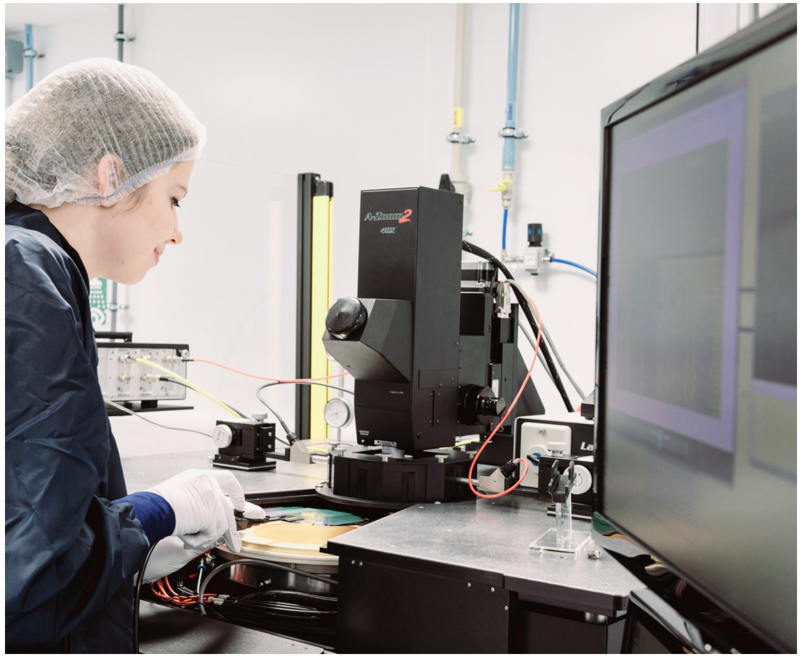
# Discovering the Invisible:
# Pixel Detectors In Particle Physics

Maria Mironova (LBNL)
QuarkNet workshop
Thursday, July 11, 2024

# About me

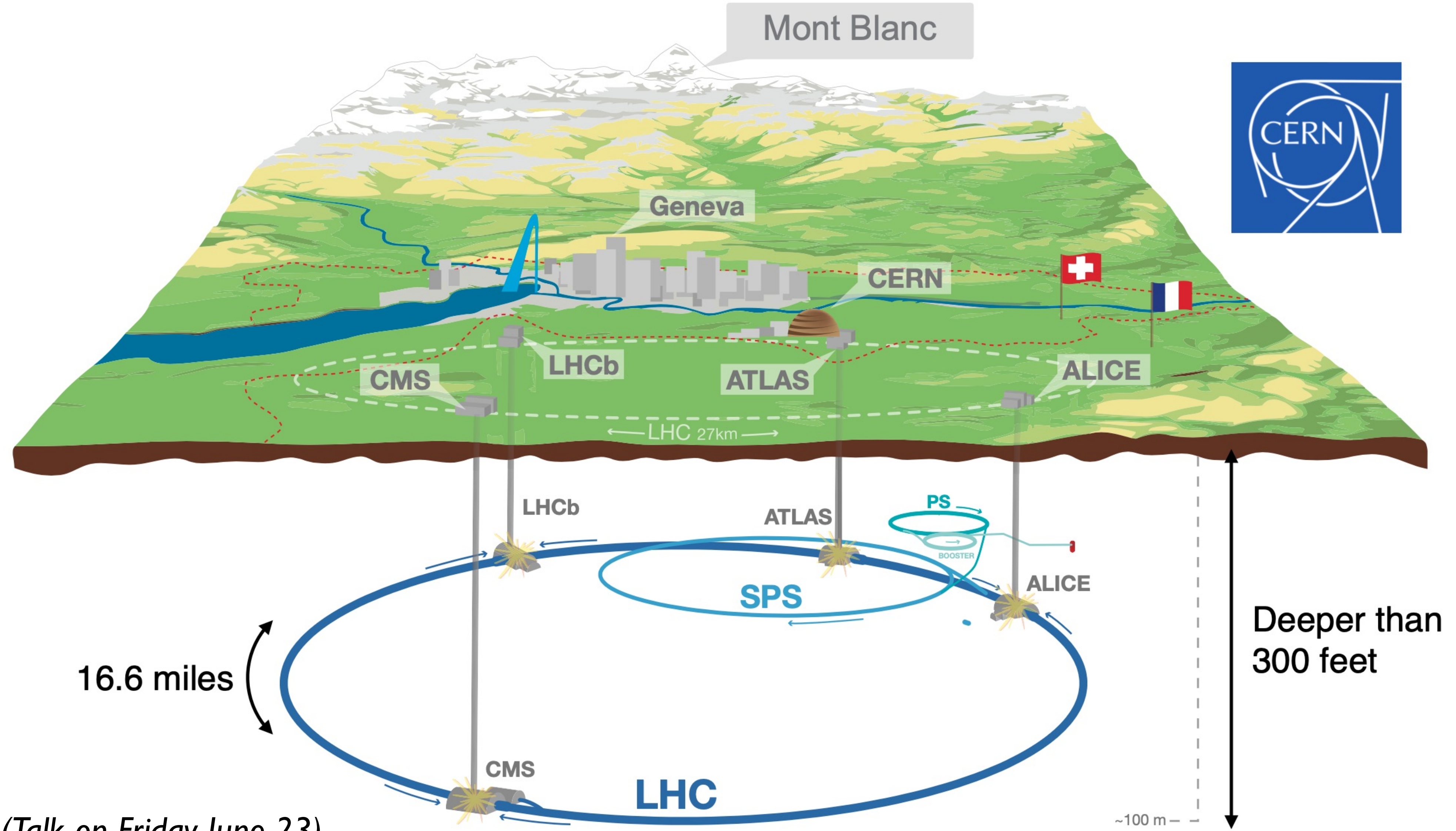
- Moved around Europe for my studies at University (between 2014 and 2022):
  - Bachelor: University of Göttingen (Germany) & University of Cambridge (UK)
  - Masters: Imperial College London (UK)
  - PhD: University of Oxford (UK)
- PhD in particle physics, using data collected by the ATLAS experiment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

