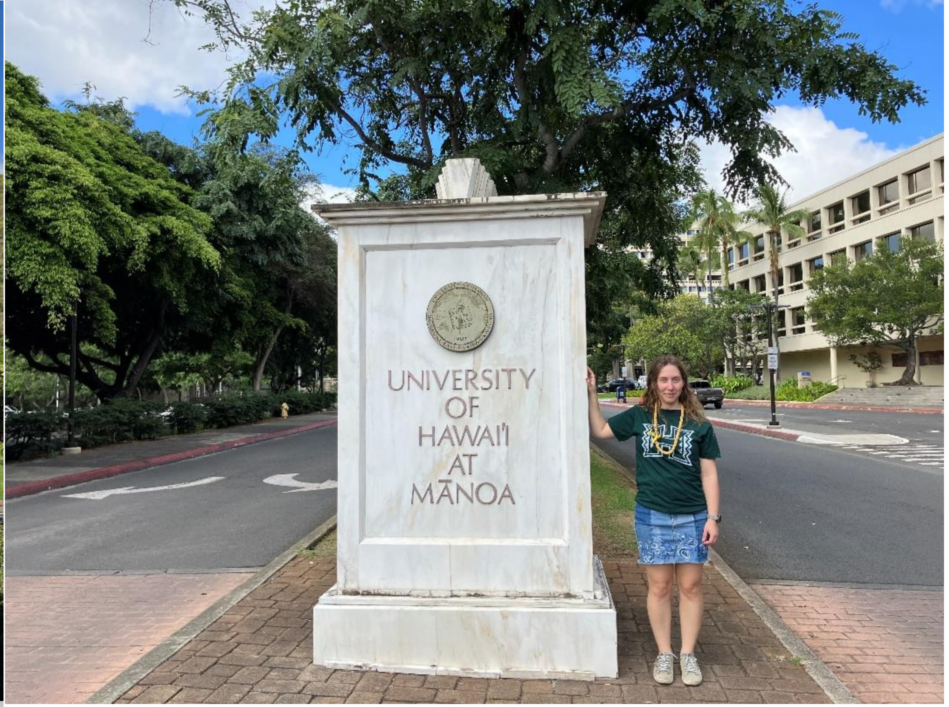
Other semiconductor materials

SiC

- Multiple crystal structures, ‘3C’, ‘4H’, ‘6H’
- Band gap 2.35-3.05 eV
- High melting point
- Higher breakdown field compared to Si
- Operation in high currents and temperatures possible

CdTe

- II-VI compound semiconductor
- Band gap 1.5 eV
- Popular variations (alloys) with Hg, Zn
- Significantly heavier than Si, C, Ge – high absorption efficiency



Graduate student positions and undergraduate research opportunities available!

