Discovering the Invisible: Pixel Detectors In Particle Physics

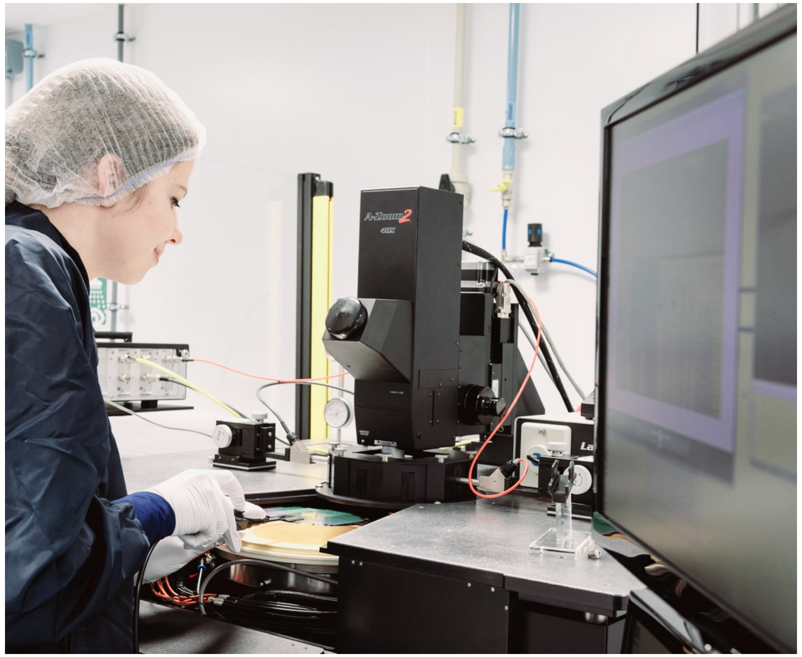
Maria Mironova (LBNL)

Physics in and Through Cosmology workshop

Tuesday, June 27, 2023

About me

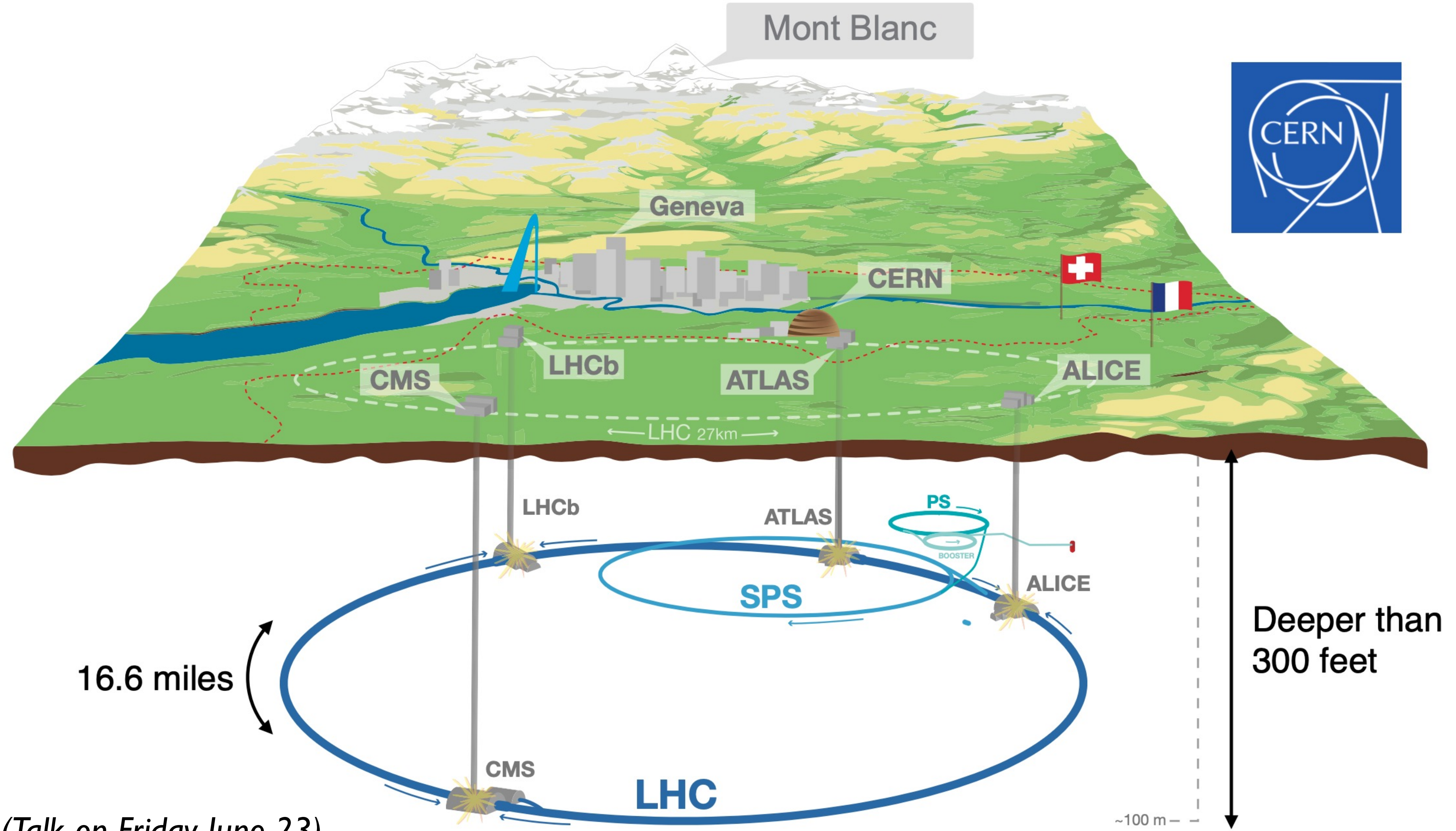
- Moved around Europe for my studies at University (between 2014 and 2022):
  - Bachelor: University of Göttingen (Germany) & University of Cambridge (UK)
  - Masters: Imperial College London (UK)
  - PhD: University of Oxford (UK)
- PhD in particle physics, using data collected by the ATLAS experiment at CERN, and building detectors for ATLAS



About me (now)

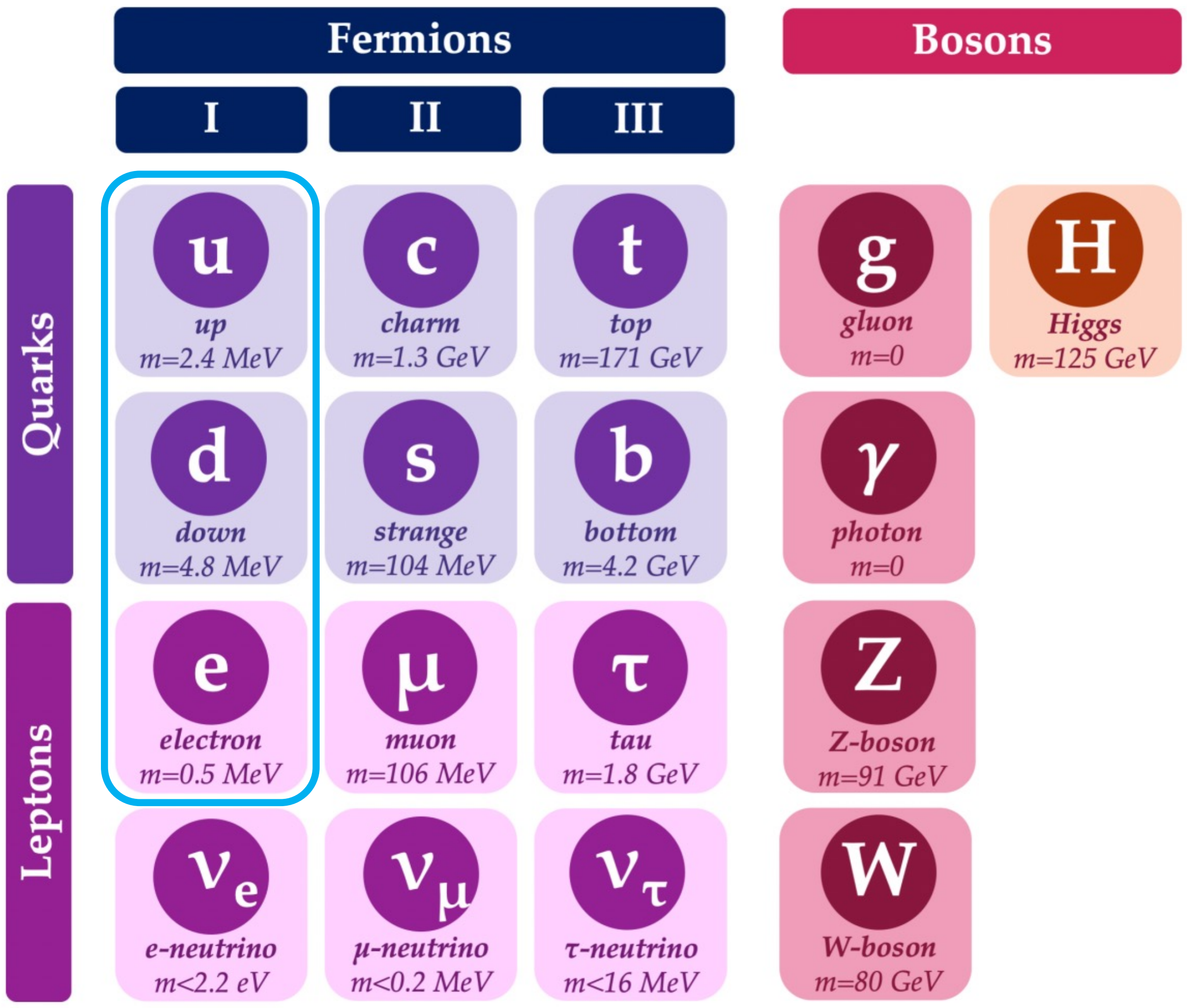
- Now working at Lawrence Berkeley National Laboratory as a Chamberlain Postdoctoral Fellow, since September 2022 (started based at CERN, now in Berkeley since January)
- Part of the ATLAS group in the physics division → working within the ATLAS collaboration, which is a collaboration of ~3000 international scientists, based at CERN
- My main areas of research:
  - Searching for Higgs bosons decaying into charm quarks
  - Construction of pixel detectors for the upgrade of the ATLAS detector

The Large Hadron Collider



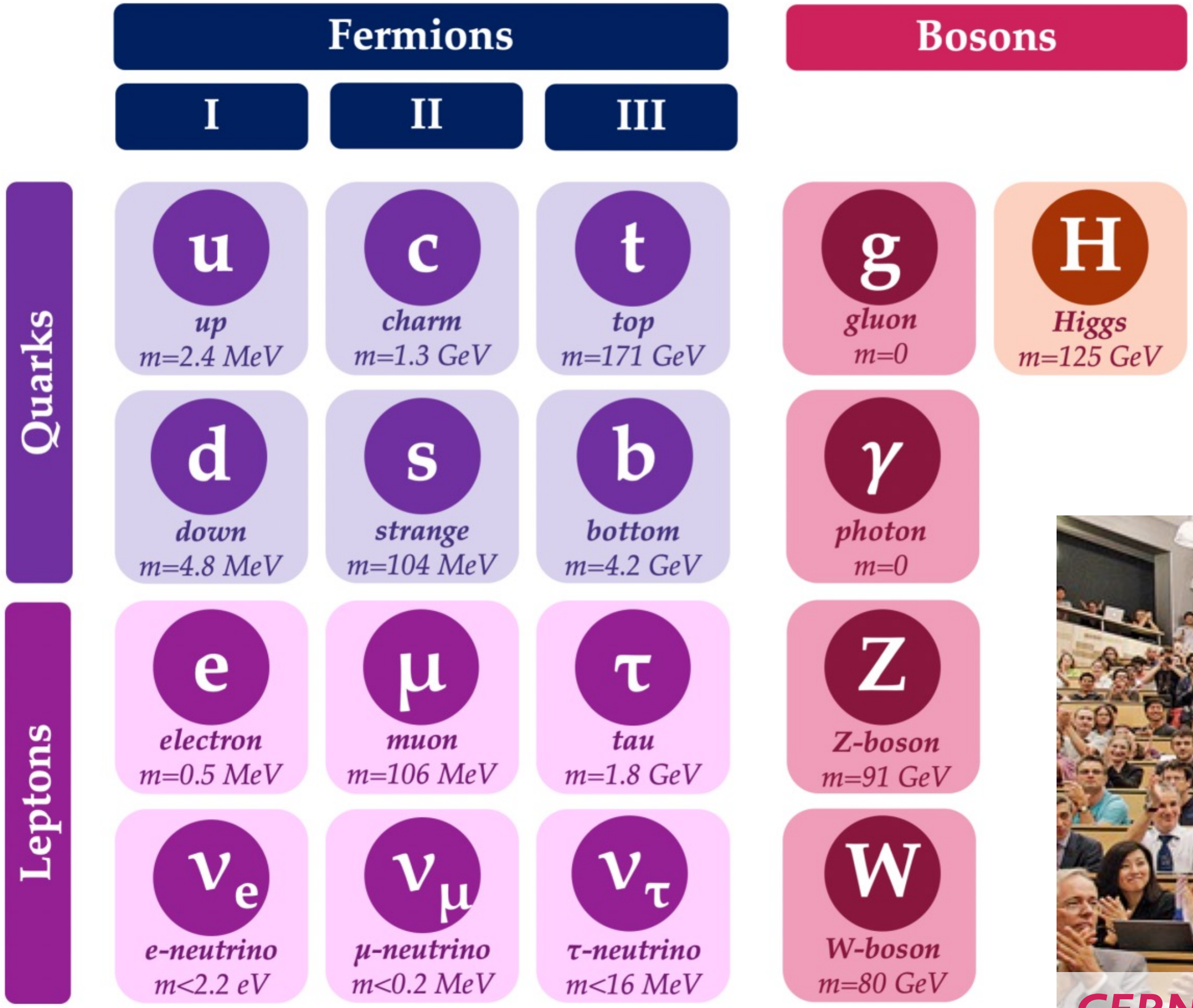
Slide from Miha (Talk on Friday June 23)

Standard Model of Particle Physics



- **Standard Model of Particle Physics** describes all we currently know of fundamental interactions
- All stable matter (atoms) made out of **first generation quarks and electrons**
- Heavier 2nd and 3rd generation quarks and leptons decay into they 1st generation counterparts
- Interactions mediated by **bosons**:
  - Strong interaction (holding together nuclei)→ **gluons**
  - Electromagnetic interaction → **photons**
  - Weak interaction (radioactive decay) → **W and Z bosons**

Higgs Boson



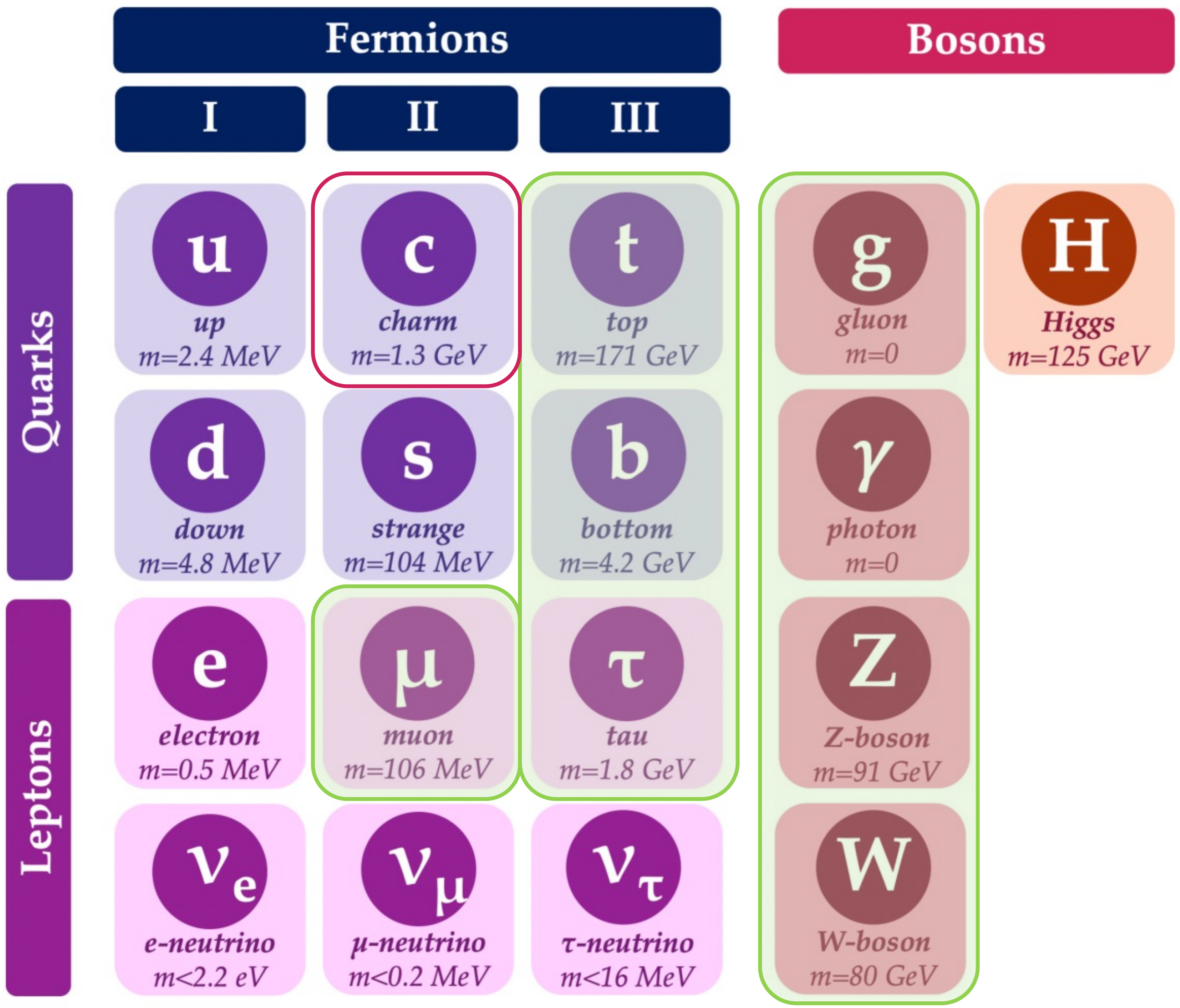
- Last part of the Standard Model: **Higgs boson**
- Higgs mechanism explains how particles in the Standard Model have mass

→ The more often particles interact with the Higgs field the heavier they are

- Higgs boson postulated in 1964 and discovered in 2012

CERN Main Auditorium at the Higgs Boson discovery

Higgs Boson



- In the 10 years since discovery, we have measured many properties of the Higgs boson
- Higgs boson can decay into different Standard Model particles, at predicted rates
- Measured **many decay modes of the Higgs boson**: bosons, heavy fermions

→ Measurements show good agreement with our expectations

- But, many decay modes have not been measured yet!
- For example: **Higgs boson decays to charm quarks**

Open questions

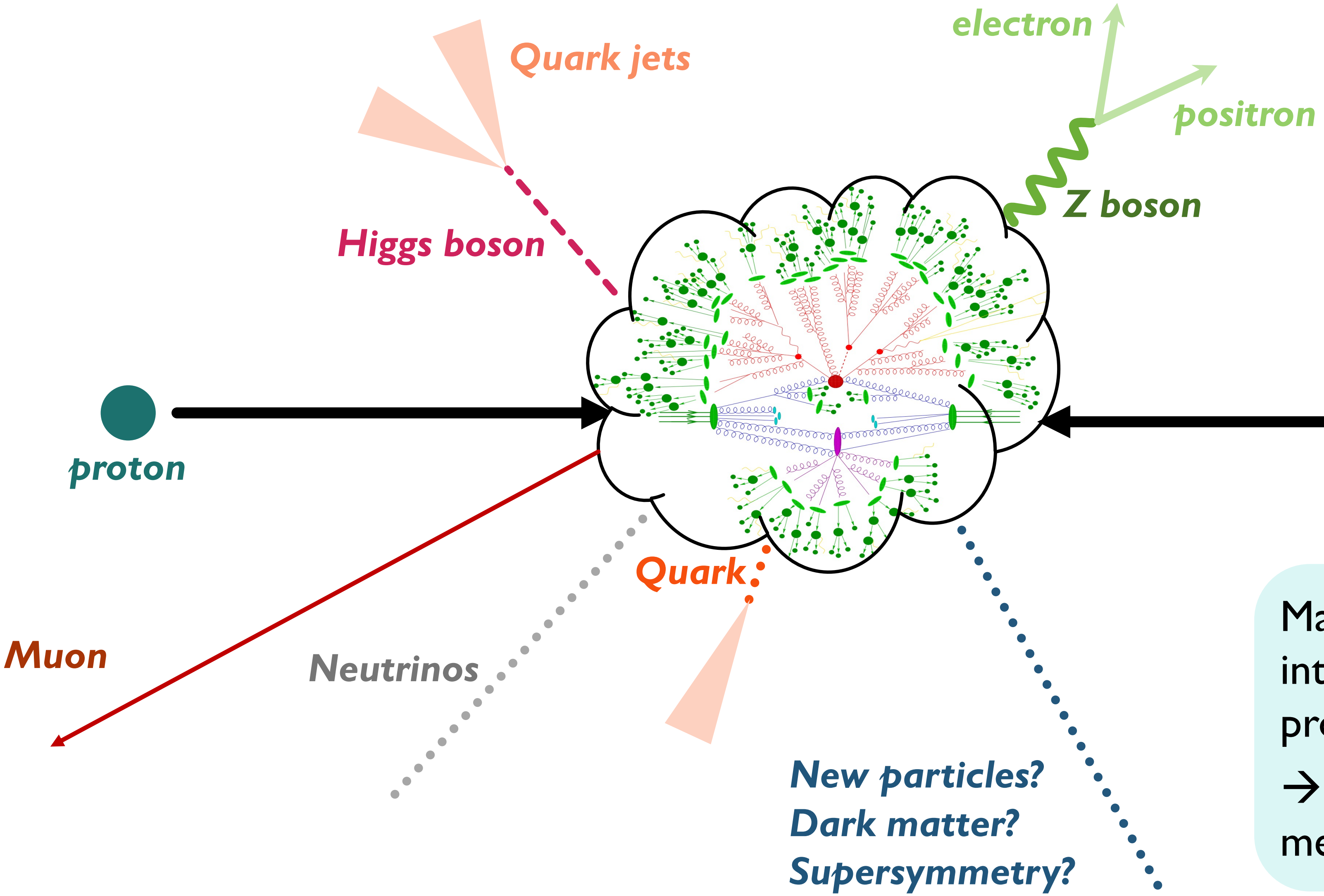
So far, the Standard Model of Particle Physics is an excellent description of what we see in nature