# About me (now)

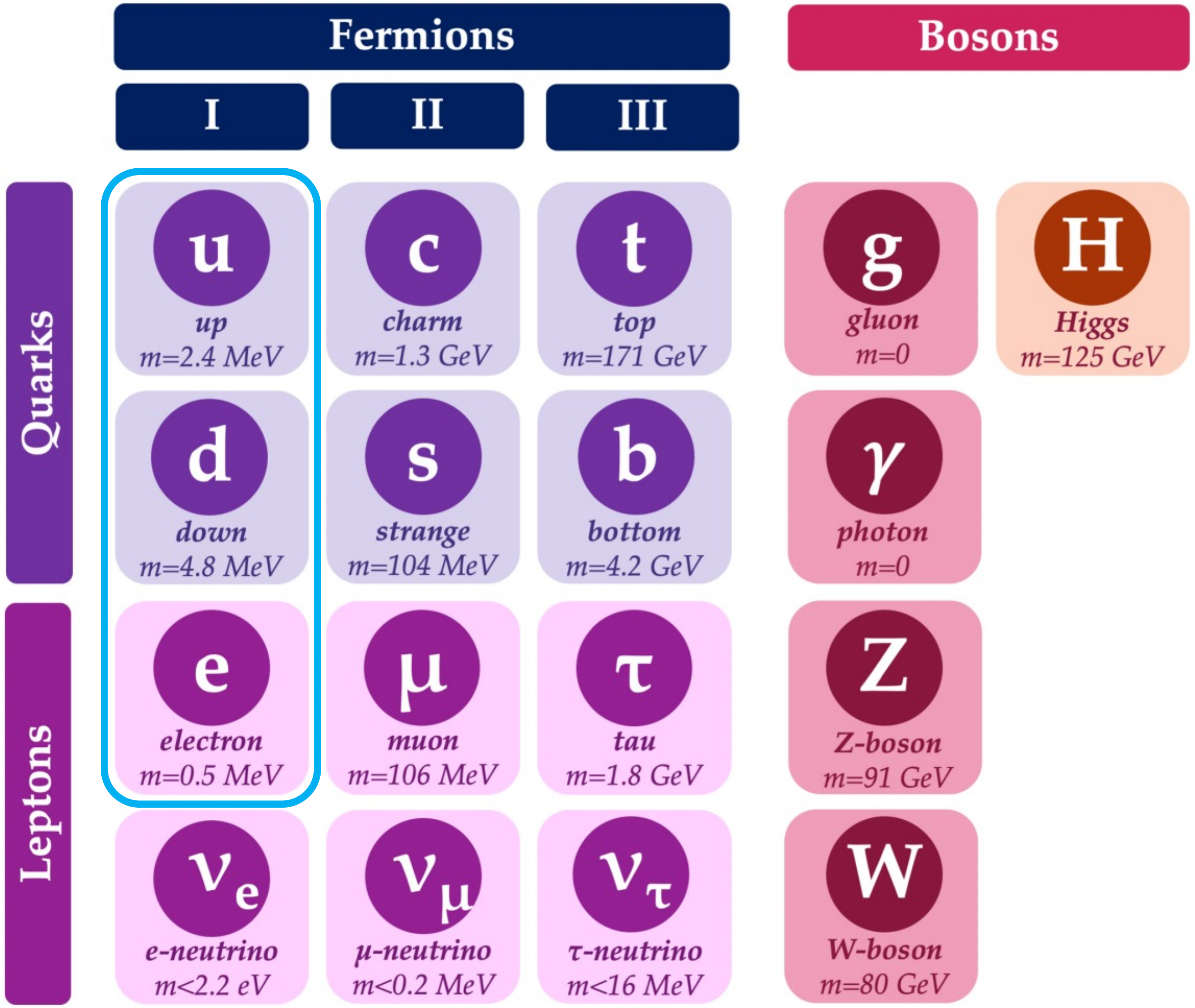
- Now working at Lawrence Berkeley National Laboratory as a Chamberlain Postdoctoral Fellow, since September 2022 (started based at CERN, now in Berkeley since January)
- Part of the ATLAS group in the physics division → working within the ATLAS collaboration, which is a collaboration of ~3000 international 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



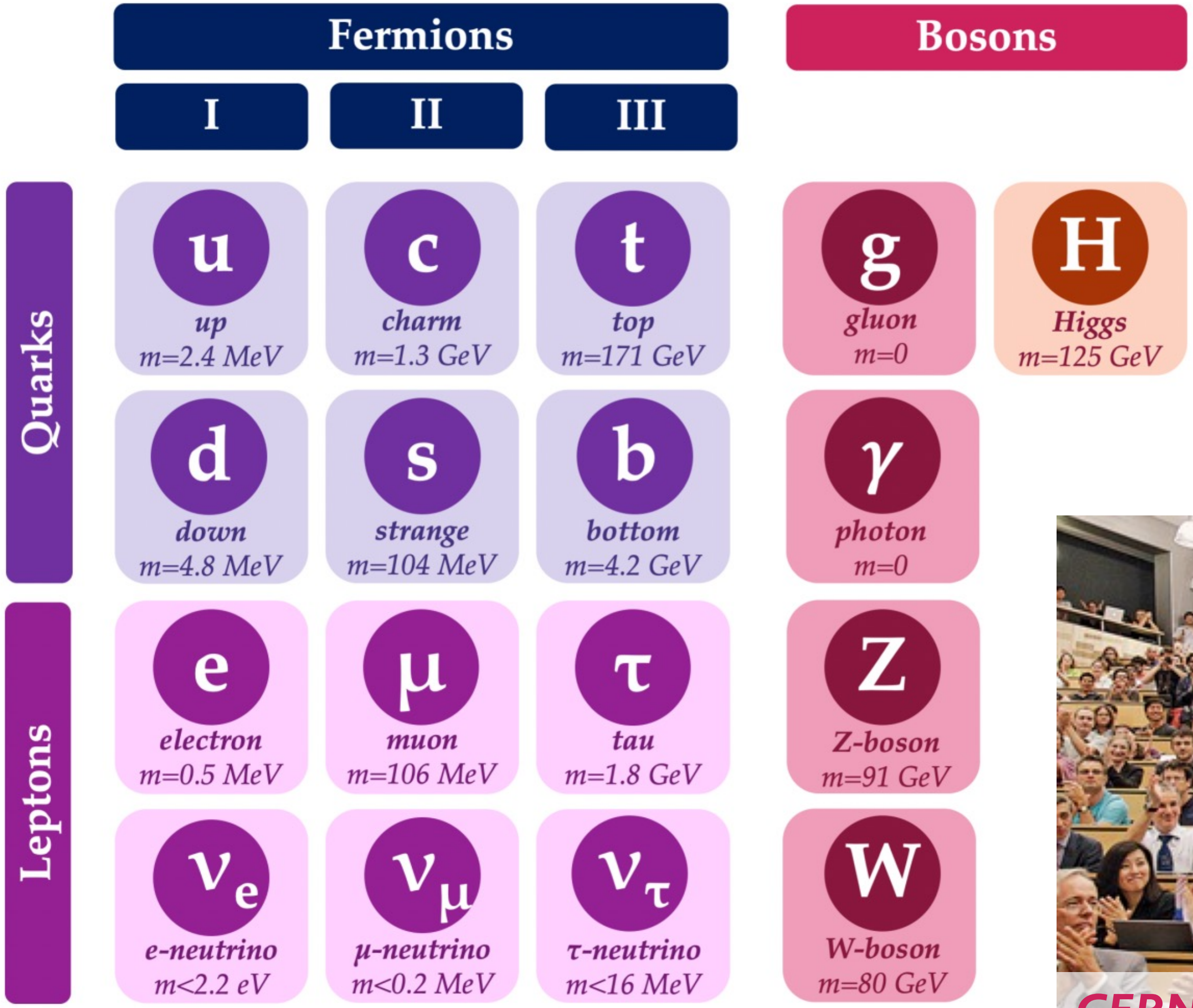

*Slide from Miha (Talk on Friday June 23)*

# 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 2$^{nd}$ and 3$^{rd}$ generation quarks and leptons decay into they 1$^{st}$ 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