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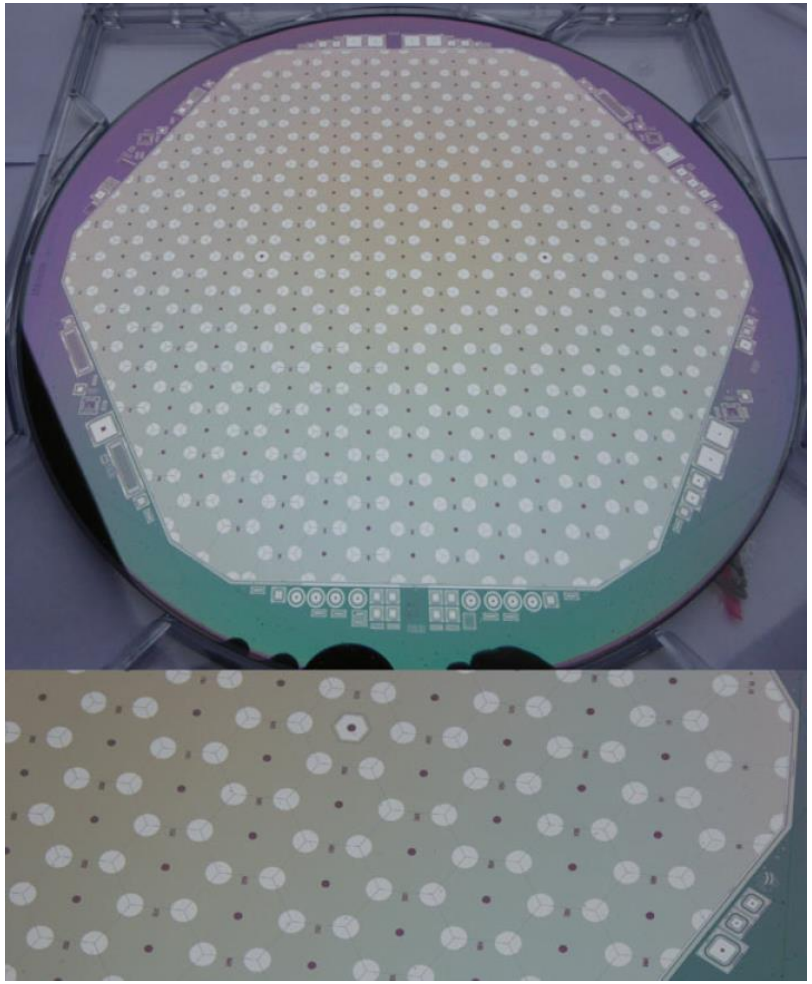
Backup

Silicon sensors in calorimetry: pad sensors in HGCAL

= High-granularity calorimeter

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

Larger area of silicon than tracking detectors!



Silicon detectors in (partial) calorimetry: Astropix

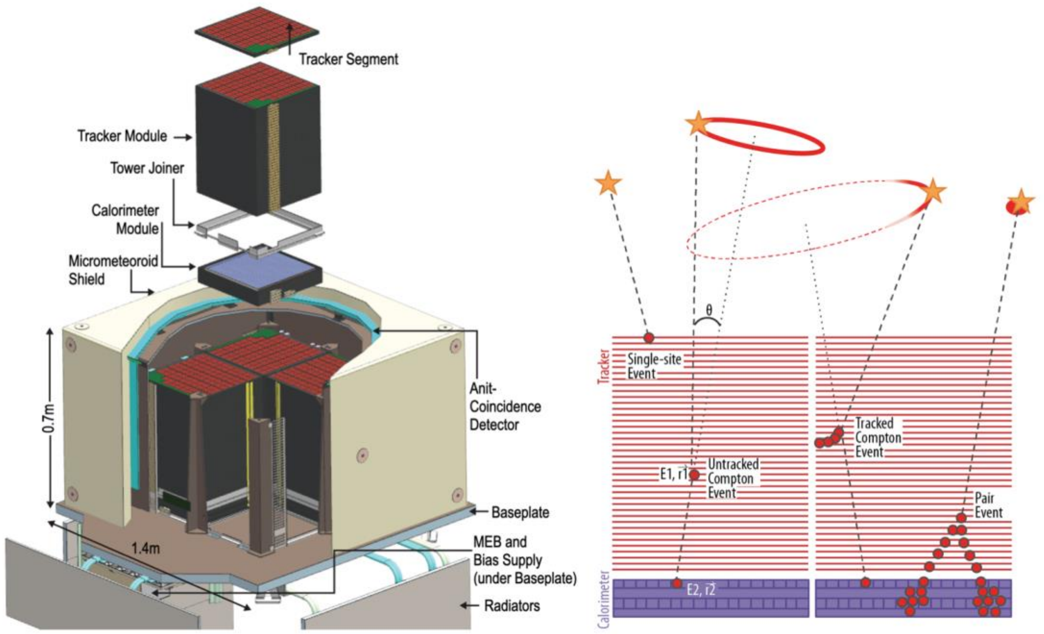
AMEGO-X satellite: Gamma ray telescope with stacks (towers) of segmented silicon detectors

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

Astropix HV-CMOS: also to be used in inner layers of EIC ePIC barrel ECAL

- thicker active sensor – 700 µm bulk
- 500x500 um pixel pitch

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



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