However, many open questions remain:

- Concerning the Higgs boson:
  - Does the Higgs couple to **lighter fermions**?
  - Does the Higgs couple to **itself**?
  - Does the Higgs interact with **invisible particles**? (for example, dark matter)
- General open questions:
  - **Dark Matter:** we know it exits from cosmology, but it is not included in the Standard Model
  - **Neutrino masses:** The origin of neutrino masses is not clear
  - **CP violation (Matter/antimatter asymmetry):** At the Big Bang equal amounts of matter/antimatter were produced, why is there more matter now?
  - **Gravity:** Is currently not included in the Standard Model

→ **We need more measurements, better accelerators and better detectors!**

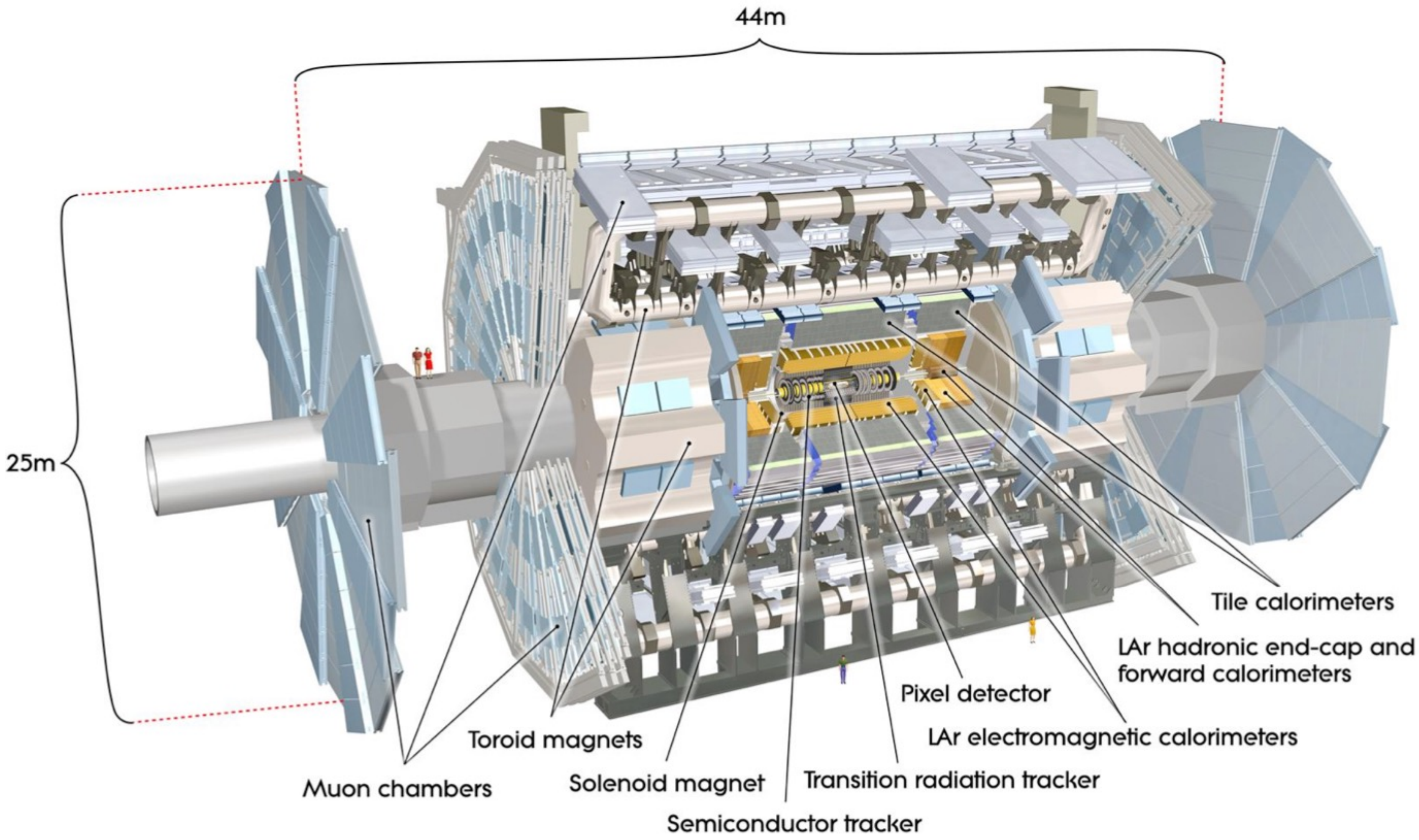
How do we make measurements?



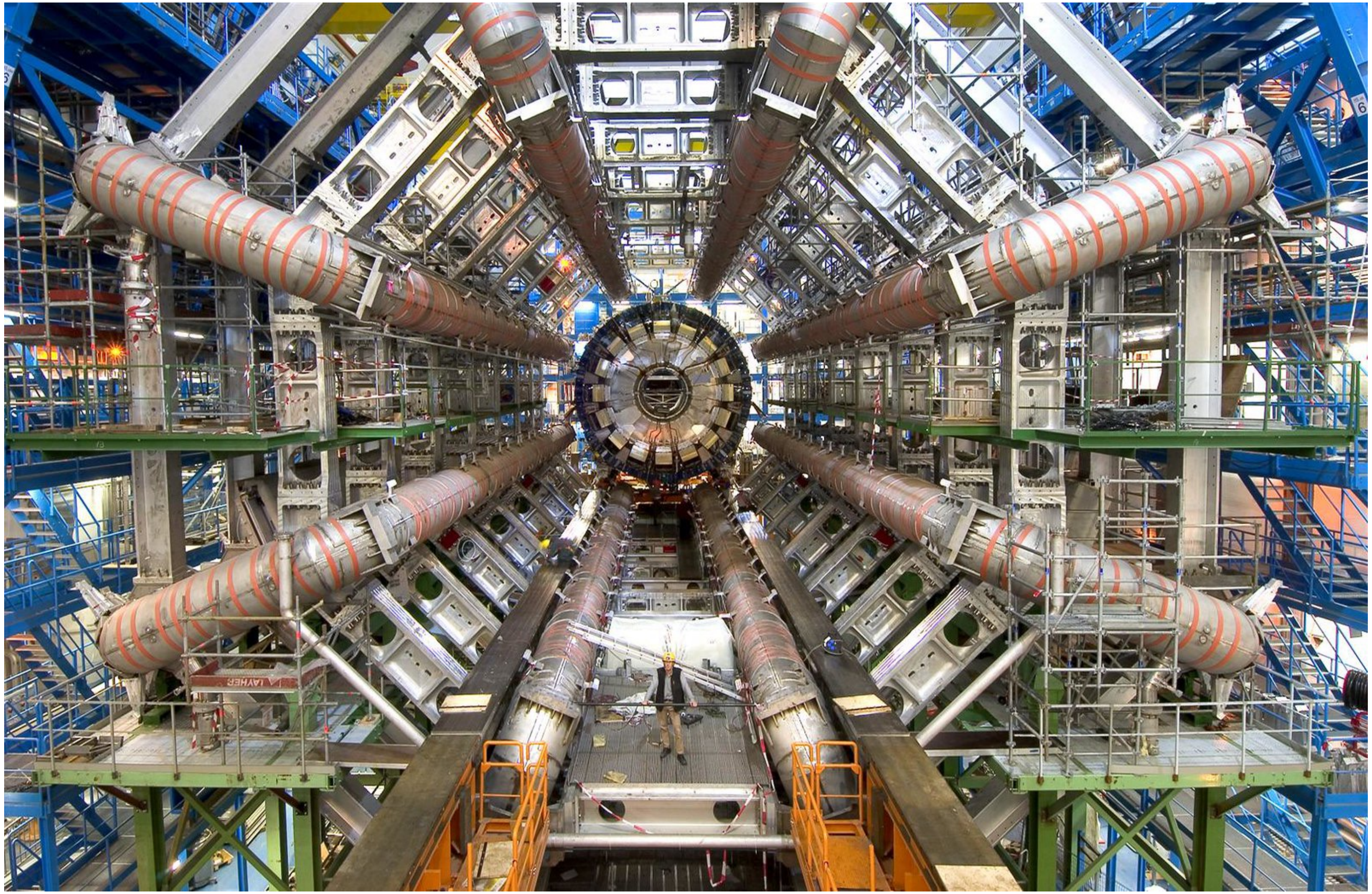
Many complicated interactions happen in proton-proton collision