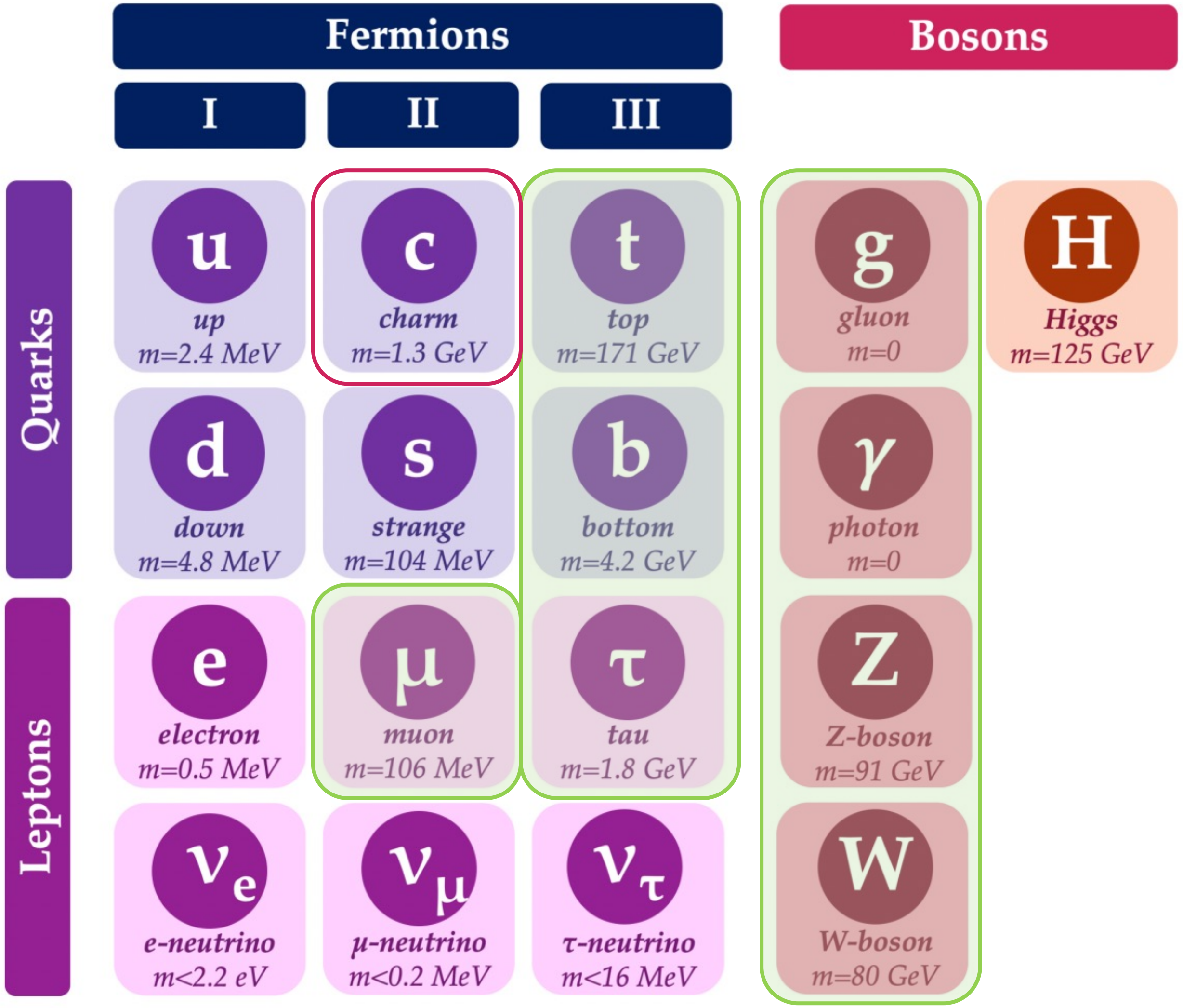

- Last part of the Standard Model: **Higgs boson**
- Higgs mechanism explains how particles in the Standard Model have mass

→ 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

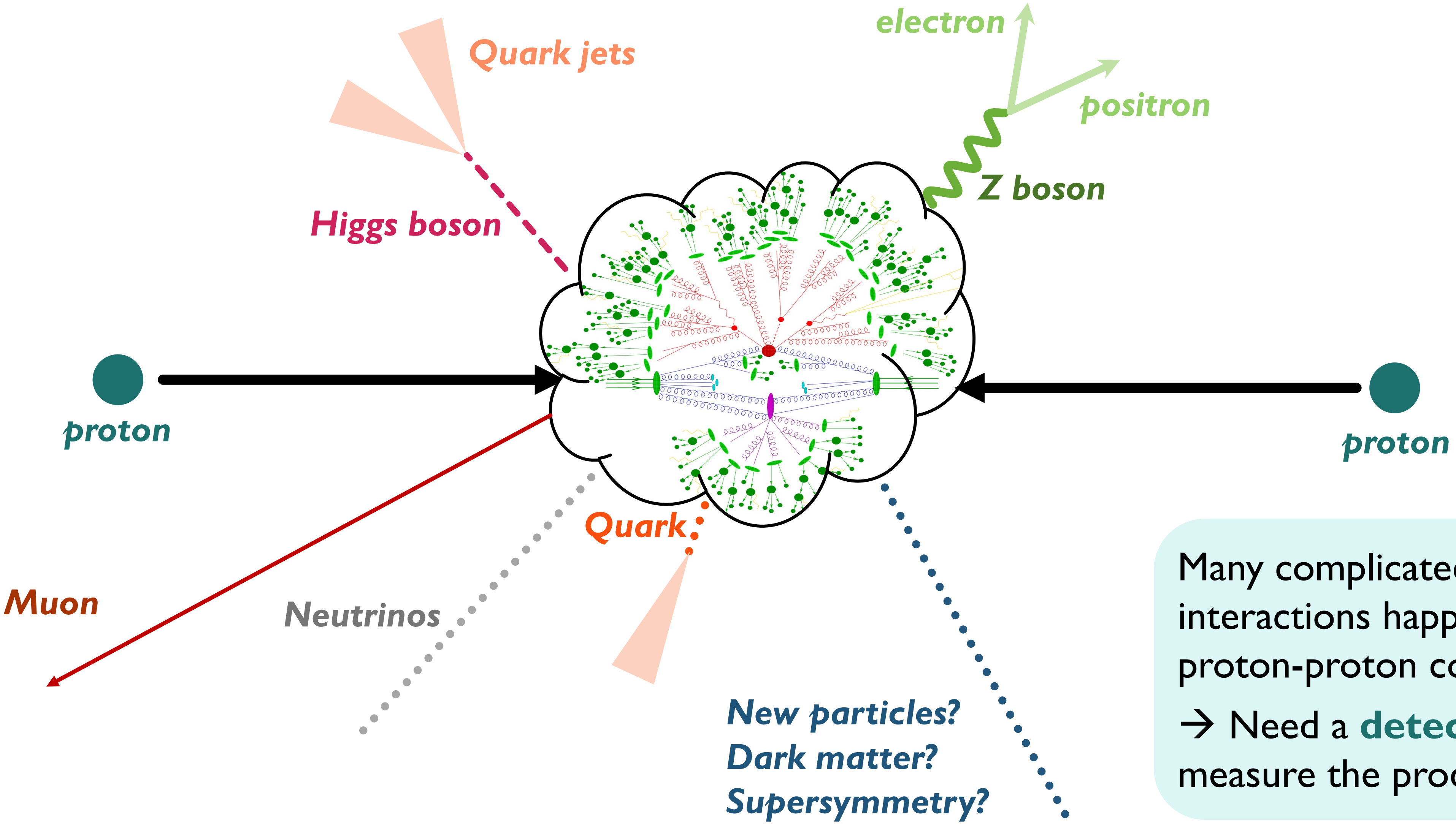
So far, the Standard Model of Particle Physics is an excellent description of what we see in nature

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!**

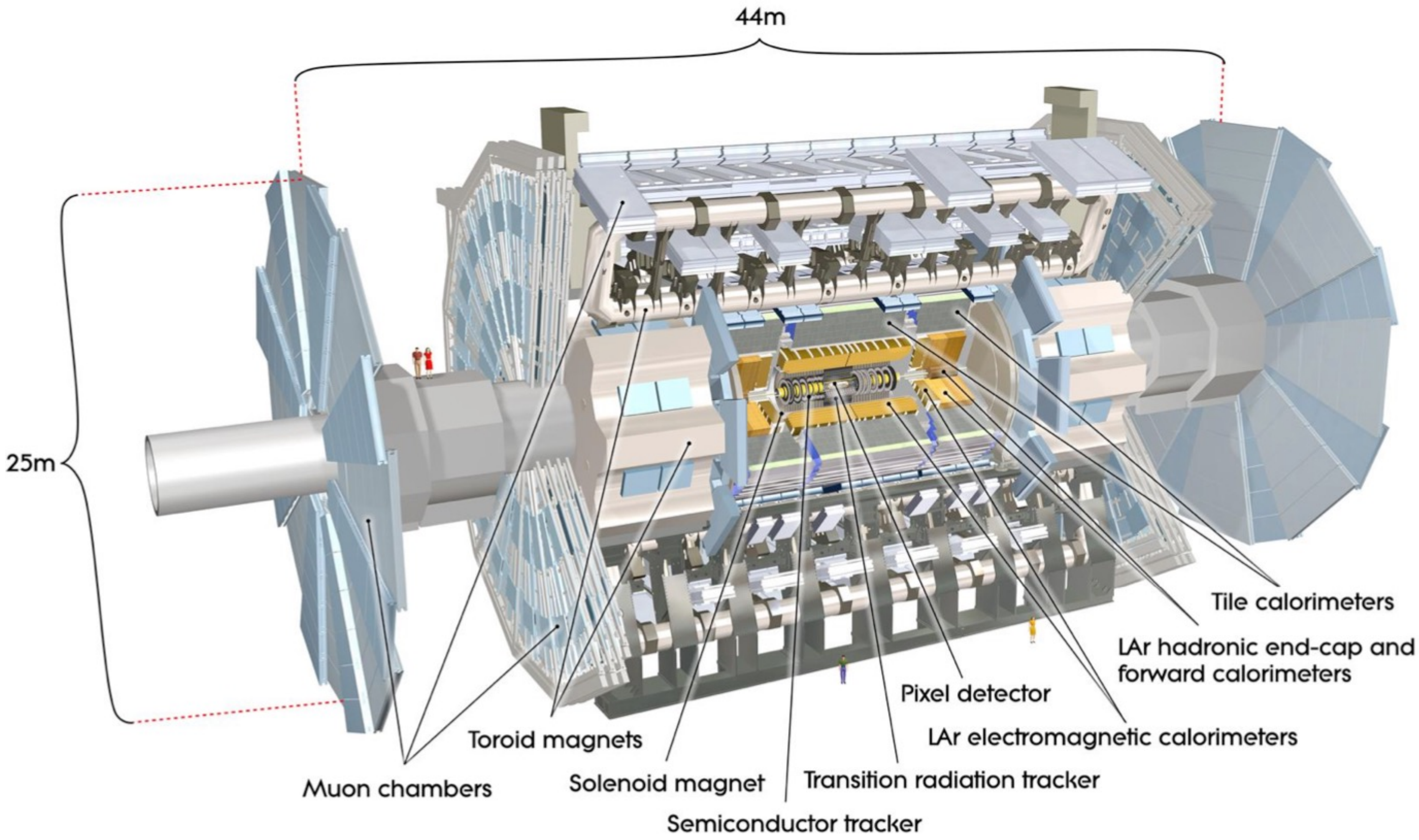
# How do we make measurements?



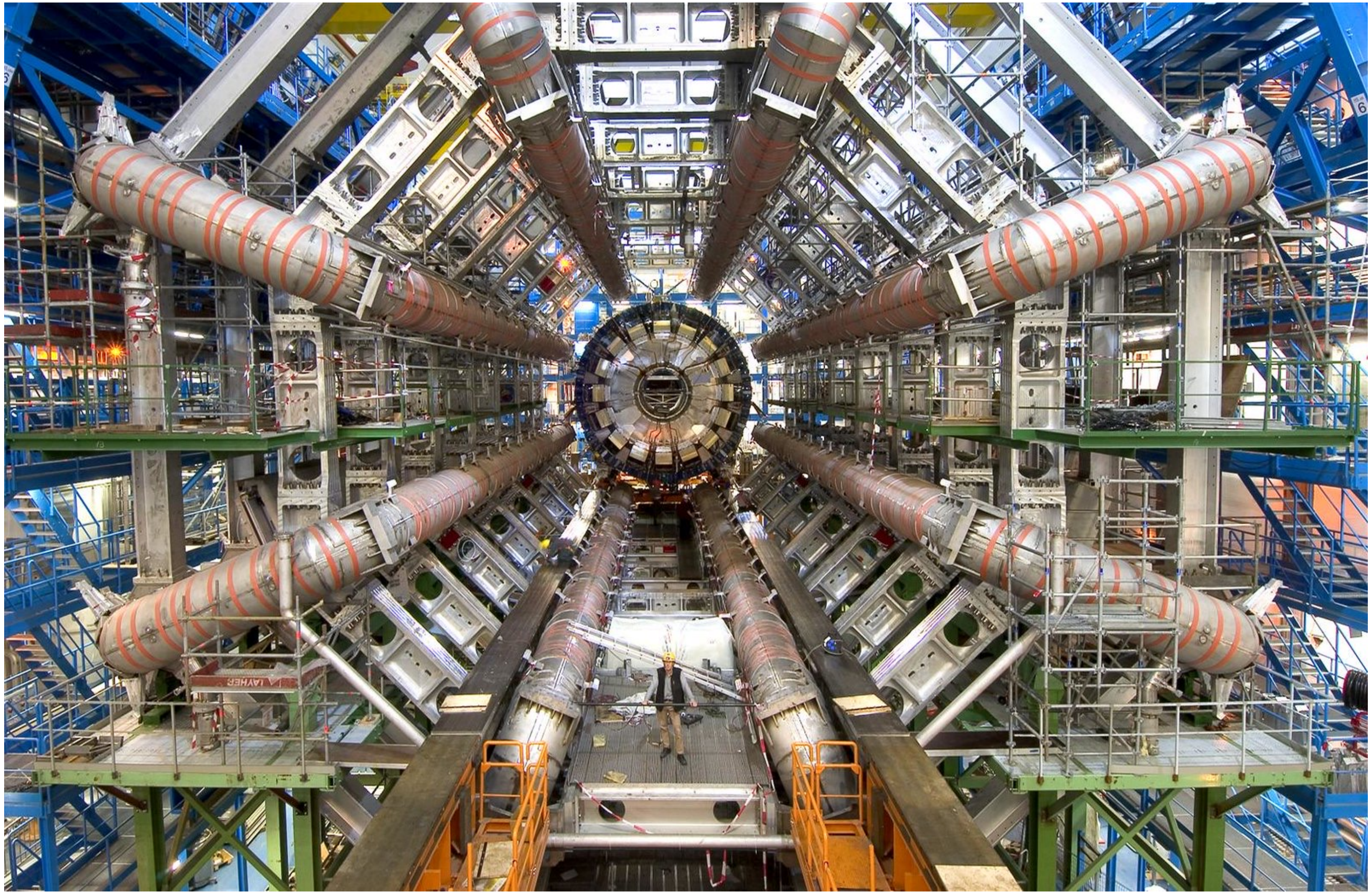

Many complicated interactions happen in proton-proton collision

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

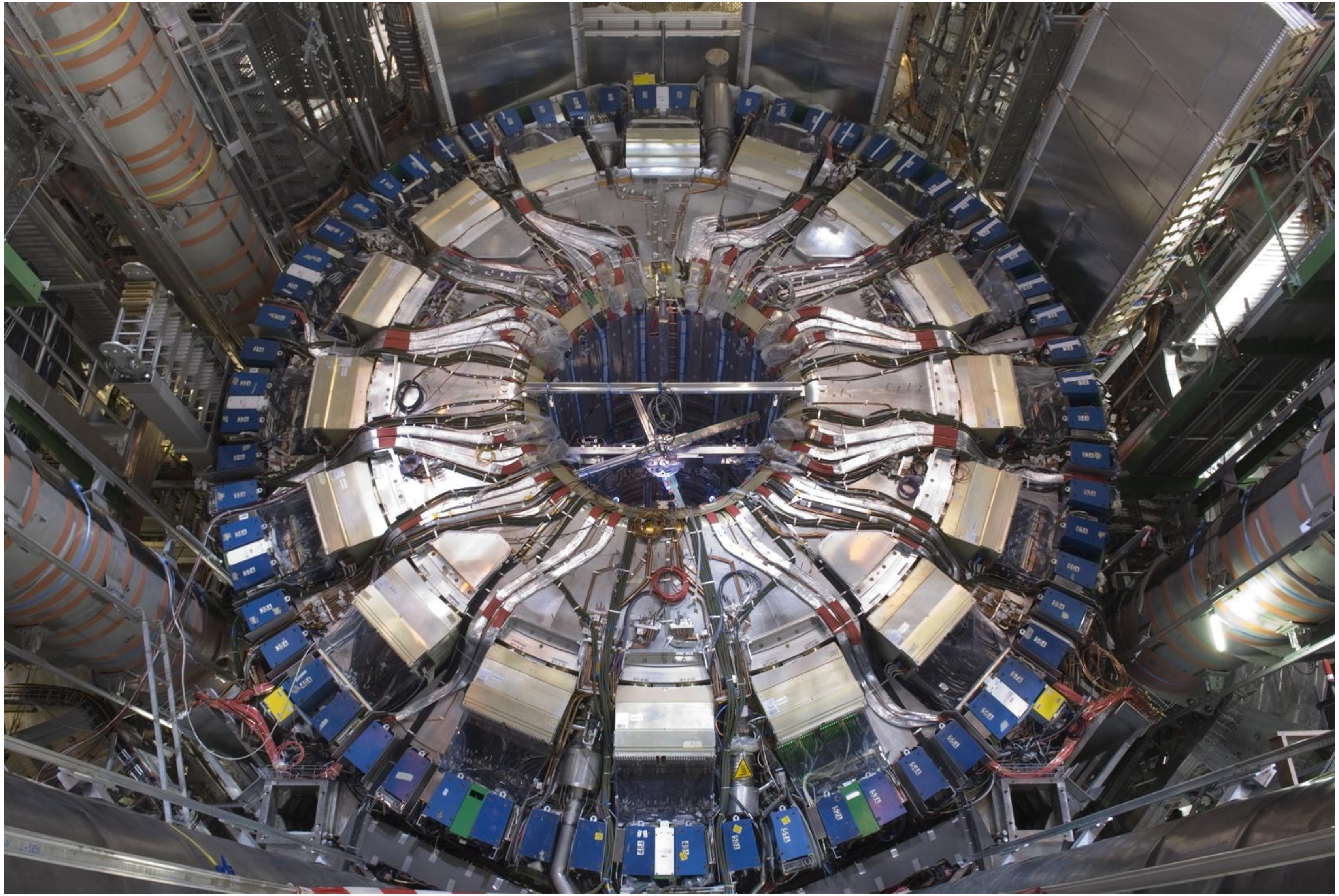
# The ATLAS detector



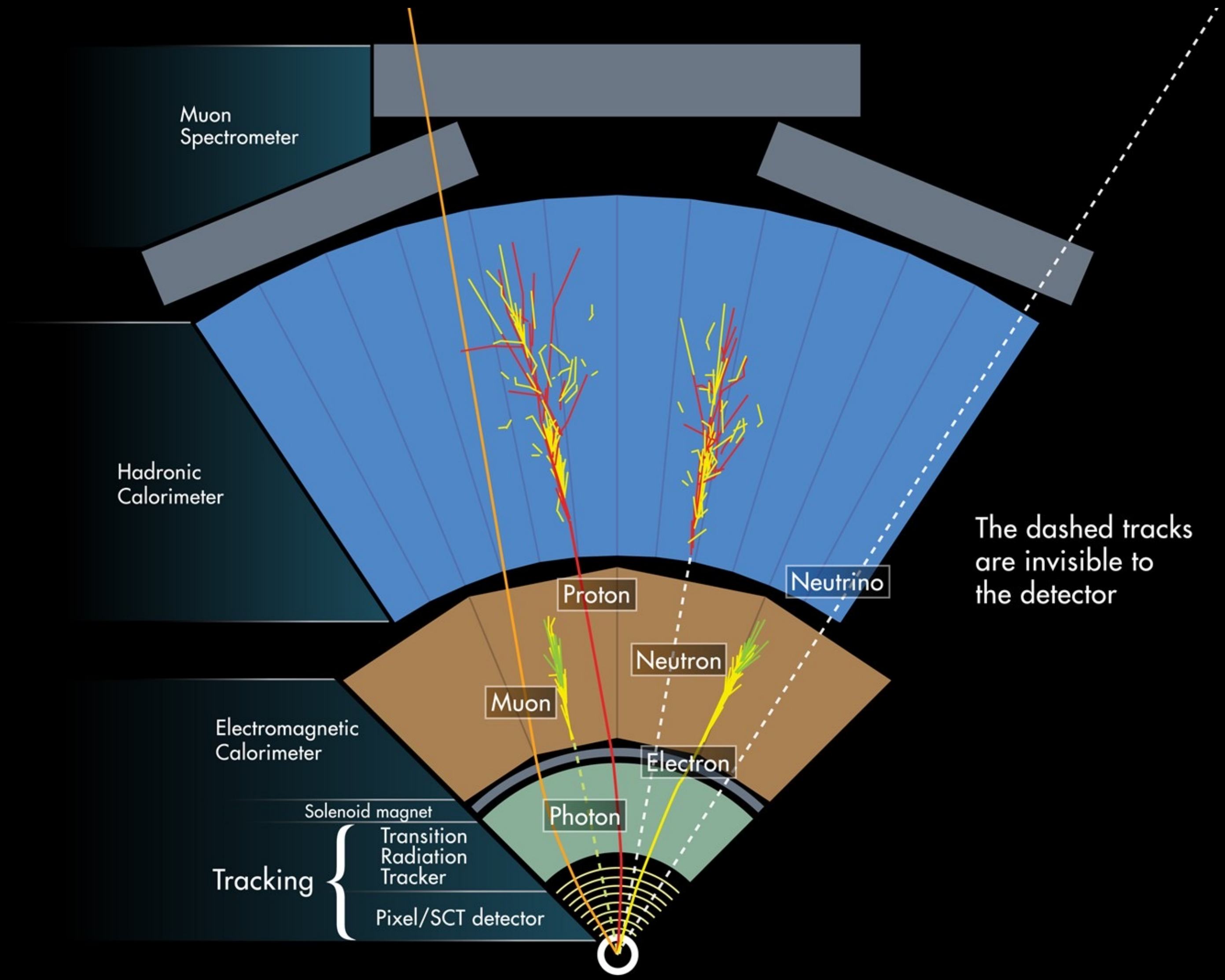