→ Need a **detector** to measure the products

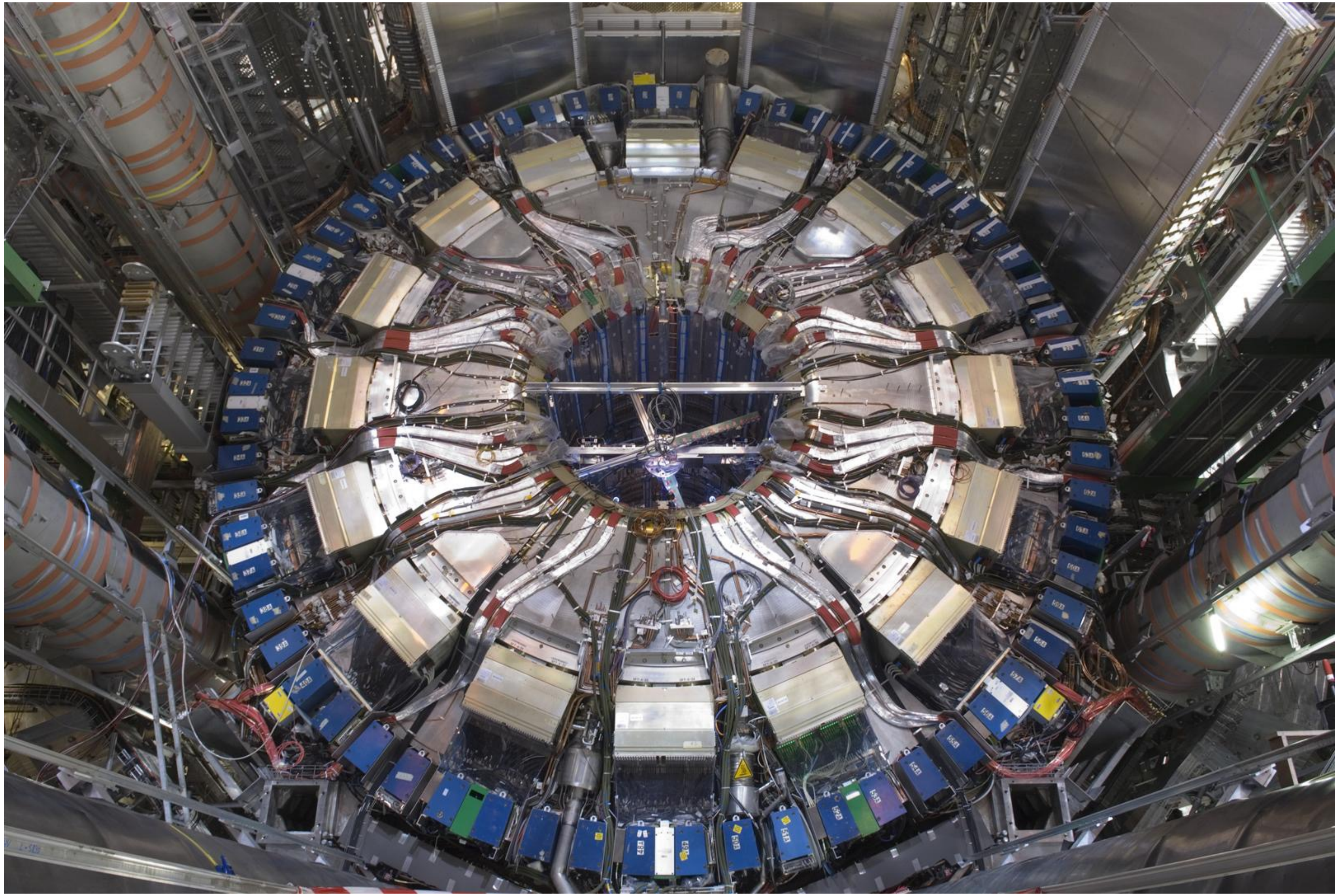
The ATLAS detector



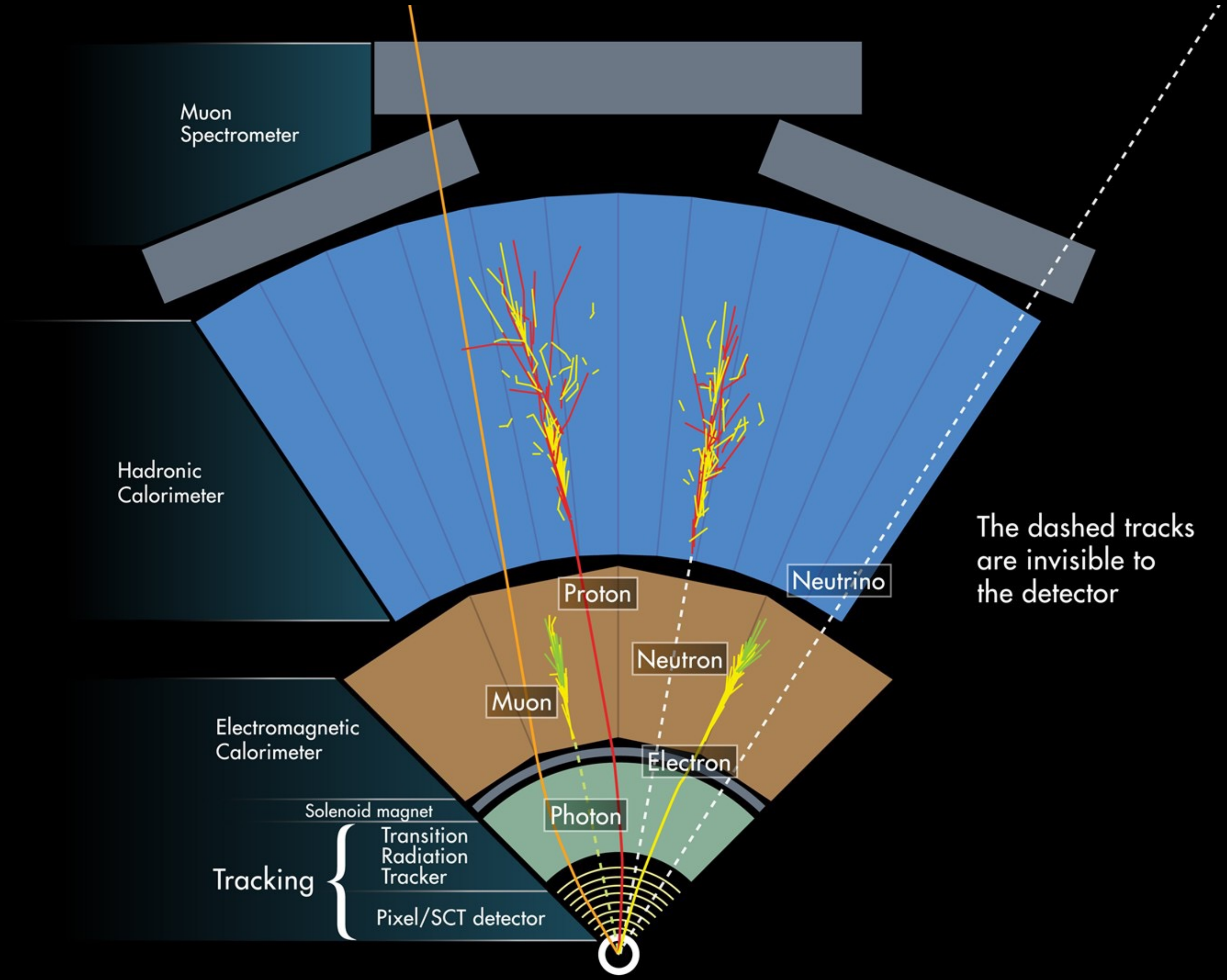
The ATLAS detector



The ATLAS detector

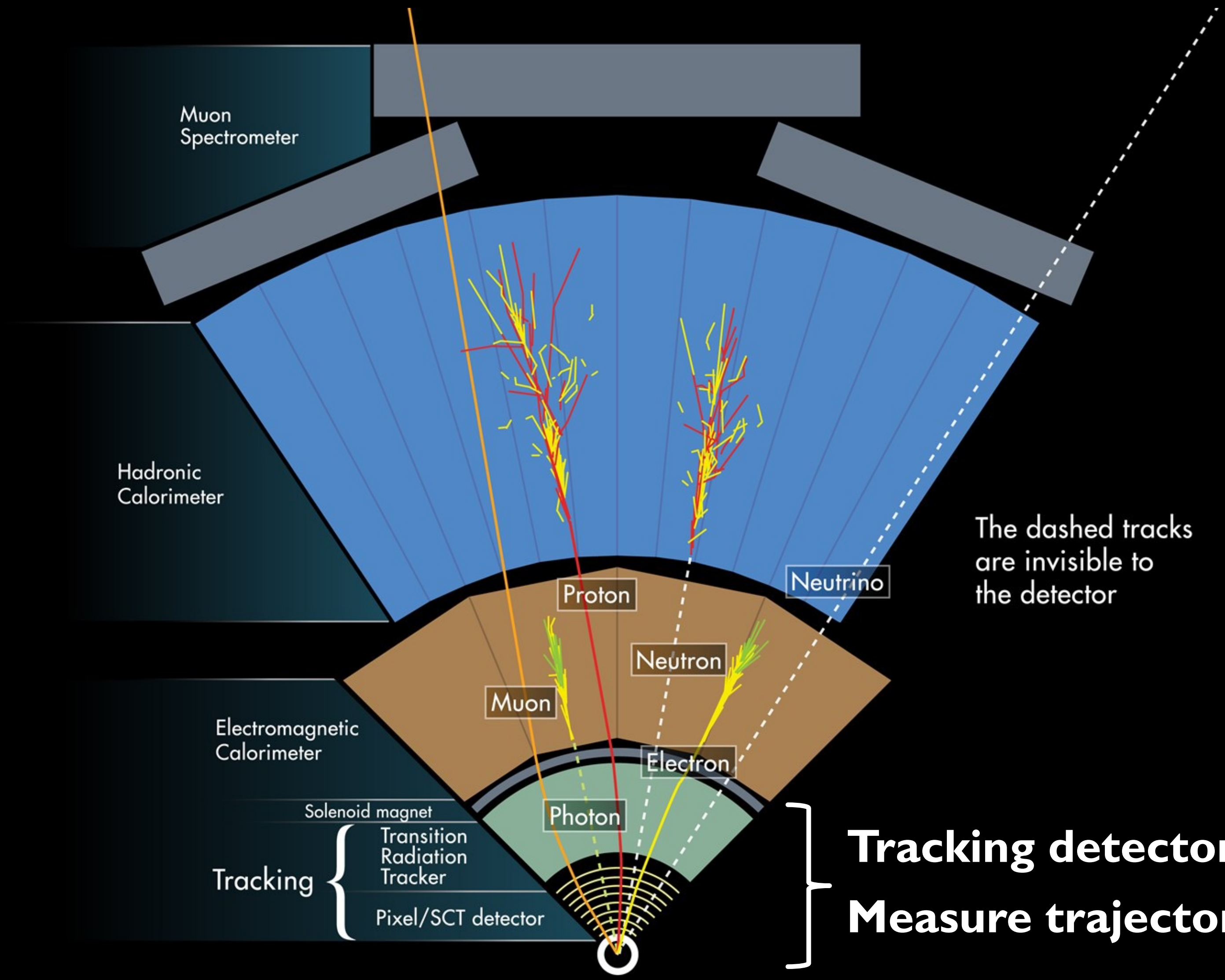


Particle identification



The dashed tracks are invisible to the detector

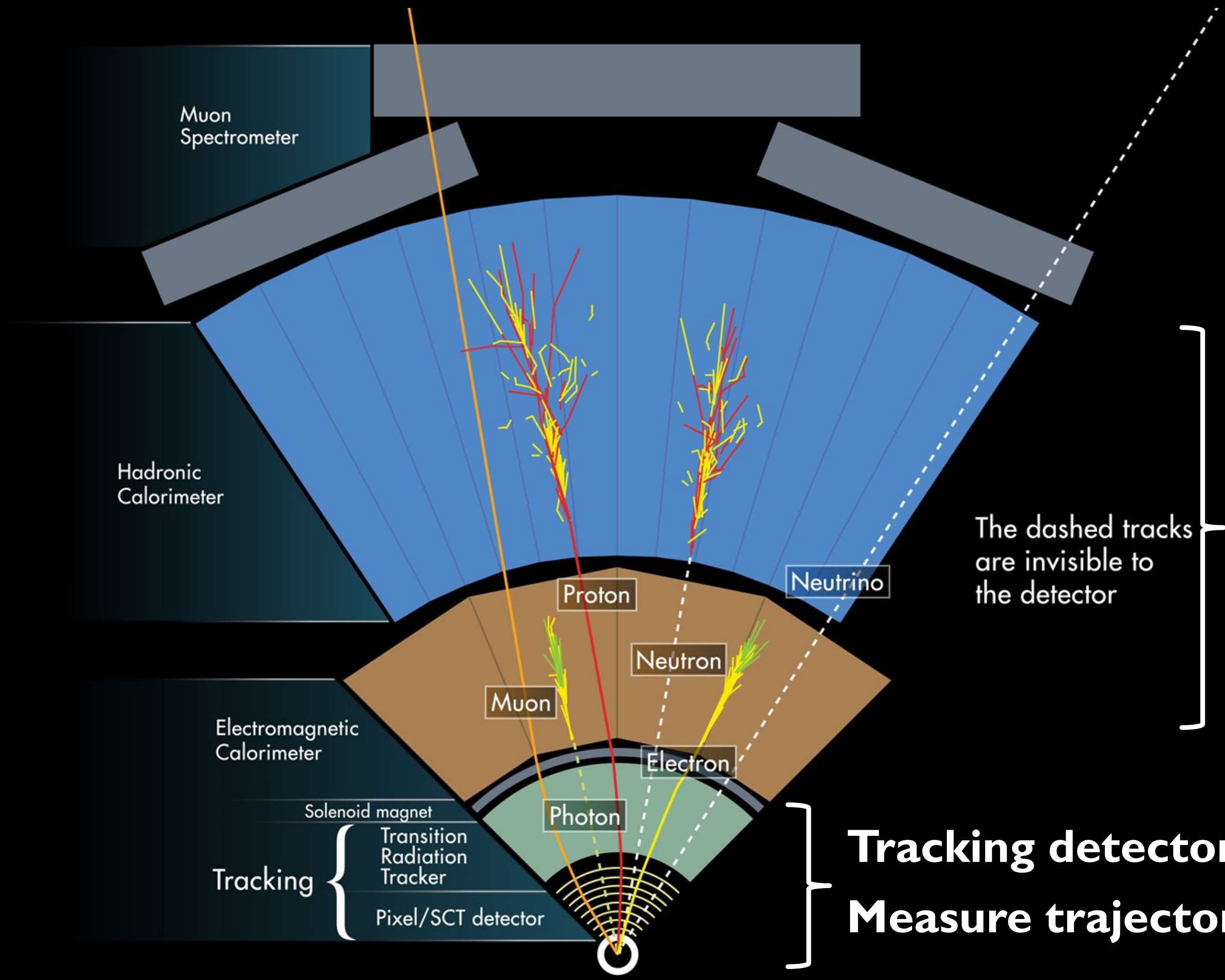
Particle identification



Tracking detector:

Measure trajectory of charged particles in a magnetic field

Particle identification



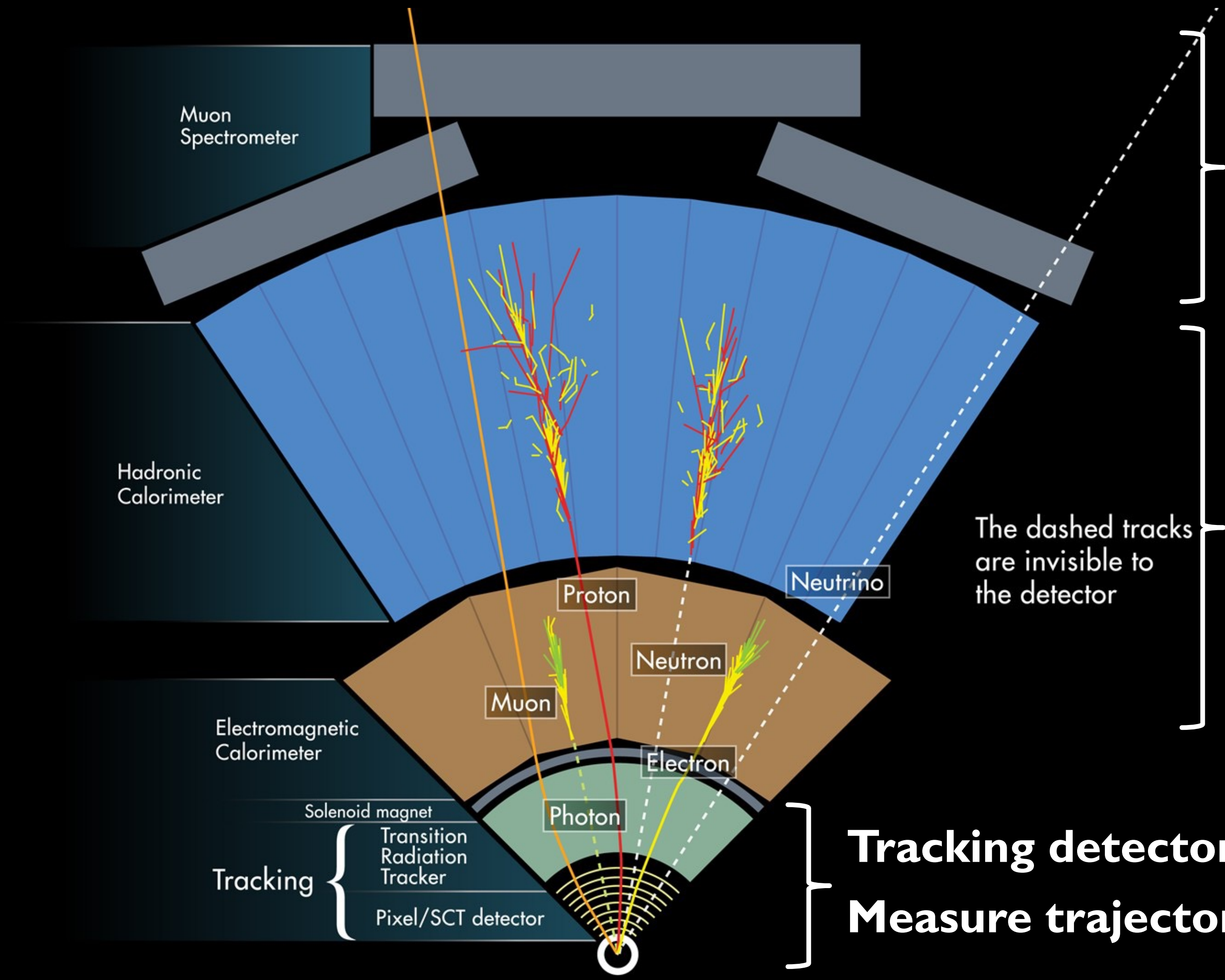
Electromagnetic and hadronic calorimeter:

Measure energy of particles

Tracking detector:

Measure trajectory of charged particles in a magnetic field

Particle identification



Muon spectrometer:

Measure trajectory of muons

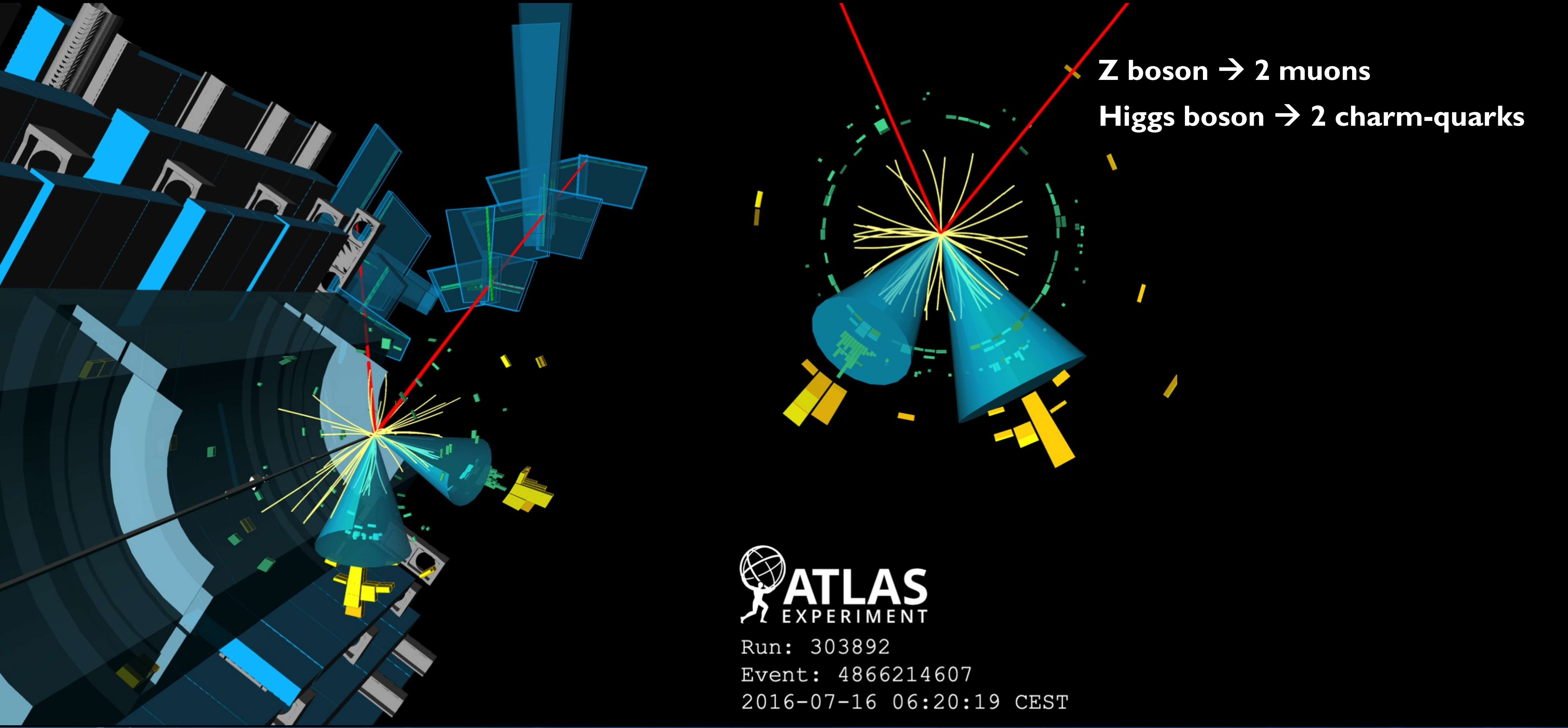
Electromagnetic and hadronic calorimeter:

Measure energy of particles

Tracking detector:

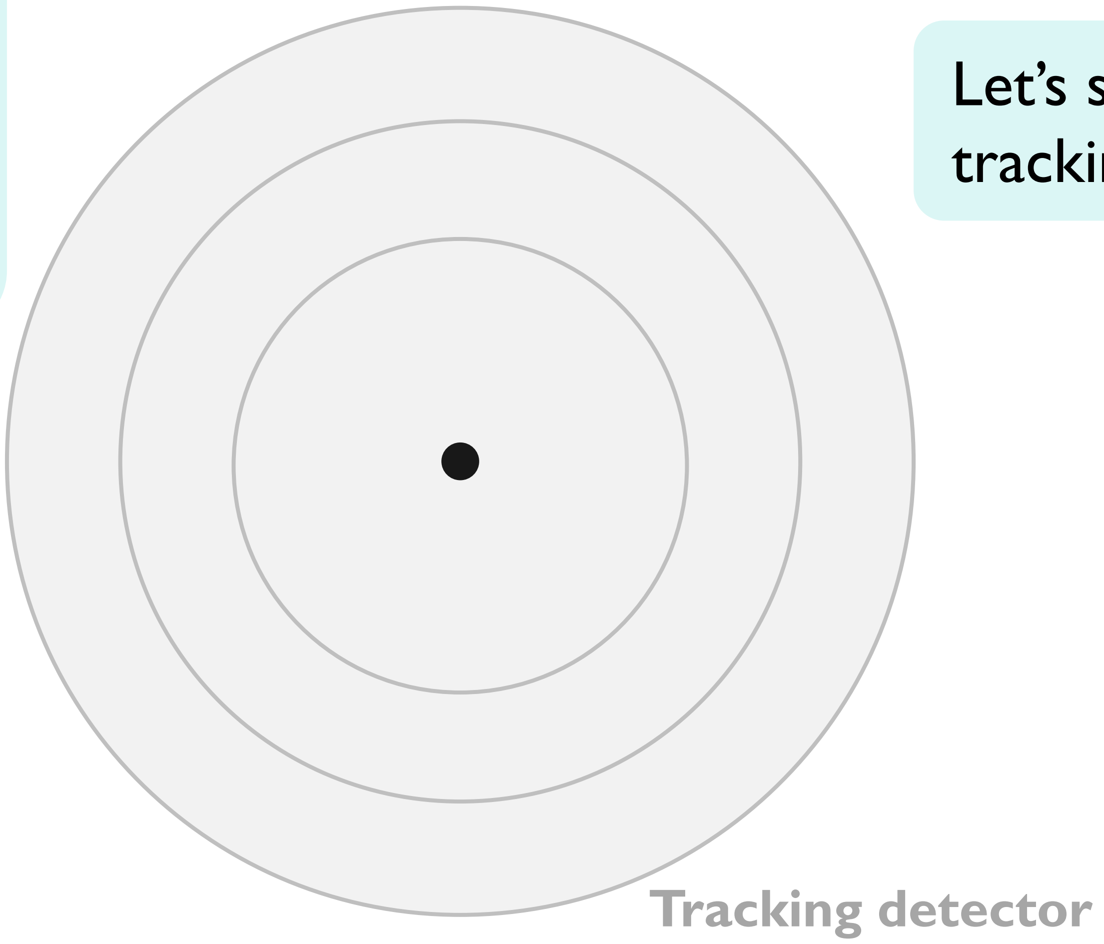
Measure trajectory of charged particles in a magnetic field

Example of a real event



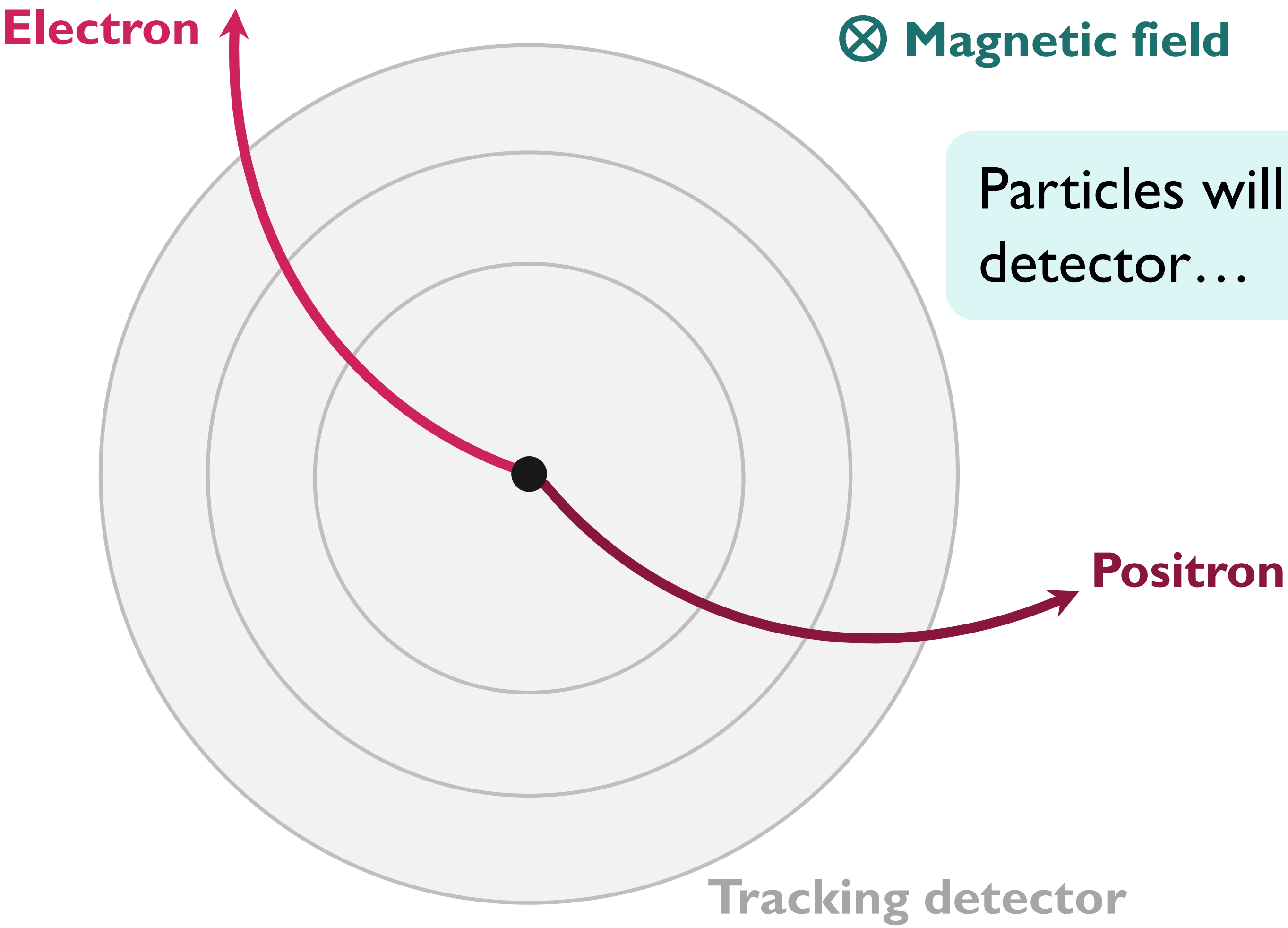
Tracking

Innermost part of ATLAS is a **tracking detector,** used for measuring the trajectories of charged particles



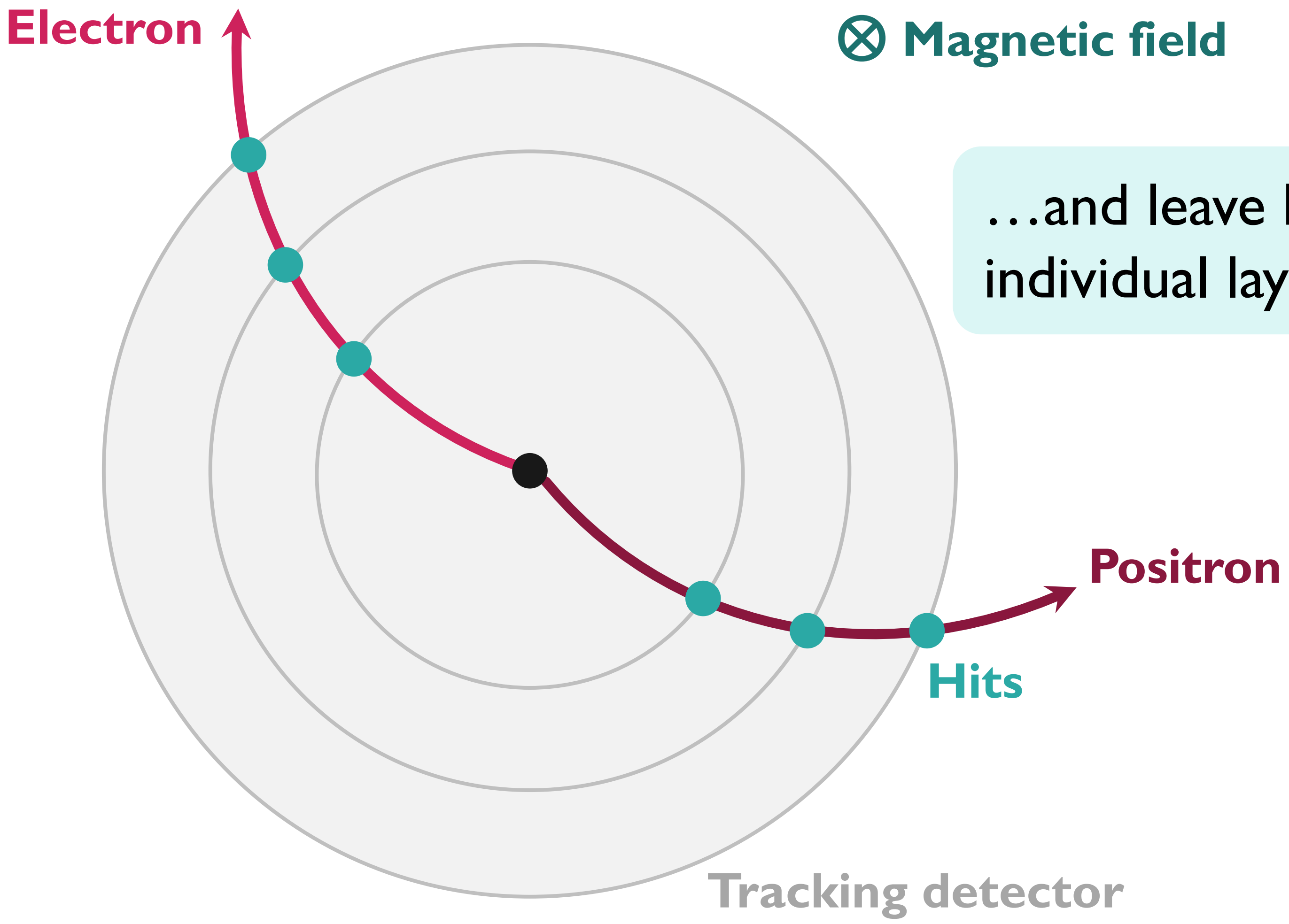
Let's start with our empty tracking detector

Tracking



Particles will fly through the detector…

Tracking



…and leave hits in the individual layers

Tracking

Why do electron and positron trajectories bend in opposite directions?

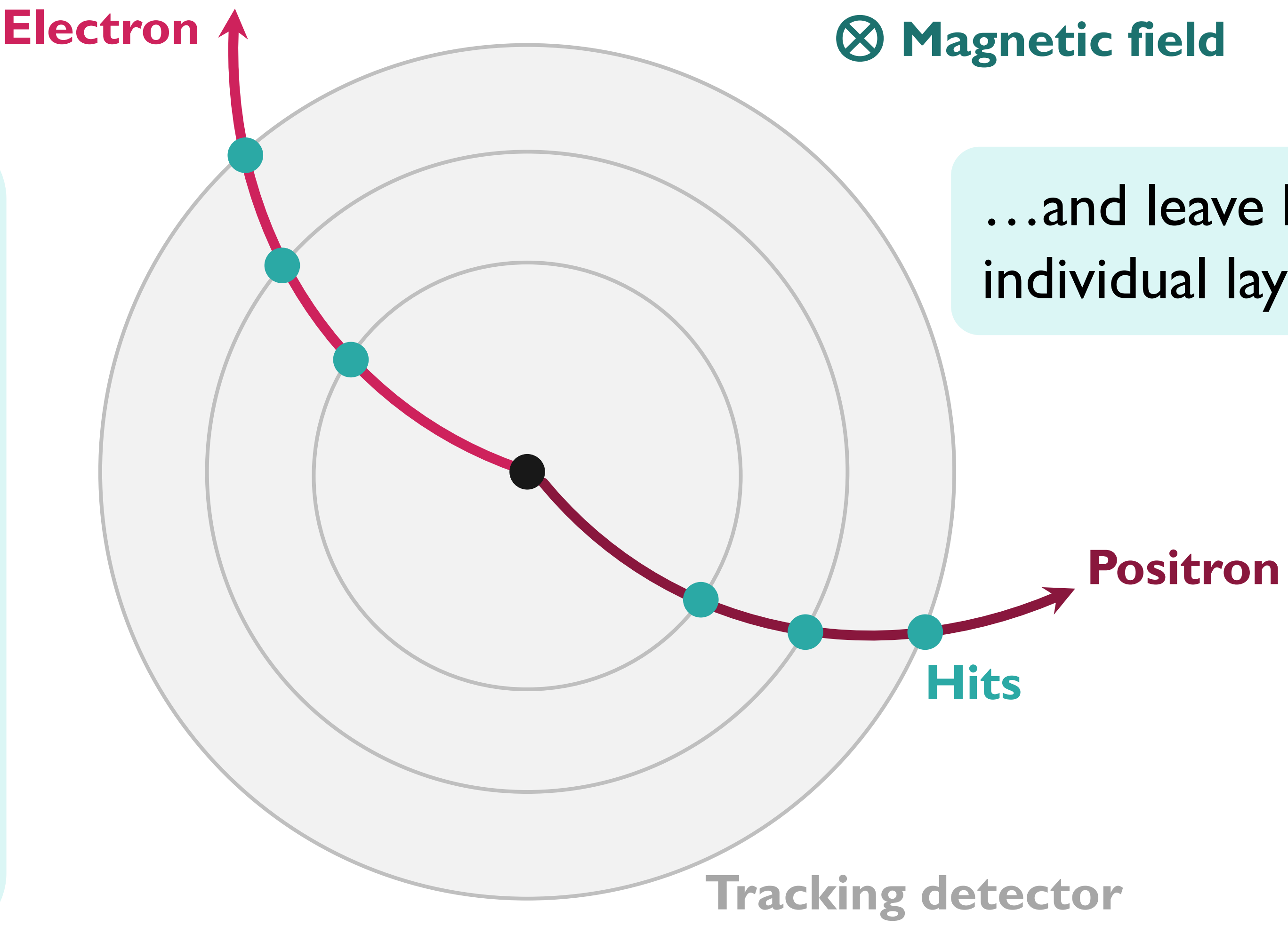
→ Charged particles bend in a magnetic field

What does the curvature of the track depend on?

→ Magnetic field

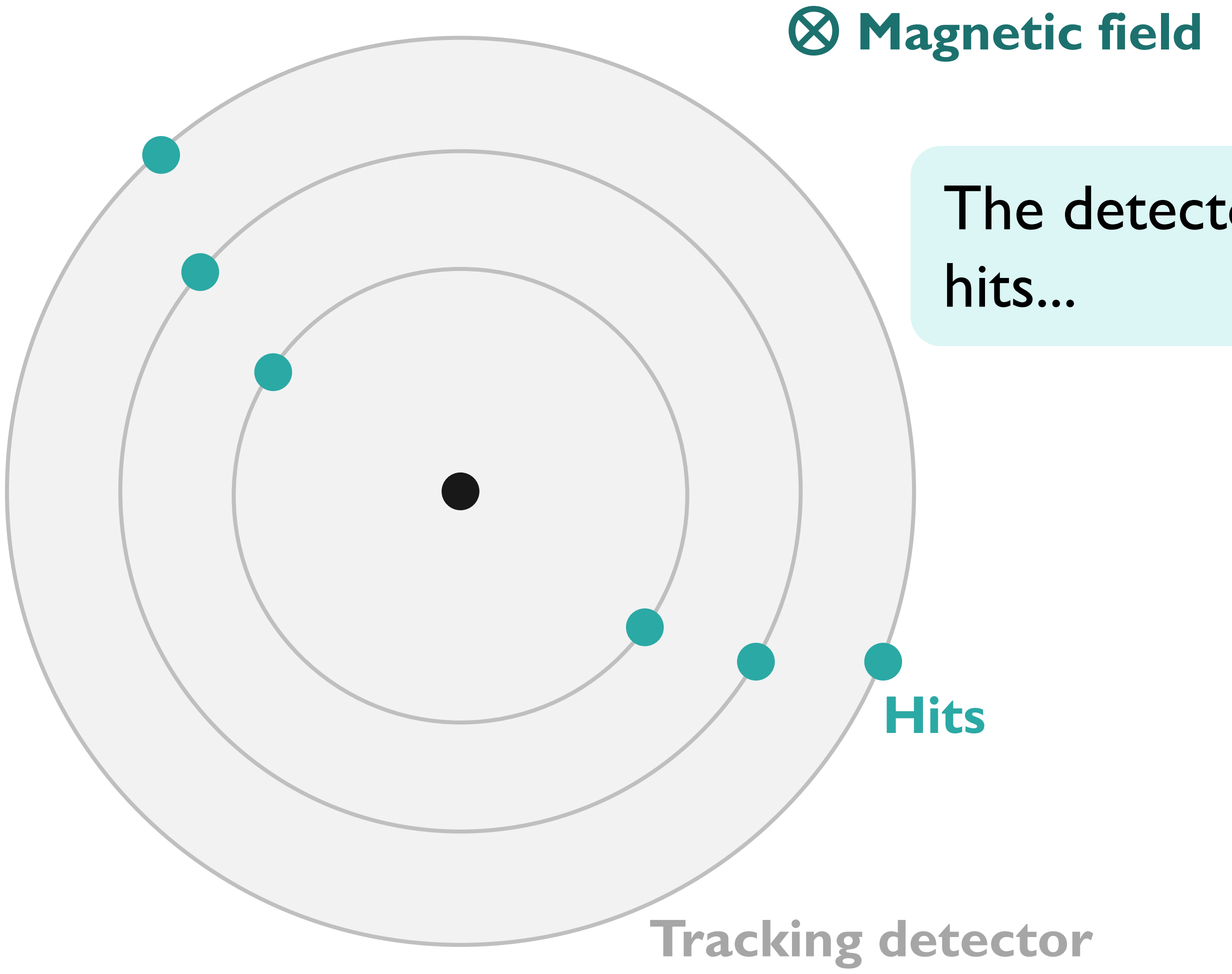
→ charge of the particle,

→ momentum/speed of the particle



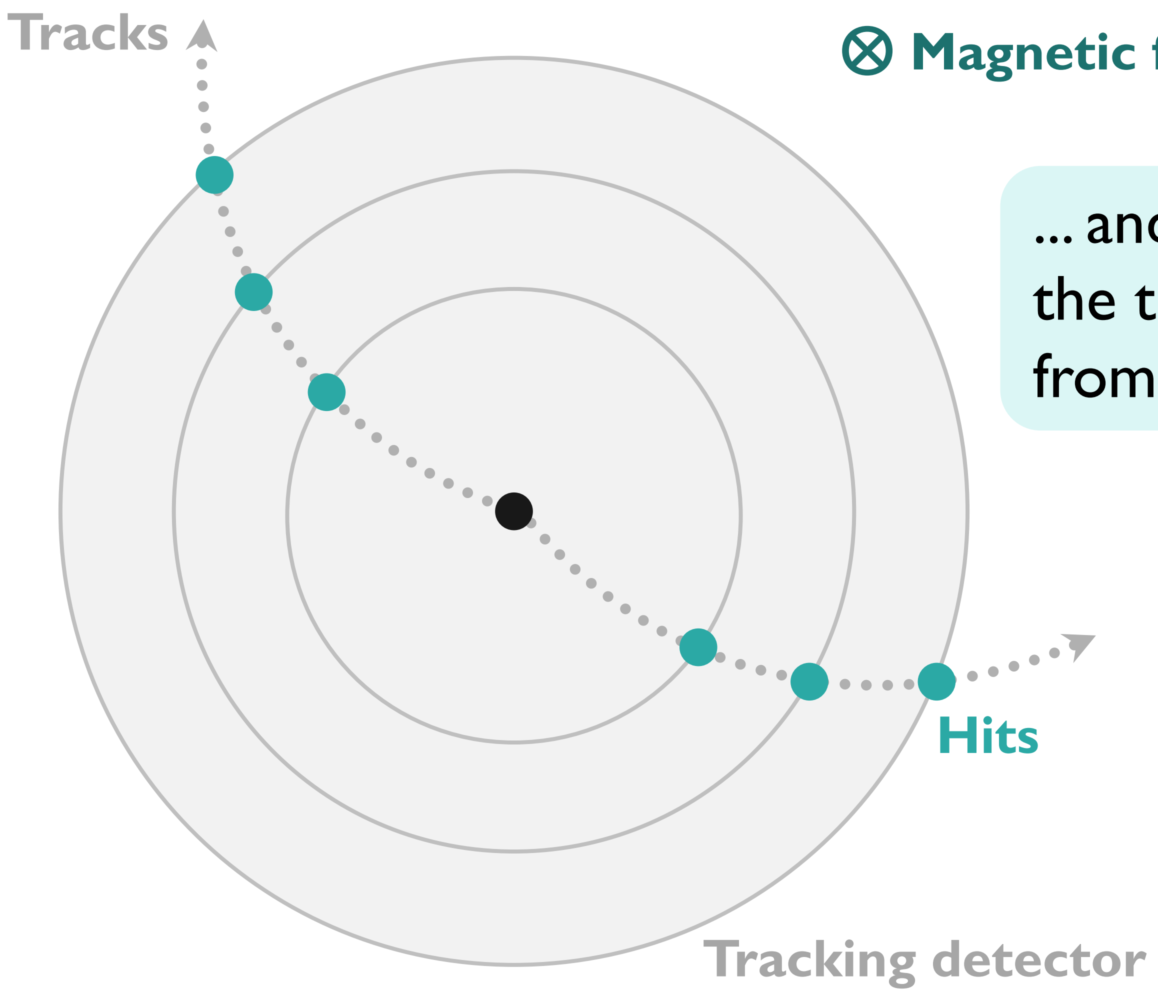
…and leave hits in the individual layers

Tracking



The detector only sees the hits...

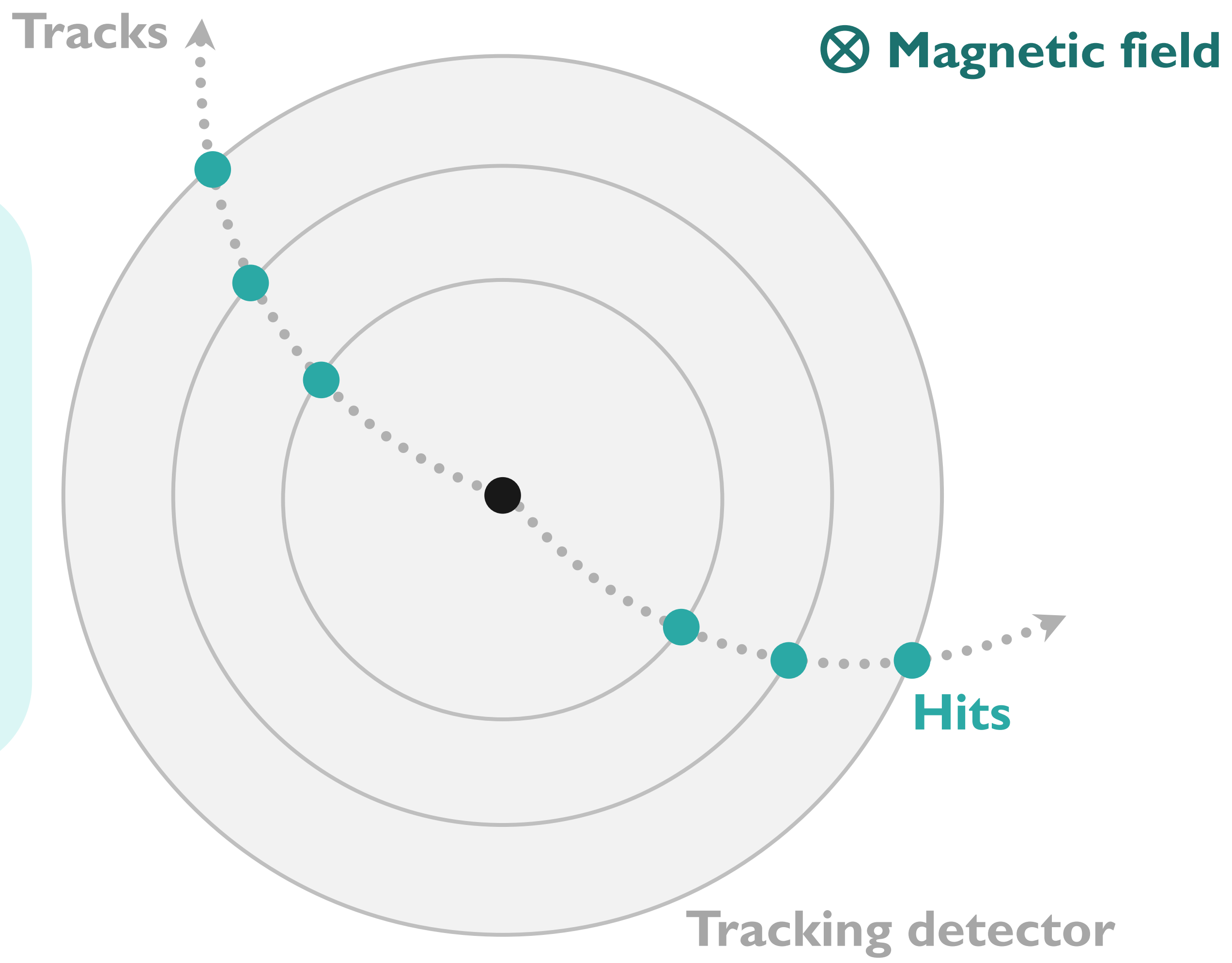
Tracking



... and has to reconstruct the tracks of the particles from the hit information

Tracking

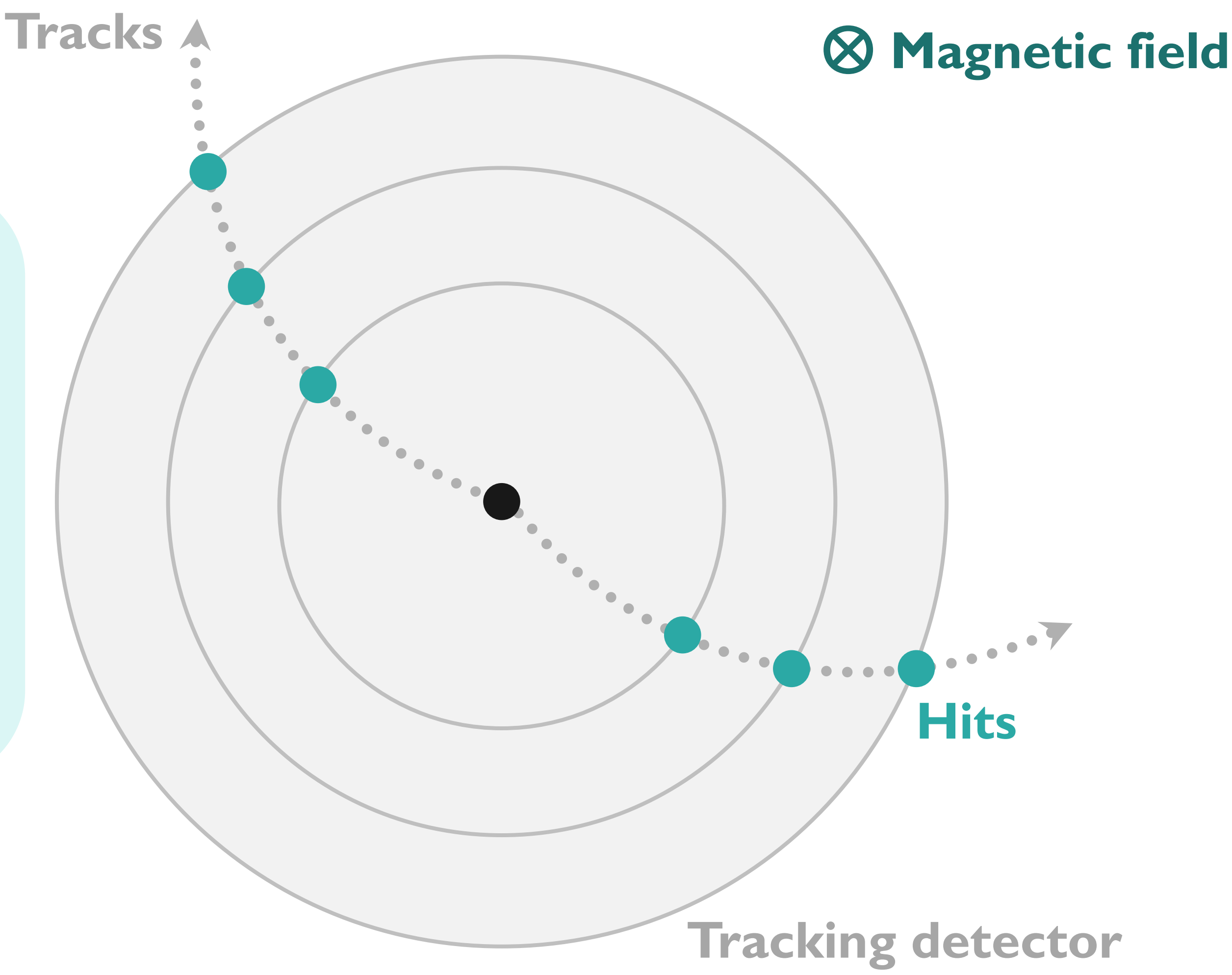
Tracking detector purposes



Tracking

Tracking detector purposes

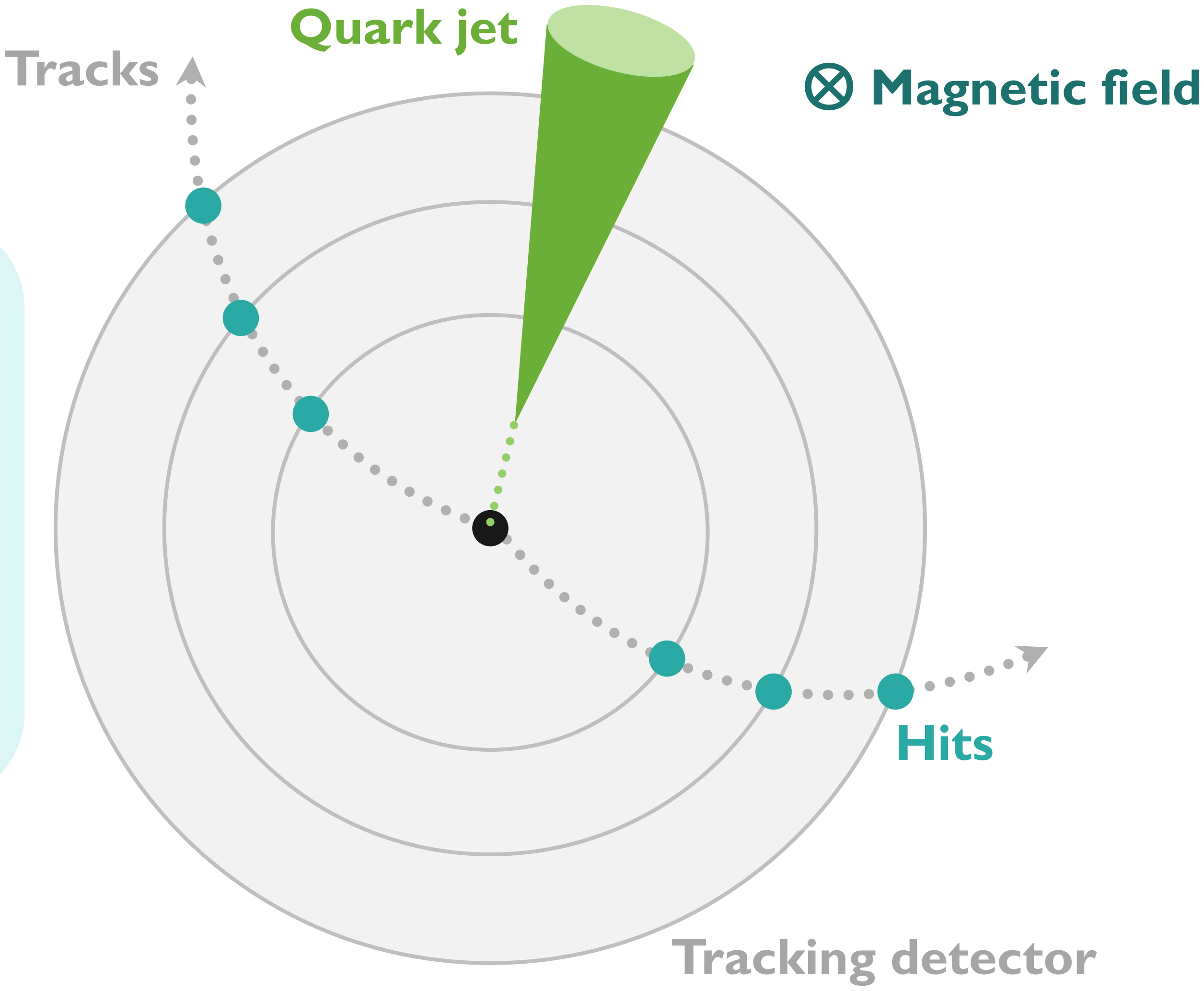
1. Measure tracks of particles to determine momentum