# The ATLAS detector



# The ATLAS detector

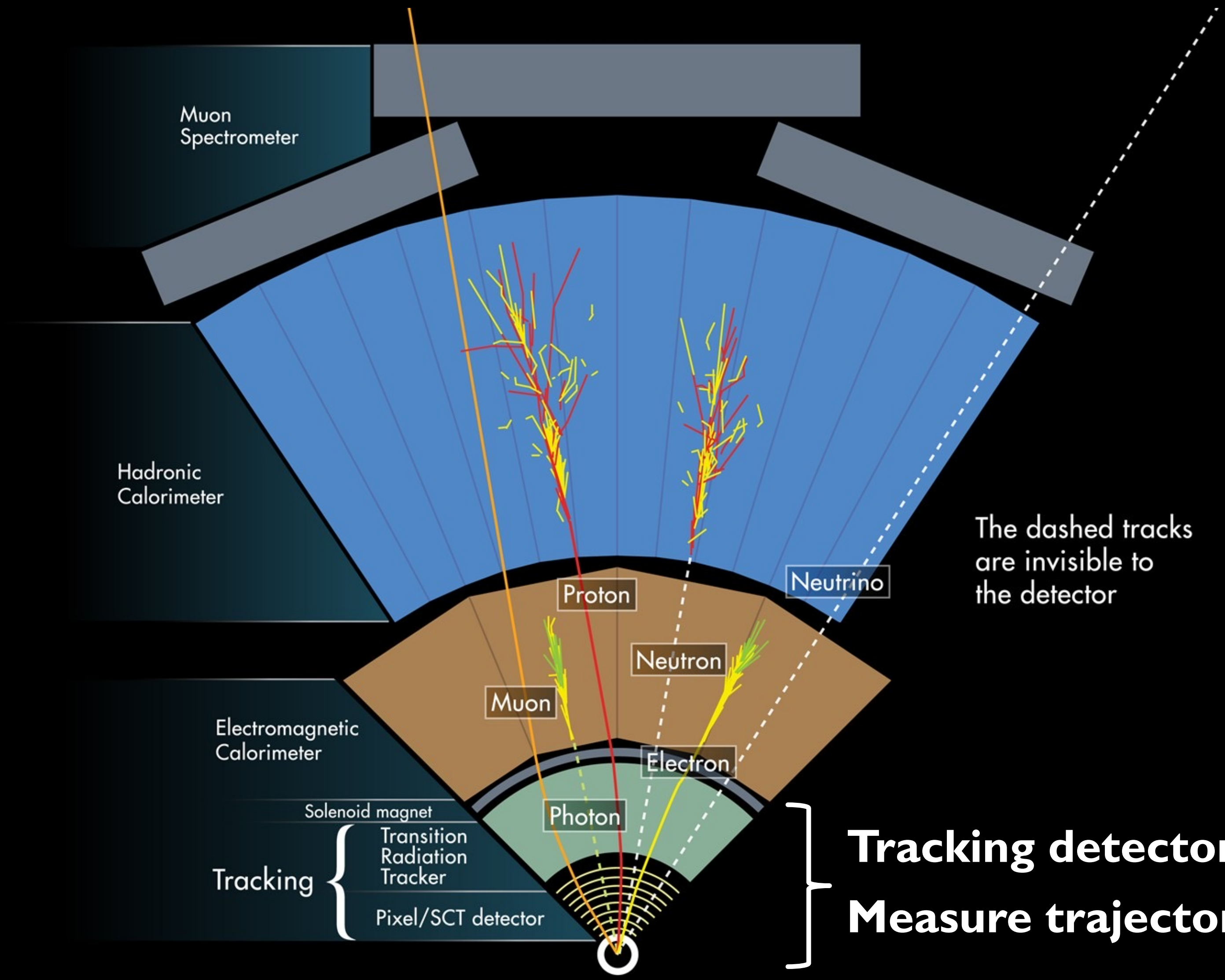


# Particle identification




The dashed tracks are invisible to the detector

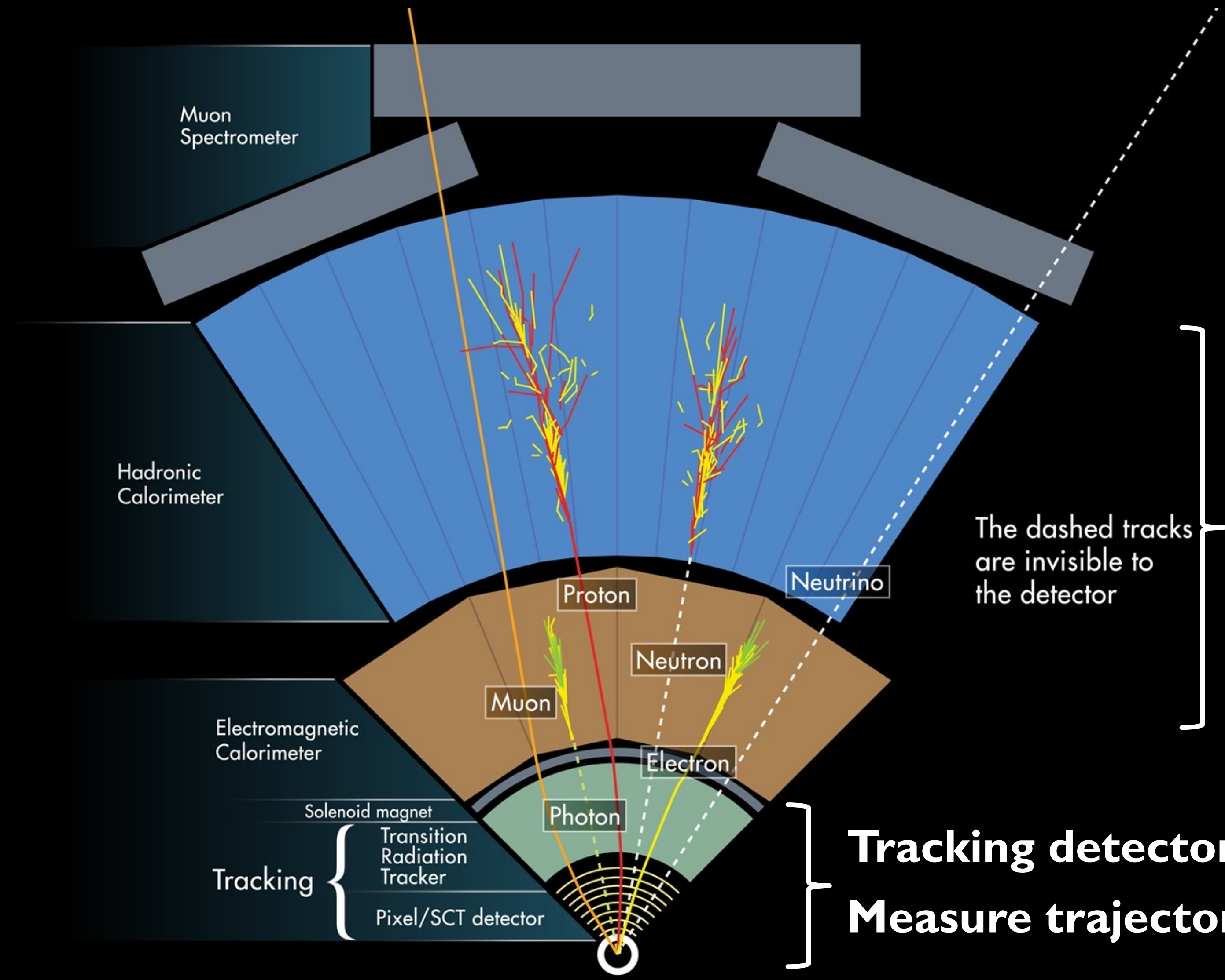
# Particle identification




**Tracking detector:**

**Measure trajectory of charged particles in a magnetic