Tracking

Tracking detector purposes

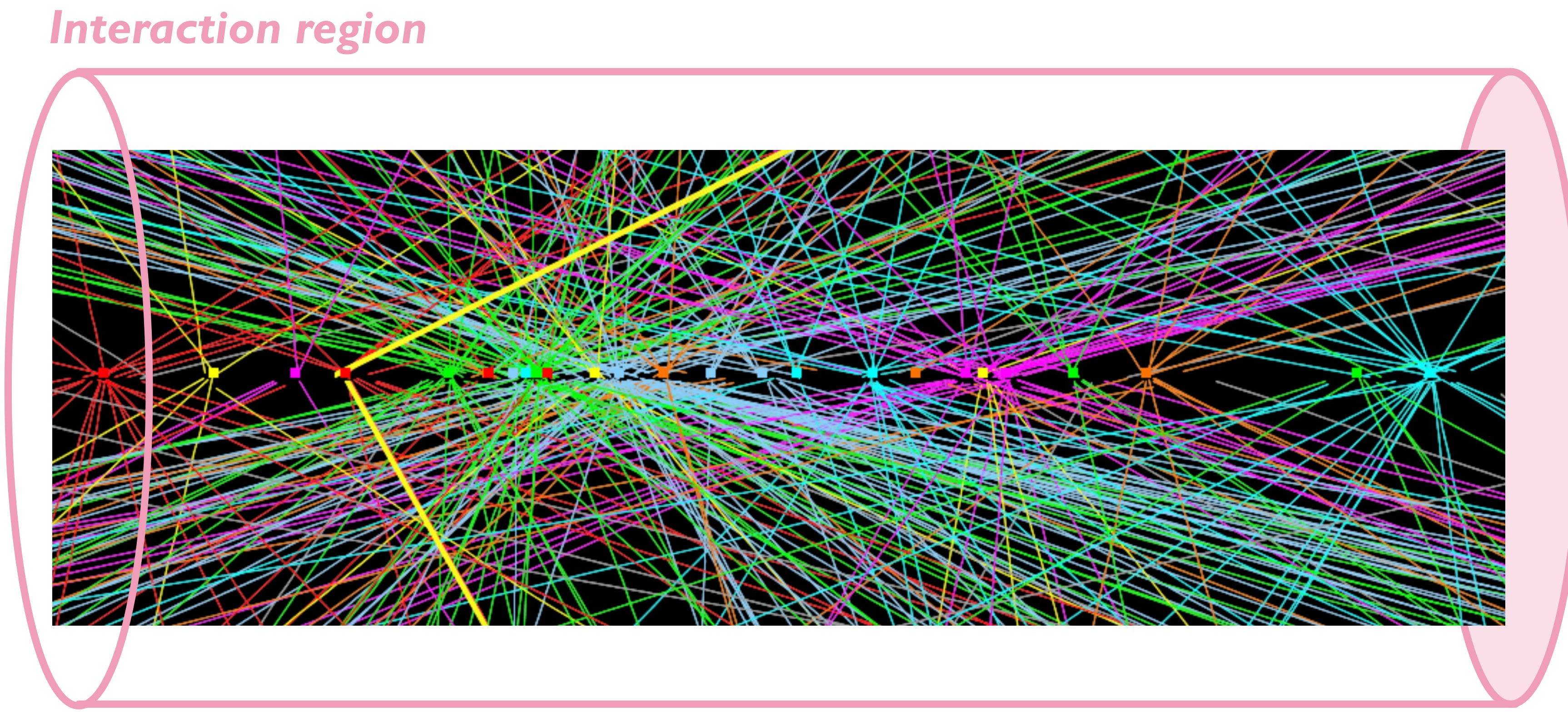
1. Measure tracks of particles to determine momentum
2. Measure ”secondary vertices”



Tracking

Tracking detector purposes

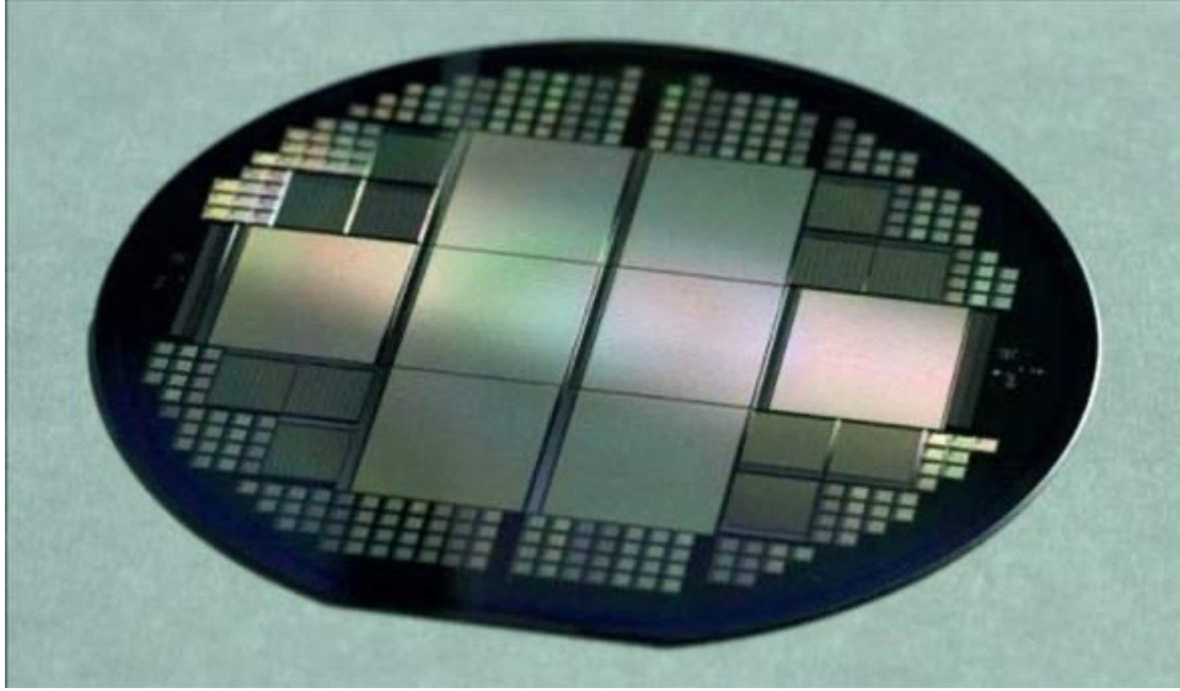
1. Measure tracks of particles to determine momentum
2. Measure ”secondary vertices”
3. Distinguish multiple interactions in one event

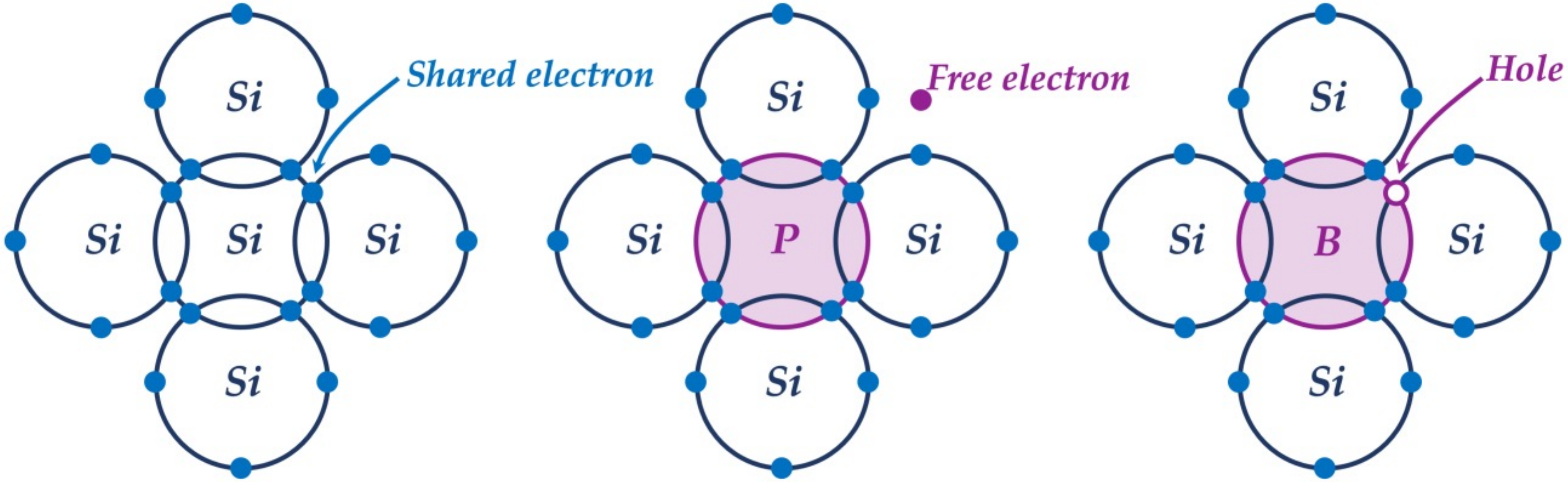


Questions?

Silicon

- Tracking detectors are commonly constructed from Silicon
- Silicon is a **semiconductor**, which is between an insulator and a conductor
- Silicon has four valence electrons and forms a crystalline lattice
- Can enhance properties of silicon by "**doping**" → including additional free positive and negative charges

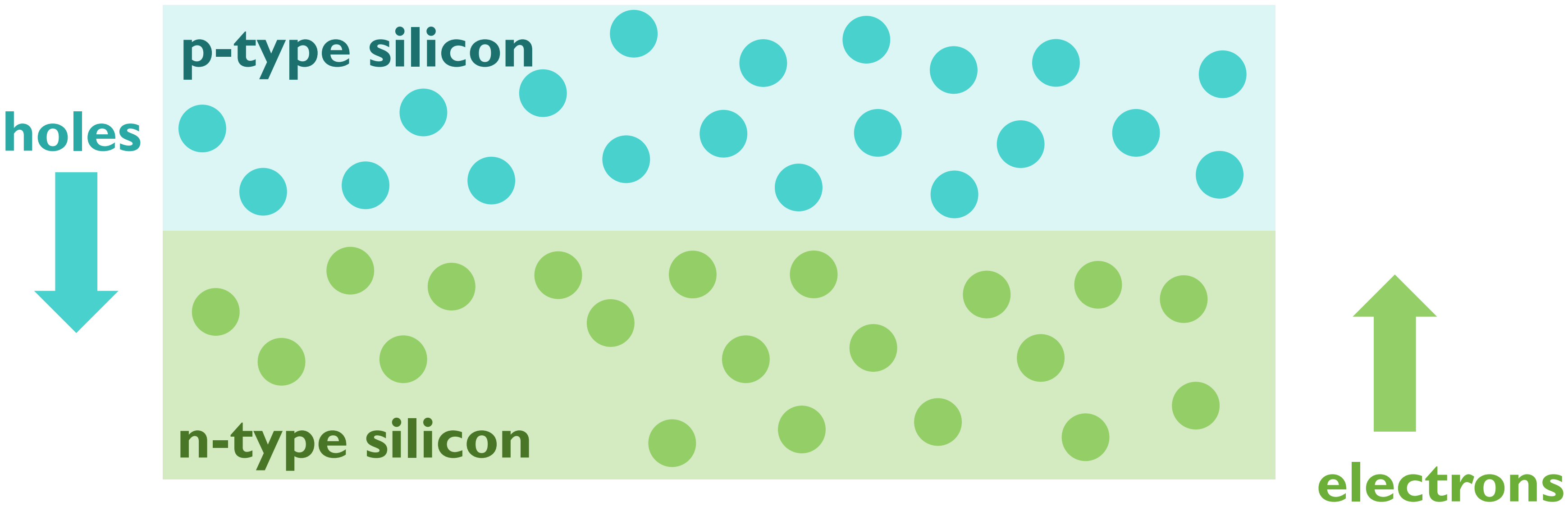




Electronic structure of pure and doped silicon

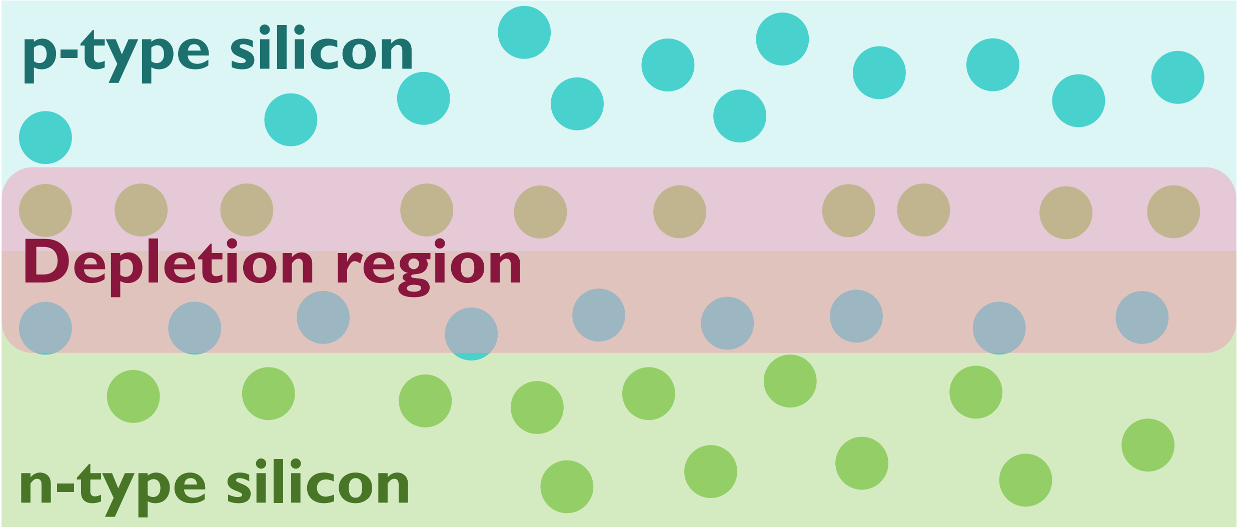
Silicon detectors

Starting with two layers of silicon, doped with additional charge carriers:



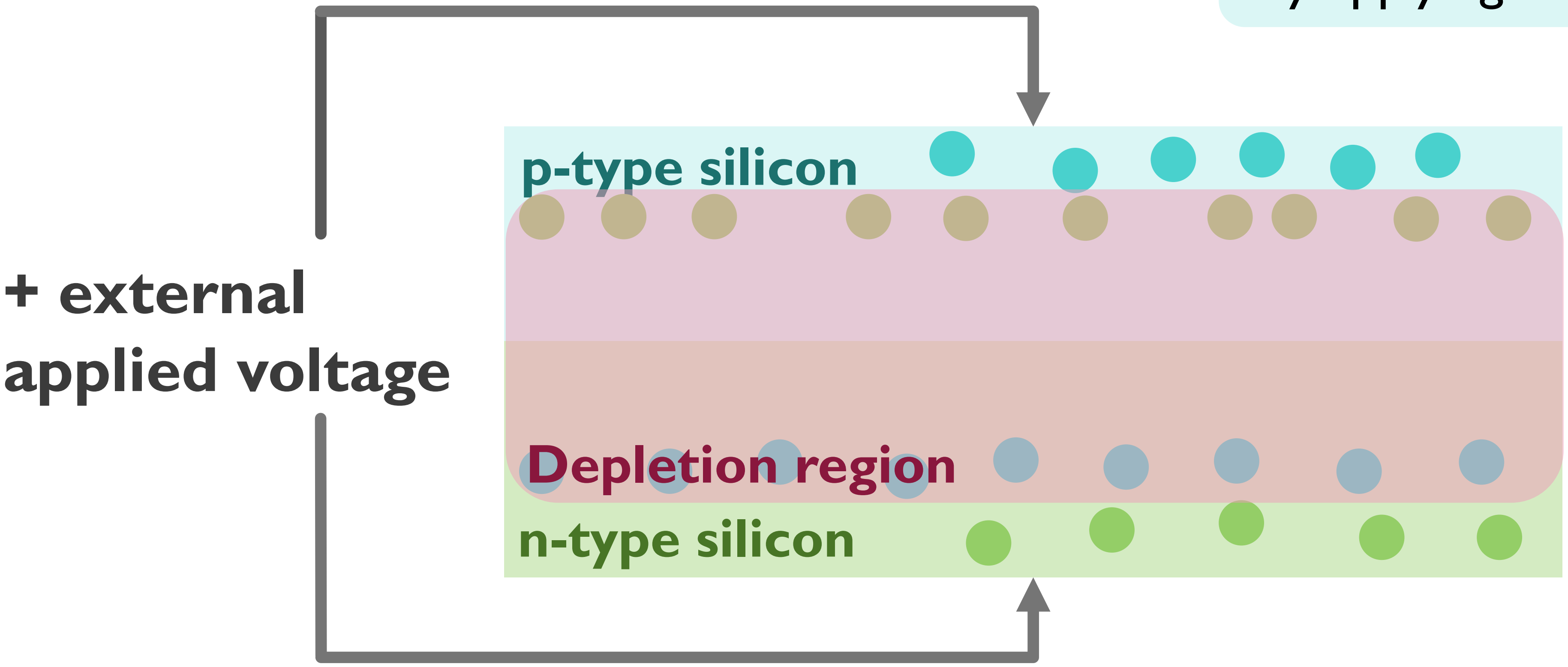
Silicon detectors

Charges will move until they are in equilibrium, creating a region without charge → **depletion region**