field**

# Particle identification



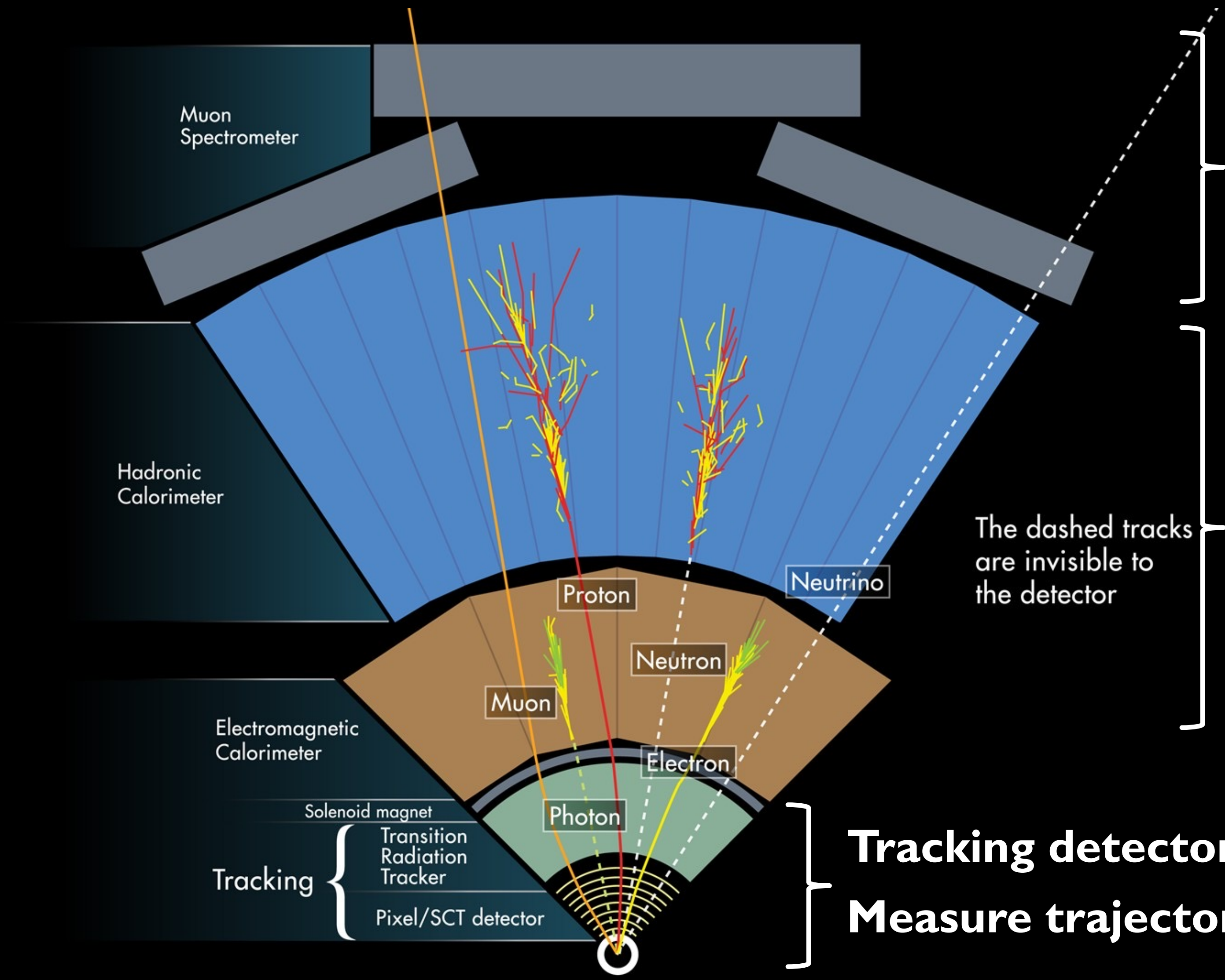

**Electromagnetic and hadronic calorimeter:**

**Measure energy of particles**

**Tracking detector:**

**Measure trajectory of charged particles in a magnetic field**

# Particle identification




**Muon spectrometer:**

**Measure trajectory of muons**

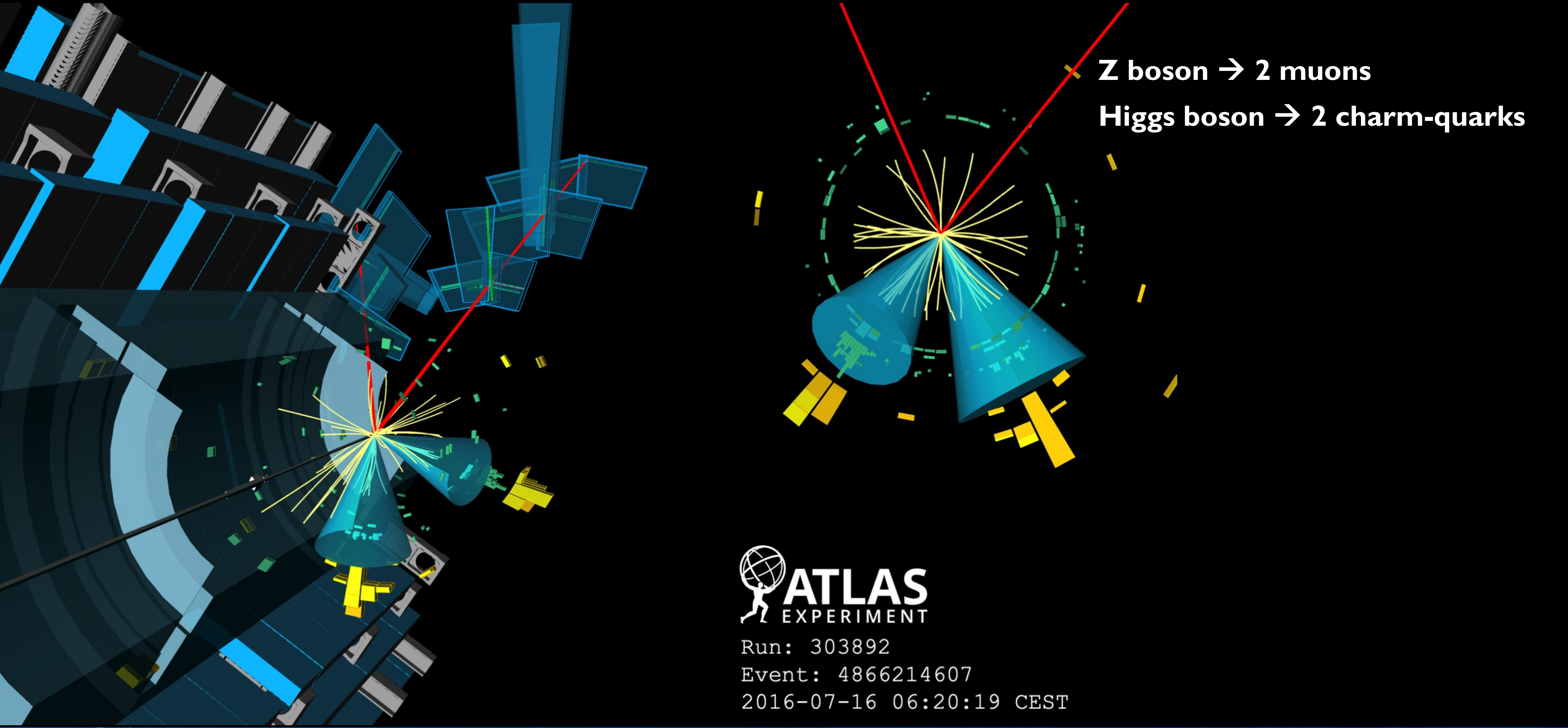
**Electromagnetic and hadronic calorimeter:**

**Measure energy of particles**

**Tracking detector:**

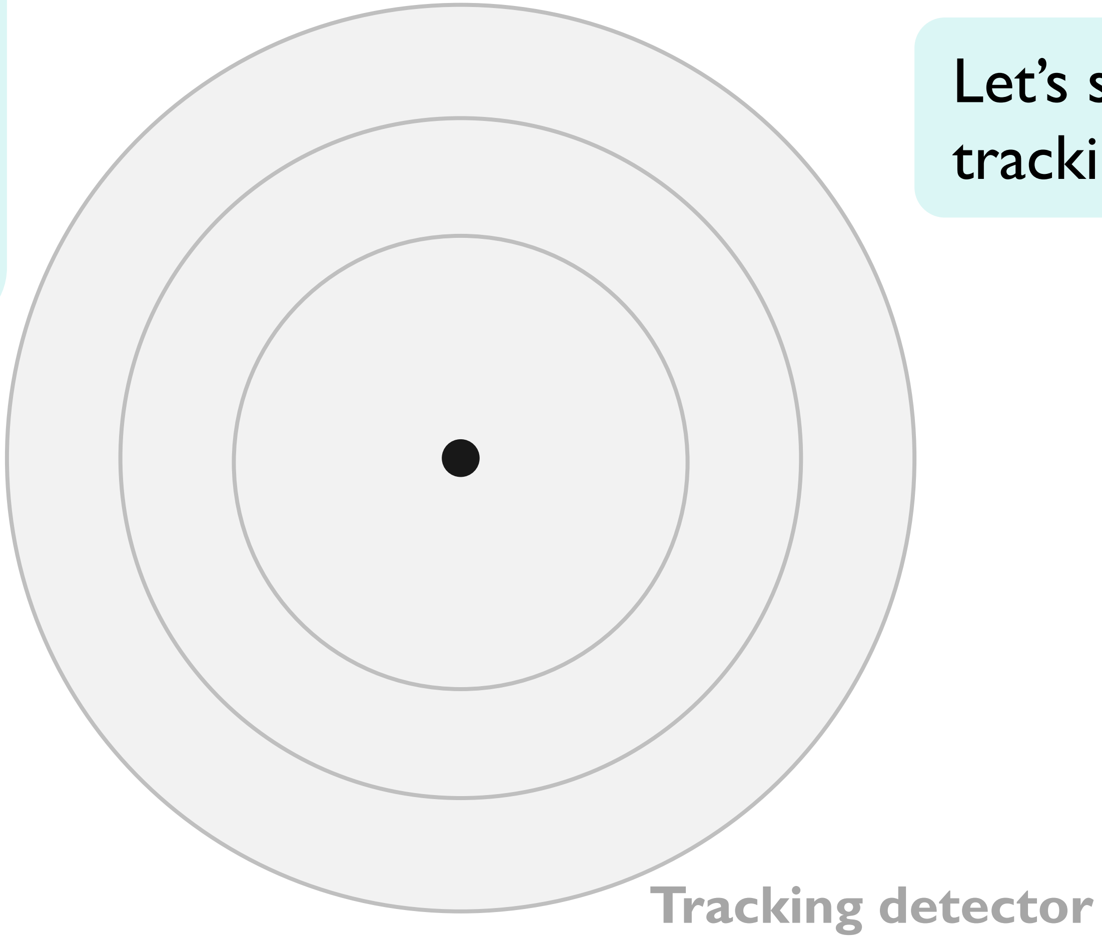
**Measure trajectory of charged particles in a magnetic field**