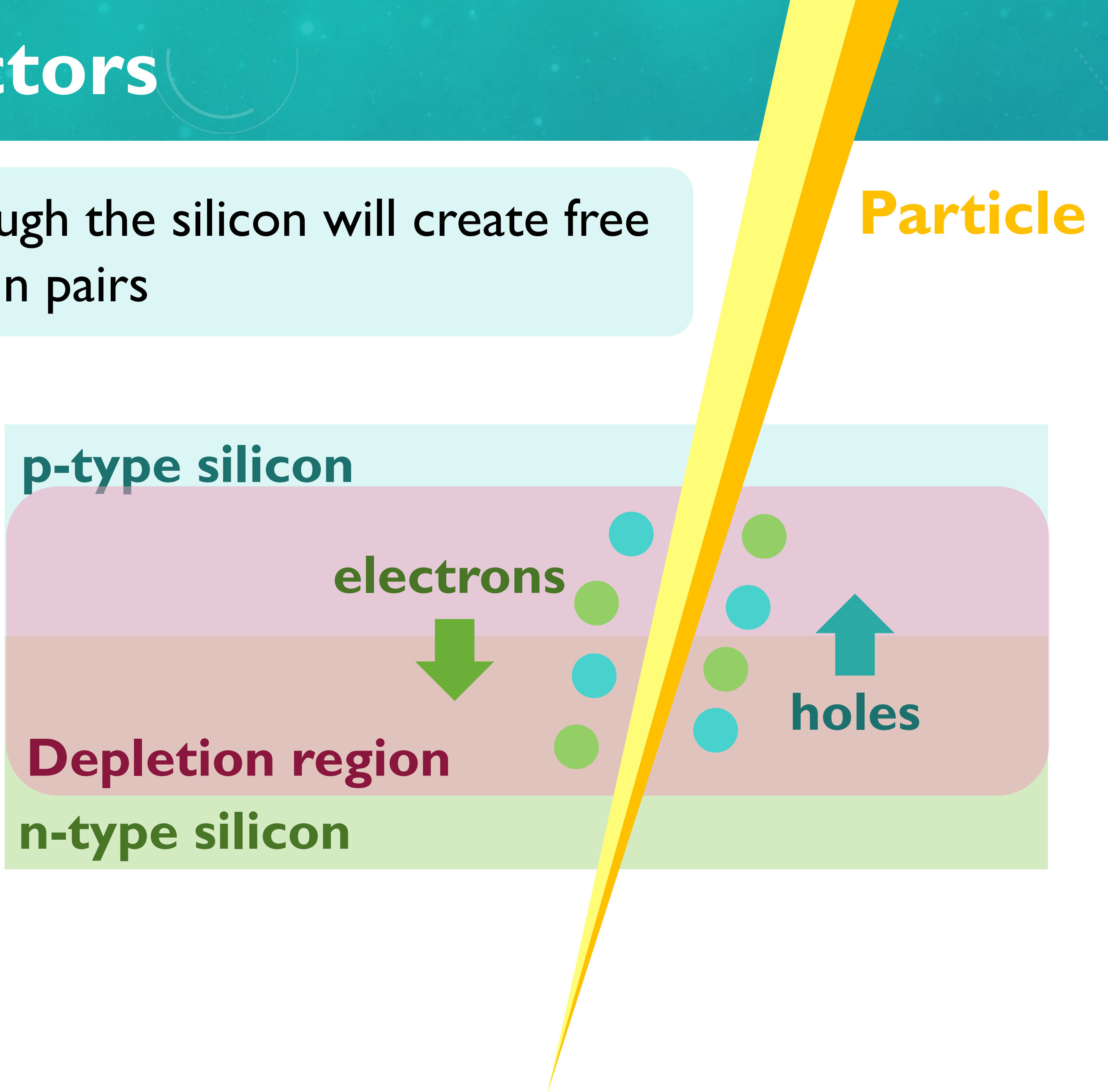
Silicon detectors

Depletion region can be extended by applying an external voltage



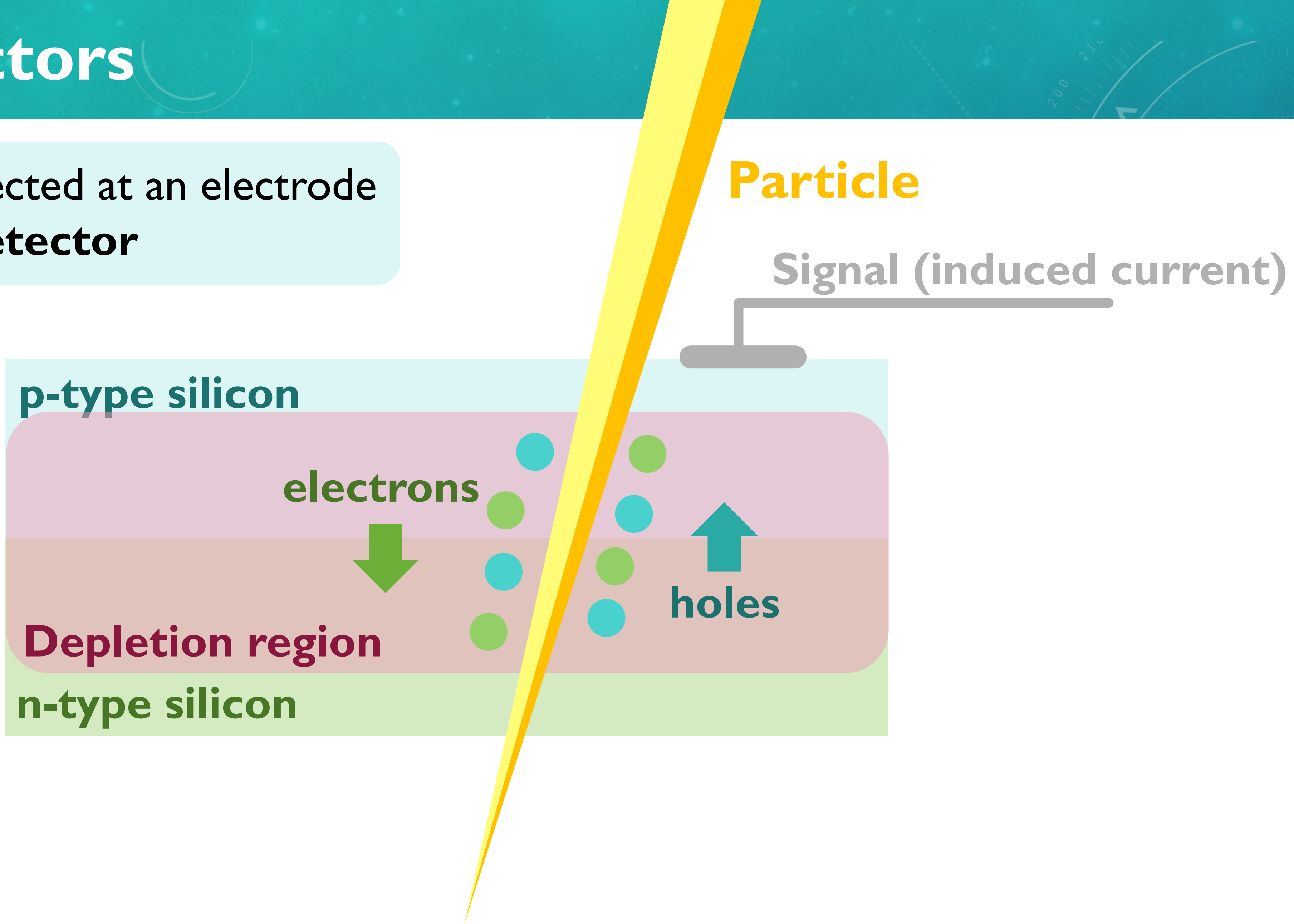
Silicon detectors

Particle passing through the silicon will create free electrons and holes in pairs



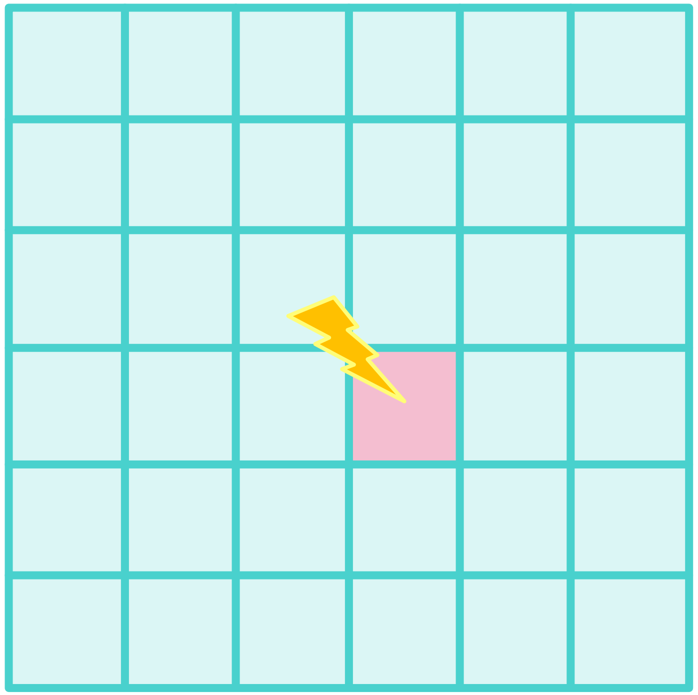
Silicon detectors

Charges can be collected at an electrode
→ **Signal in the detector**



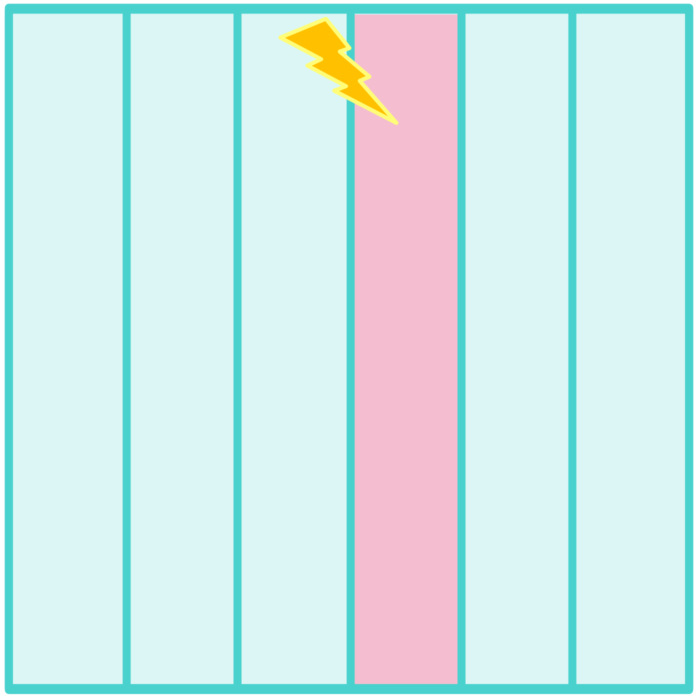
Pixel vs strip detectors

Pixel detector



Pixel pitch: 400 x 50 μm^2

Strip detector



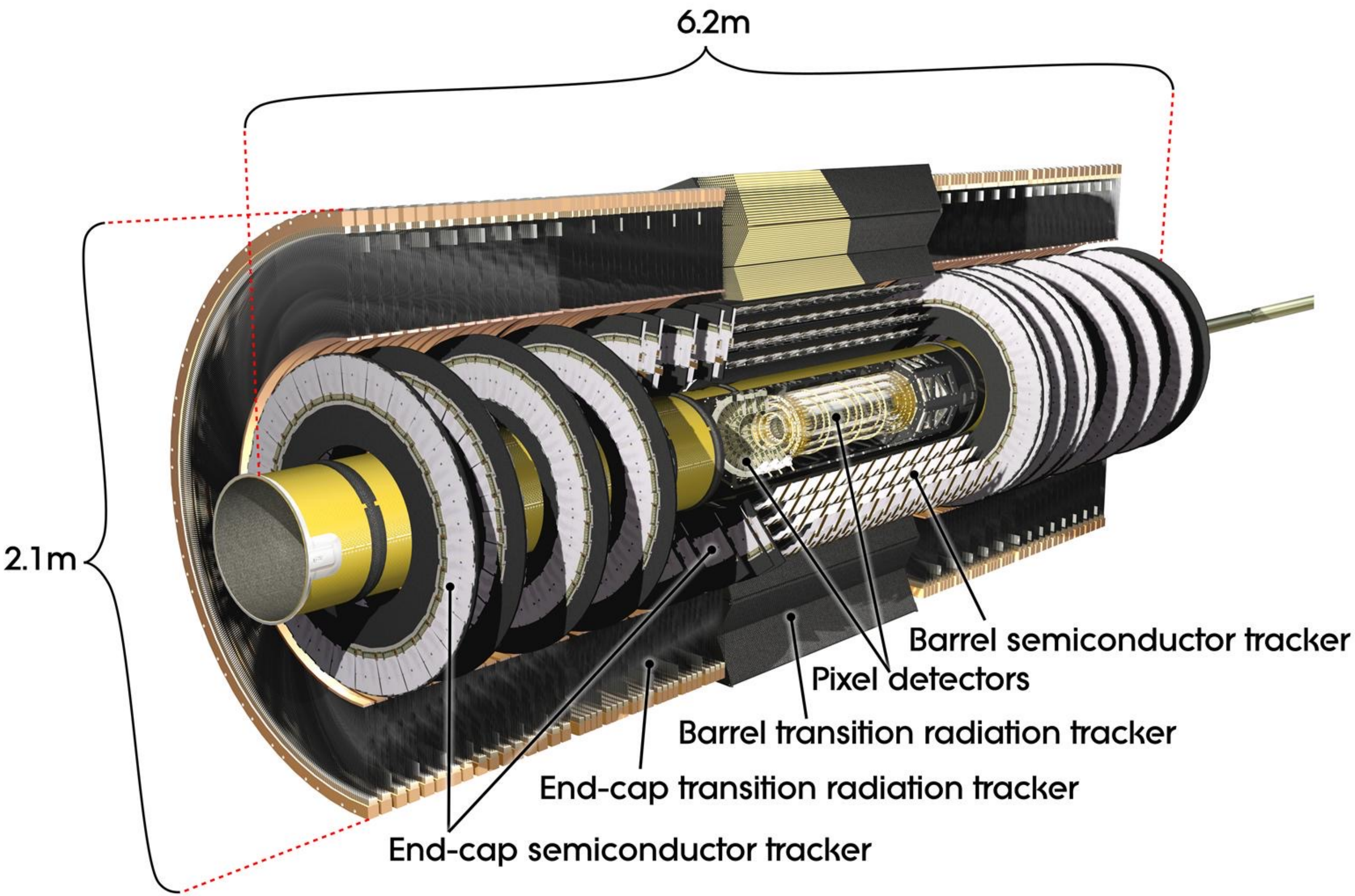
Strips pitch: 75 μm x 5 cm

Can divide the silicon in one or two dimensions, to get some position resolution

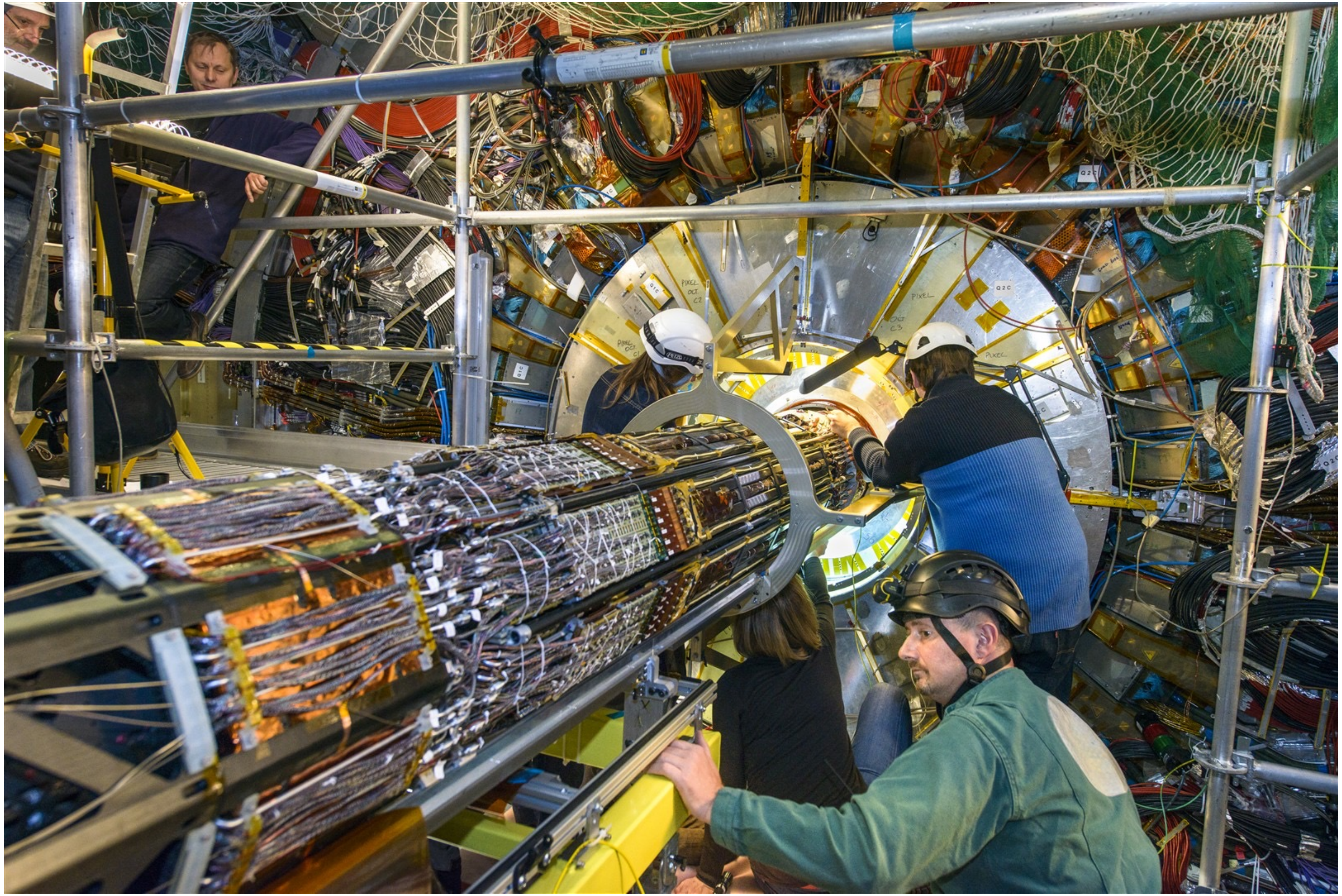
→ **Pixel and strip detectors**

→ Can get 2D resolution from strip detector by putting two layers at an angle

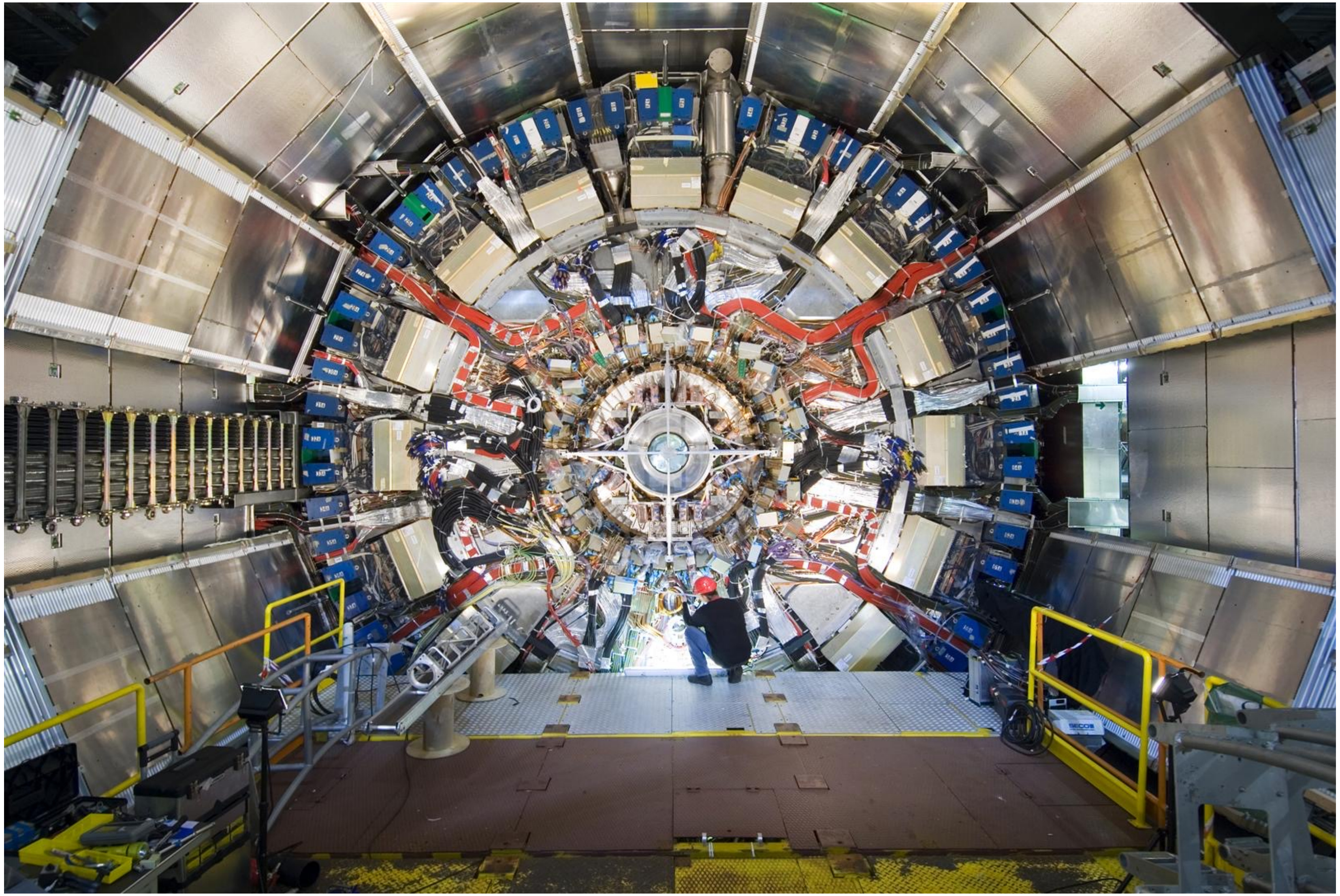
ATLAS Tracking Detector



ATLAS Pixel Detector



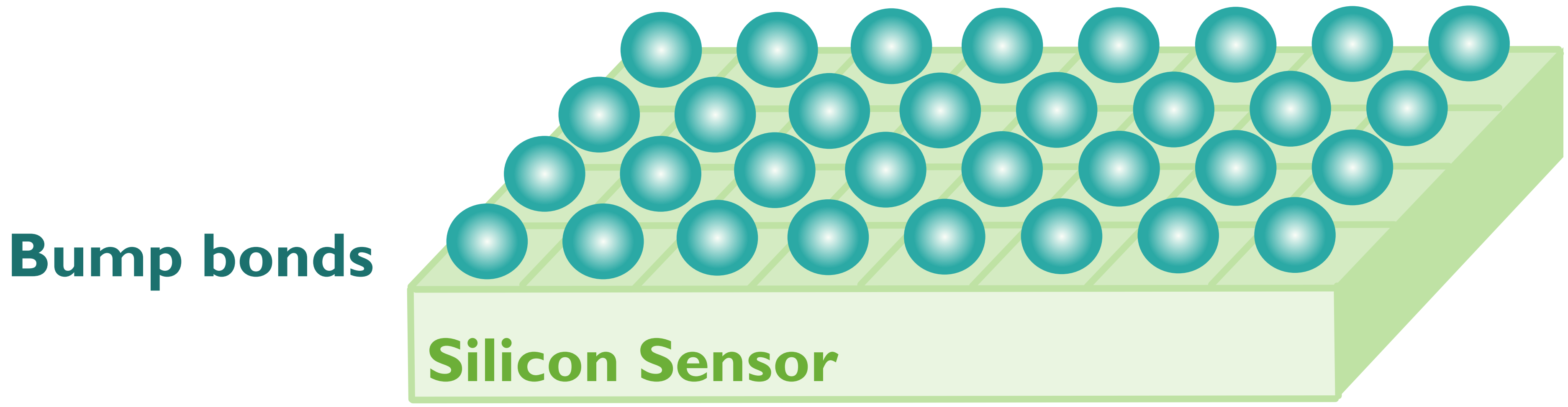
ATLAS Tracking Detector



Questions?

How to build a pixel detector

How to build a pixel detector



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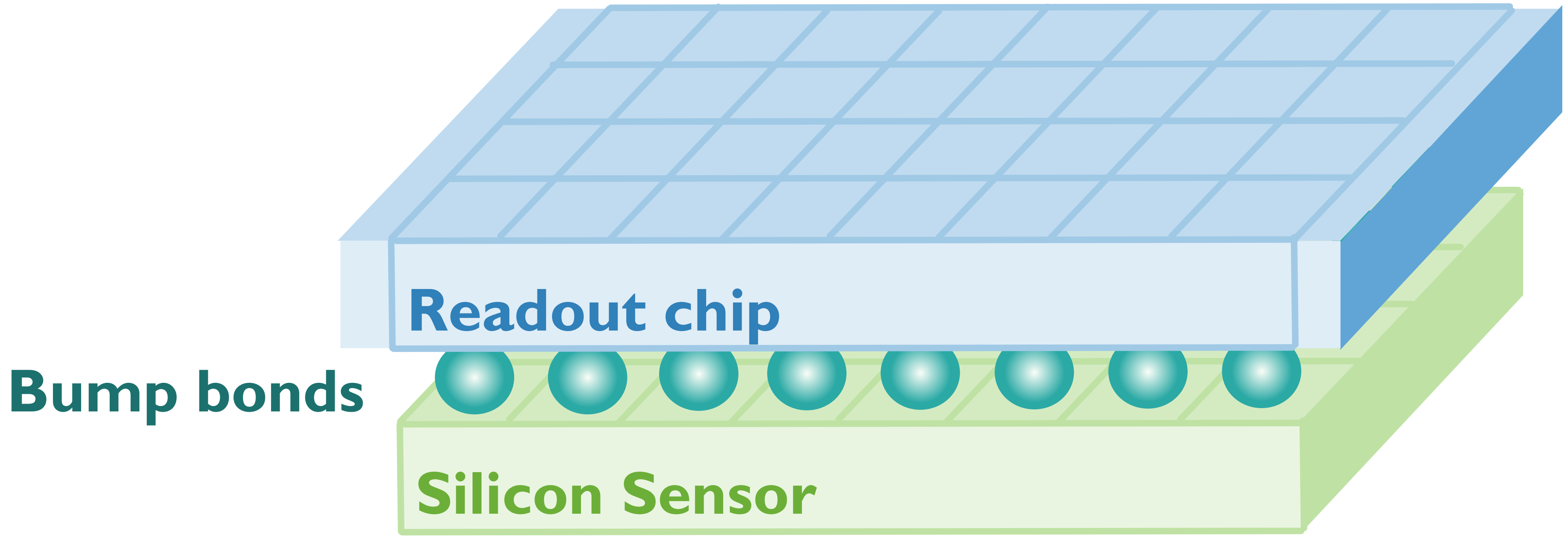

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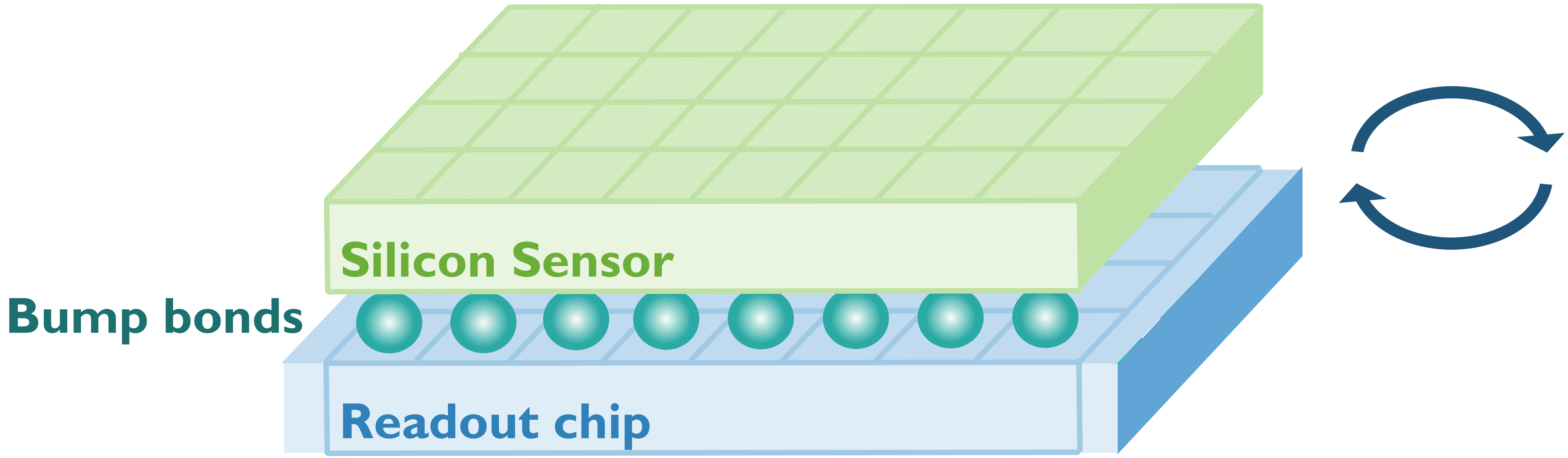

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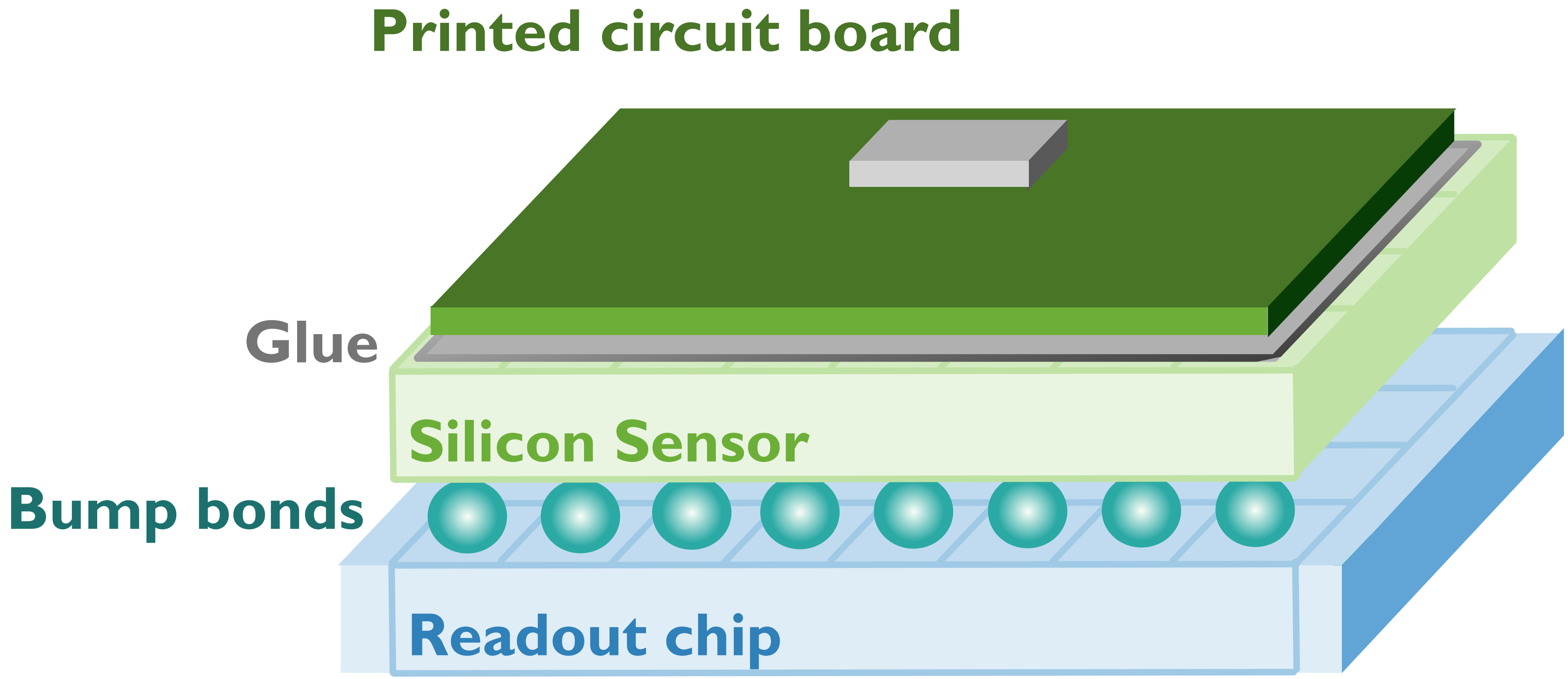
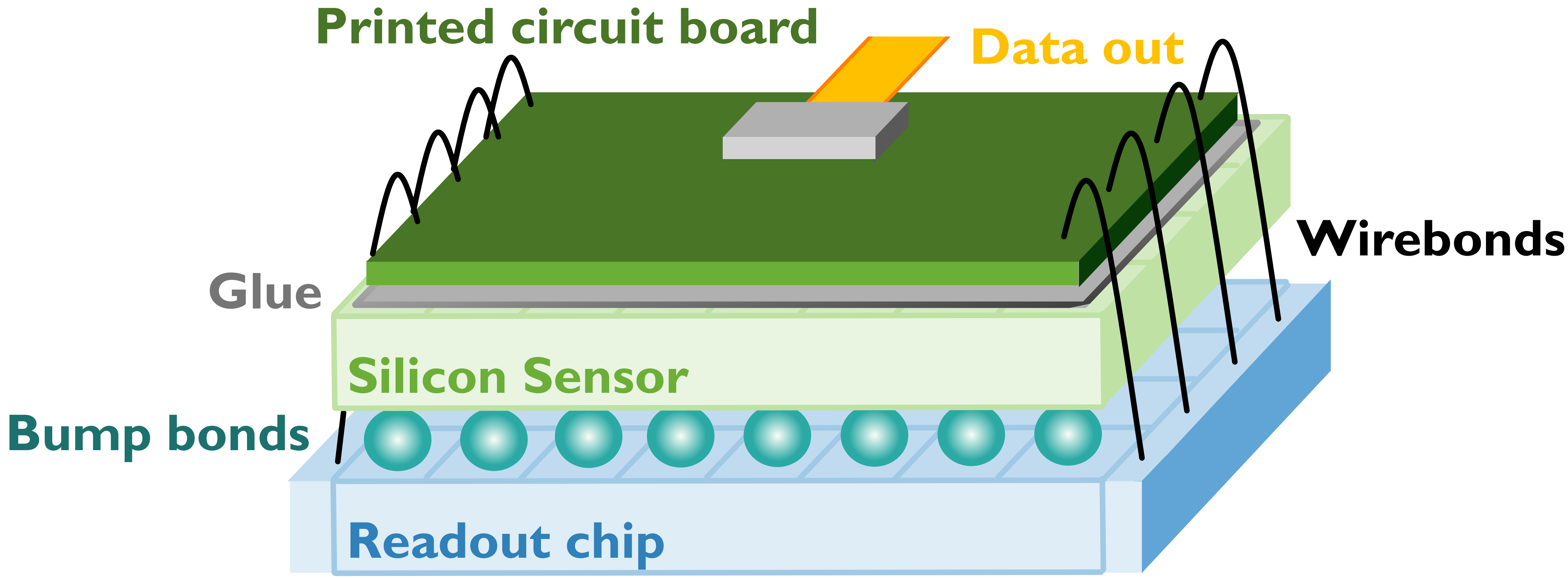
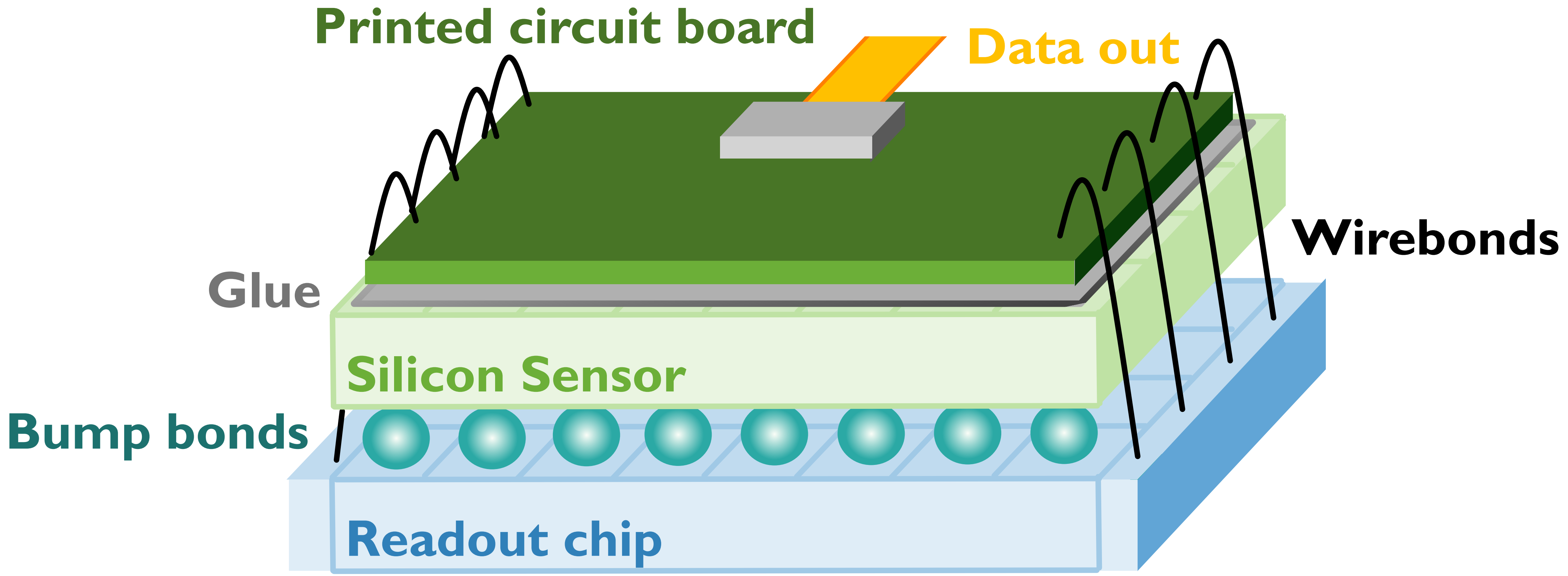


How to build a pixel detector



Pixel detector requirements



Detector requirements

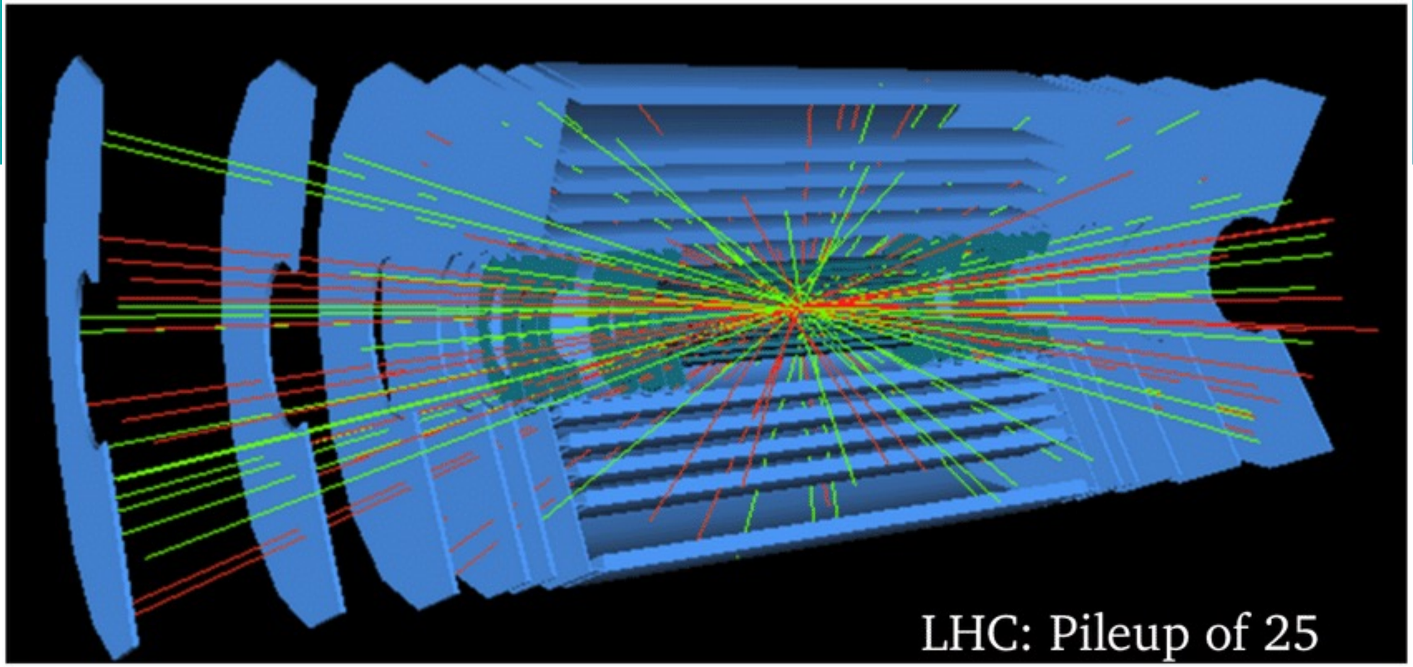
- Get the best resolution possible → **small pixel size** (400 x 50 μm^2)
- Fast enough to cope with collision rate at LHC (40 MHz) and large volume of data → **readout speed**
- Survive in a high-radiation environment → **radiation tolerance**

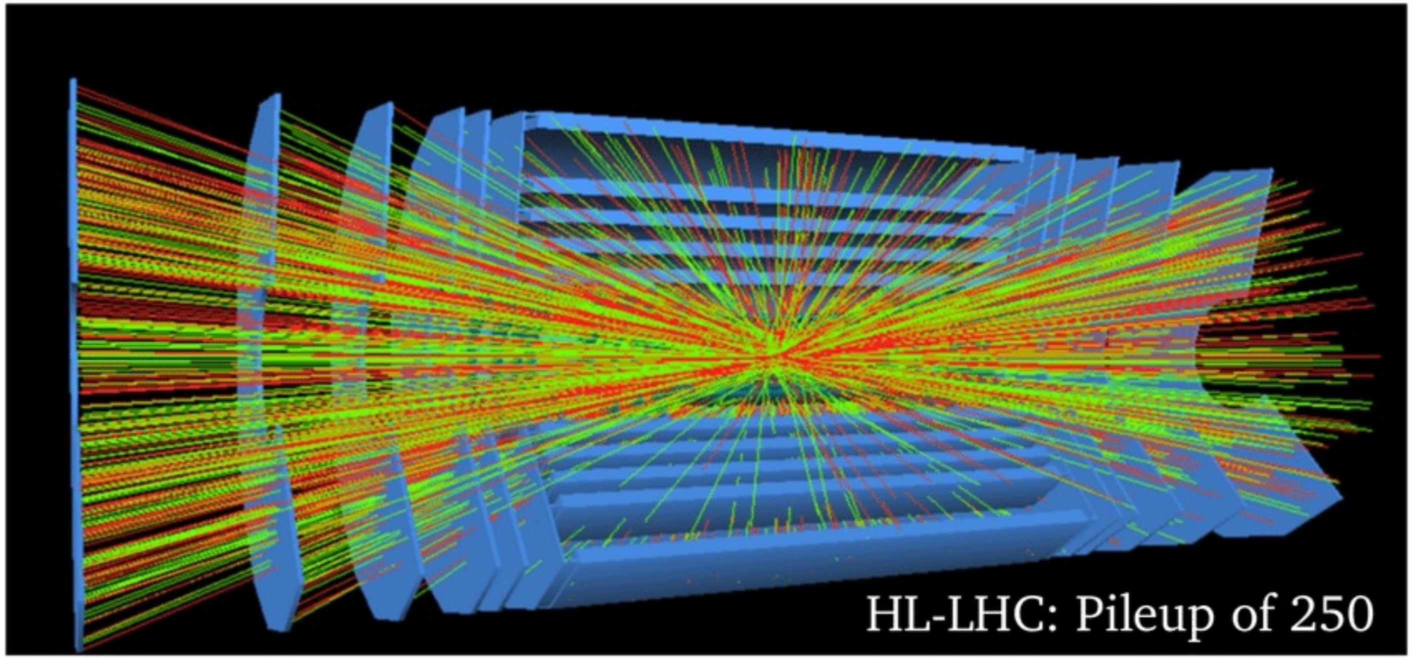
High Luminosity LHC

- Will upgrade LHC accelerator around 2025 to collect a 10 x larger dataset than we currently have

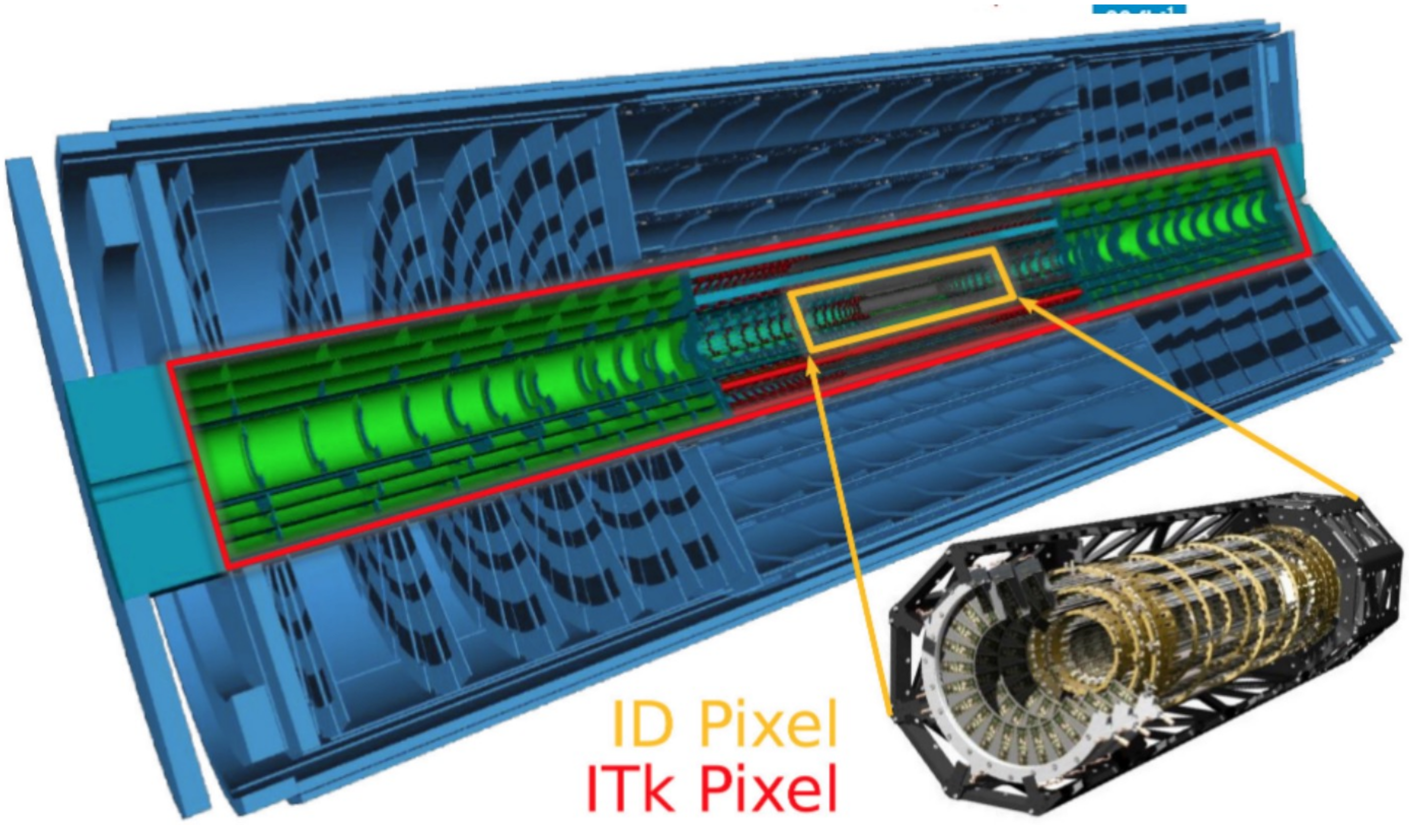
→ Increased number of interactions per collision of proton bunches

→ **High-Luminosity LHC (HL-LHC)**





ATLAS detector upgrade



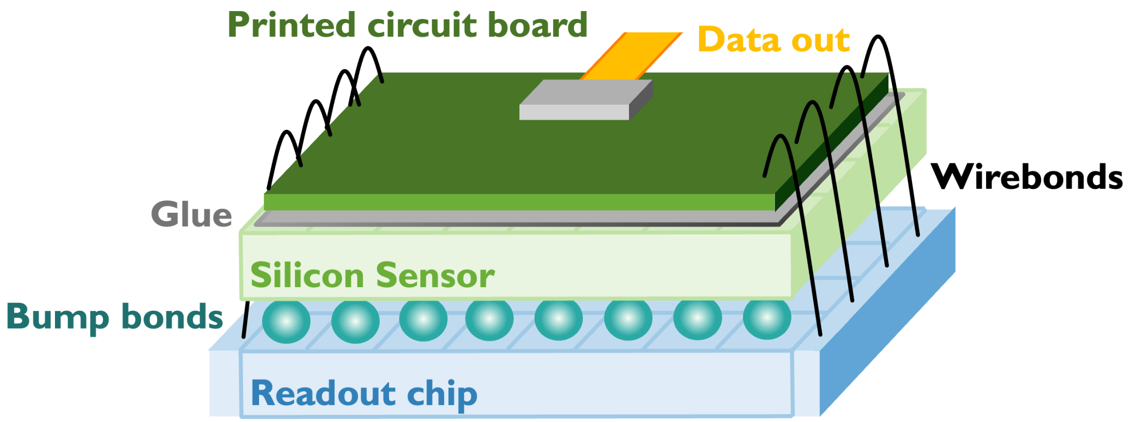
All-silicon upgraded tracking detector (ITk) for HL-LHC

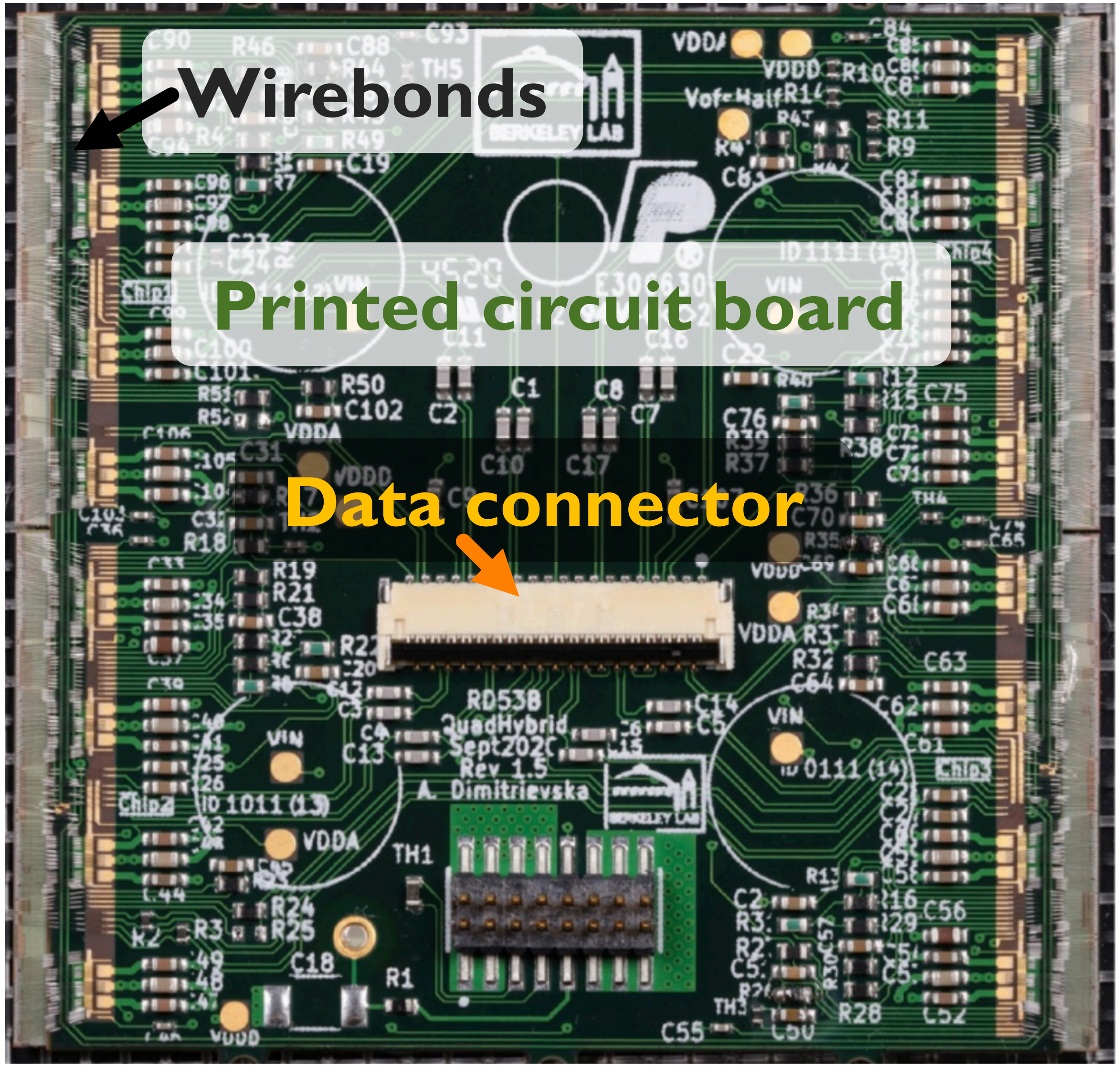
Upgraded pixel detector:

- Larger silicon area → **6x larger than current tracking detector**
    - ~13 m^2 of active area
    - 9400 pixel modules, 5.1 billion pixels
    - For comparison: iPhone 14 Pro camera 48 million pixels
- **Smaller pixel pitch:**

  400 x 50 μm^2 → 50 x 50 μm^2
- **New readout chip** to cope with higher data rates and increased radiation

Pixel modules for the ATLAS pixel upgrade



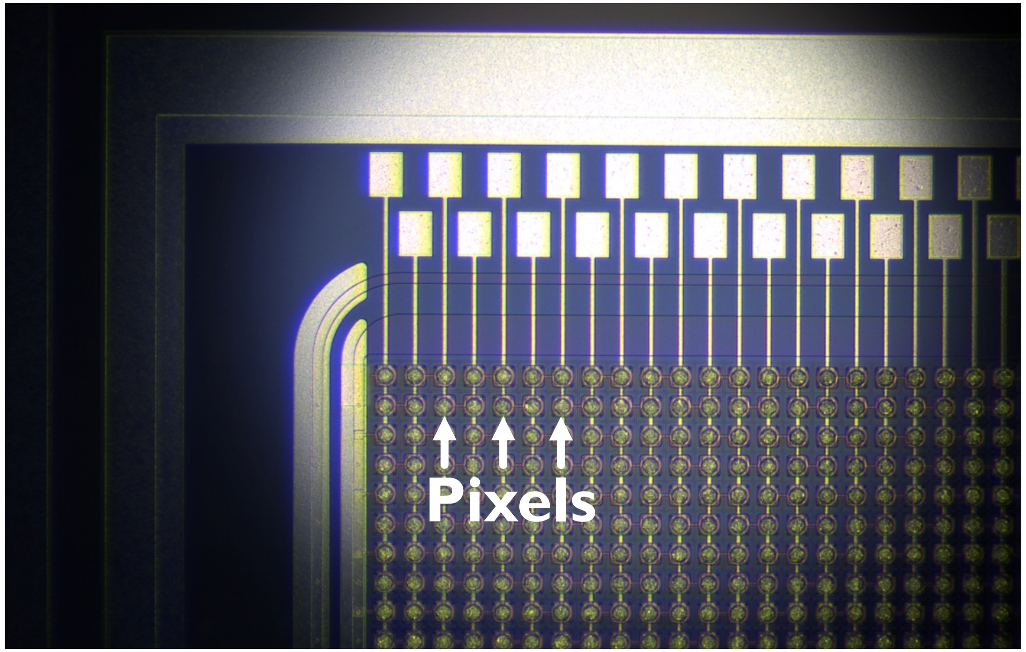


Pixel sensors for the ATLAS upgrade

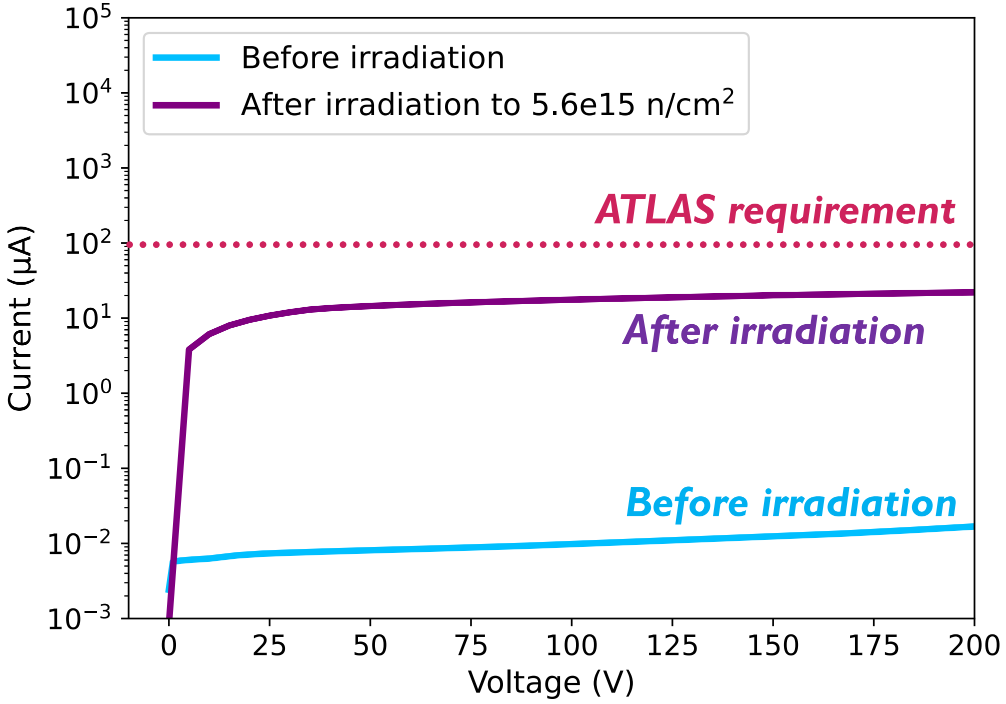
- Pixel sensors for ITk produced by industry → **need to check they meet the requirements for ATLAS**
- For example: Current flowing through the sensor must stay low throughout operation

→ check current before and after irradiation of the sensor

Close-up of silicon sensor



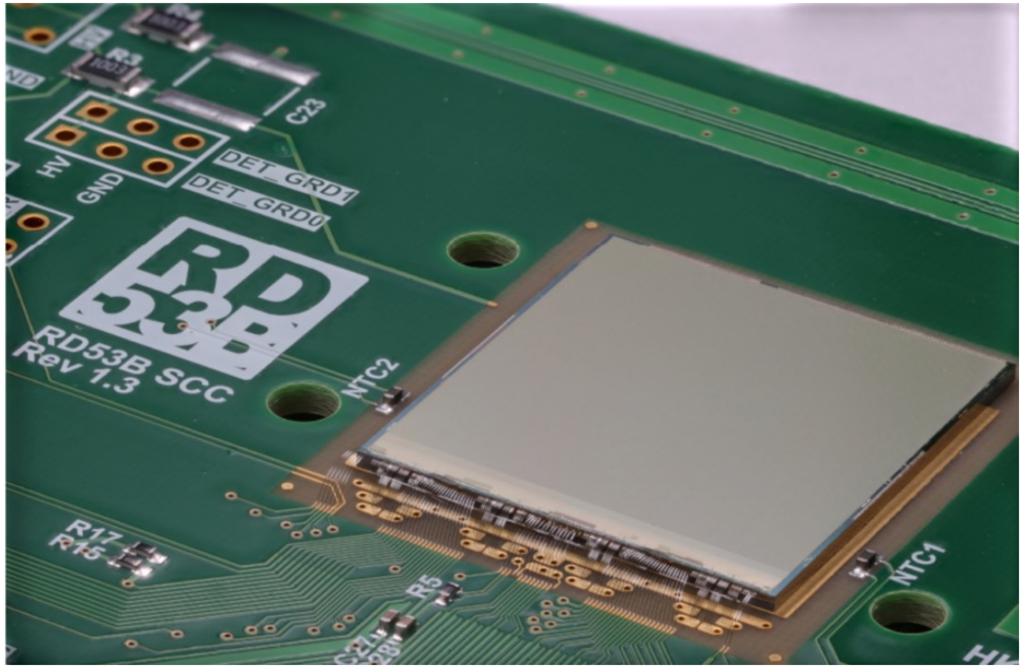
Measurement of current of silicon sensor



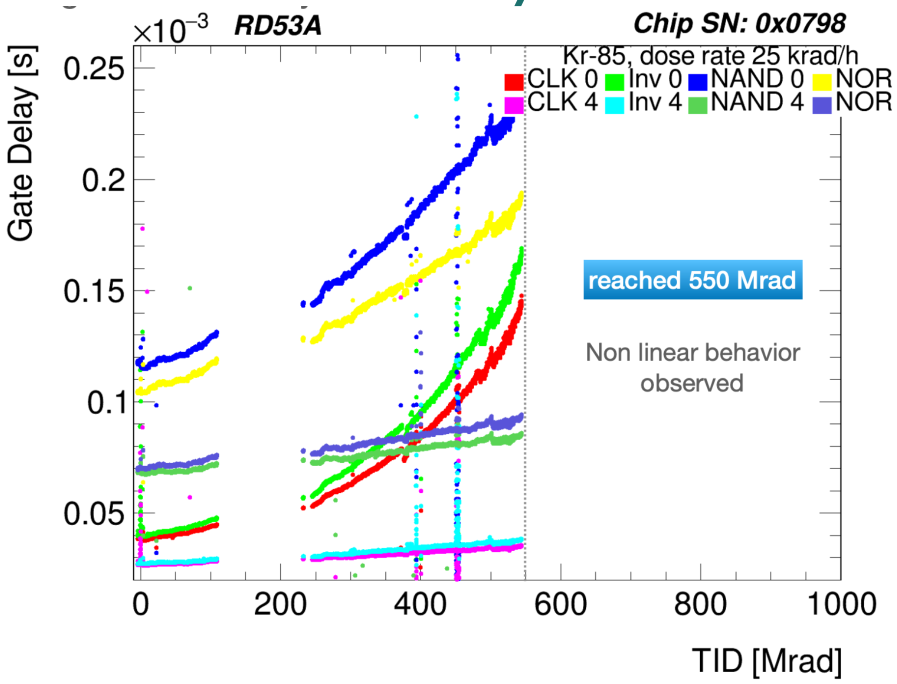
Readout chips

- ITk readout chip designed specifically for ITk upgrade → integrated circuit is designed and validated in simulation
- Need to validate the the chip performs as expected, and **will survive the lifetime in the HL-LHC**
- E.g. Check the delay of logic gates is sufficiently fast to process all of the collision data

ATLAS pixel upgrade readout chip



Gate delay vs dose



Summary

- ATLAS experiment at the LHC analyses proton collisions to probe the Standard Model and search for new physics

- Decay products of collisions are reconstructed with detectors that measure the momentum and energy of particles

→ e.g. tracking detectors determine momentum of charged particles

- Tracking detectors are made of silicon and consist of active area (sensor) and readout chip, connected by bump bonds

- Berkeley Lab is heavily involved in construction and testing of pixel detector modules for the ATLAS upgrade for High-Luminosity LHC

Thank you!

Any questions?