# Example of a real event



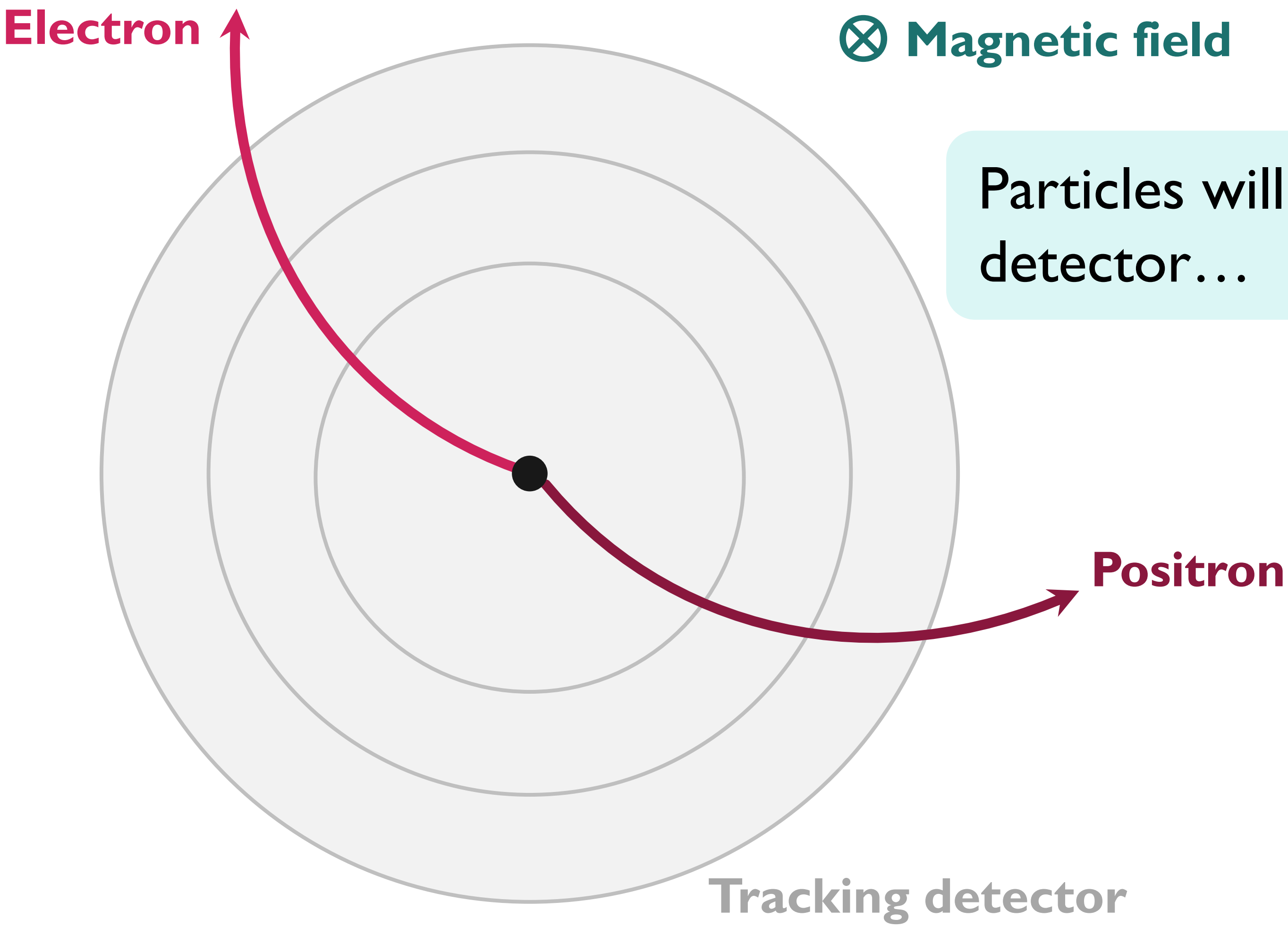
# Tracking

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



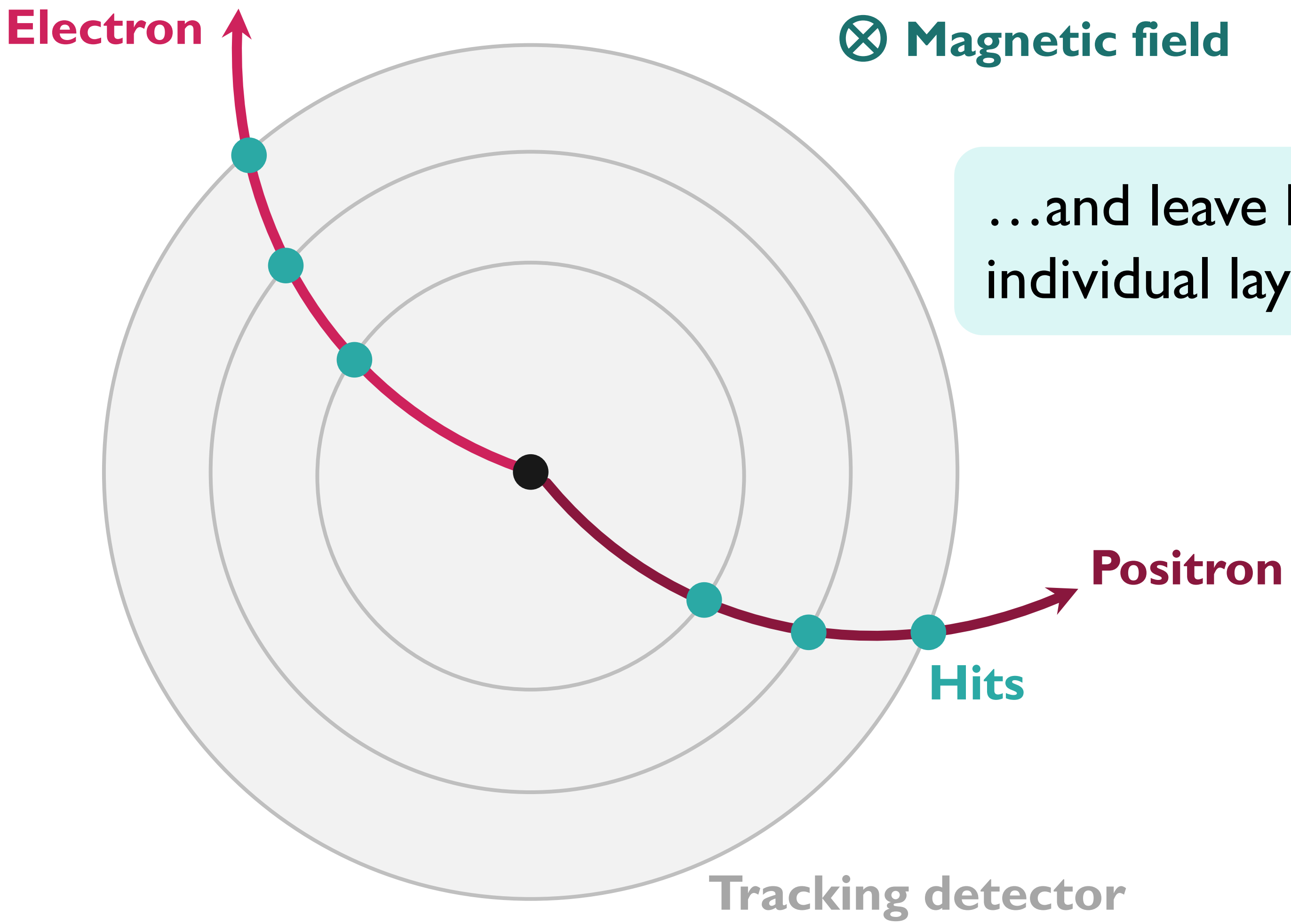

Let's start with our empty tracking detector

# 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?**

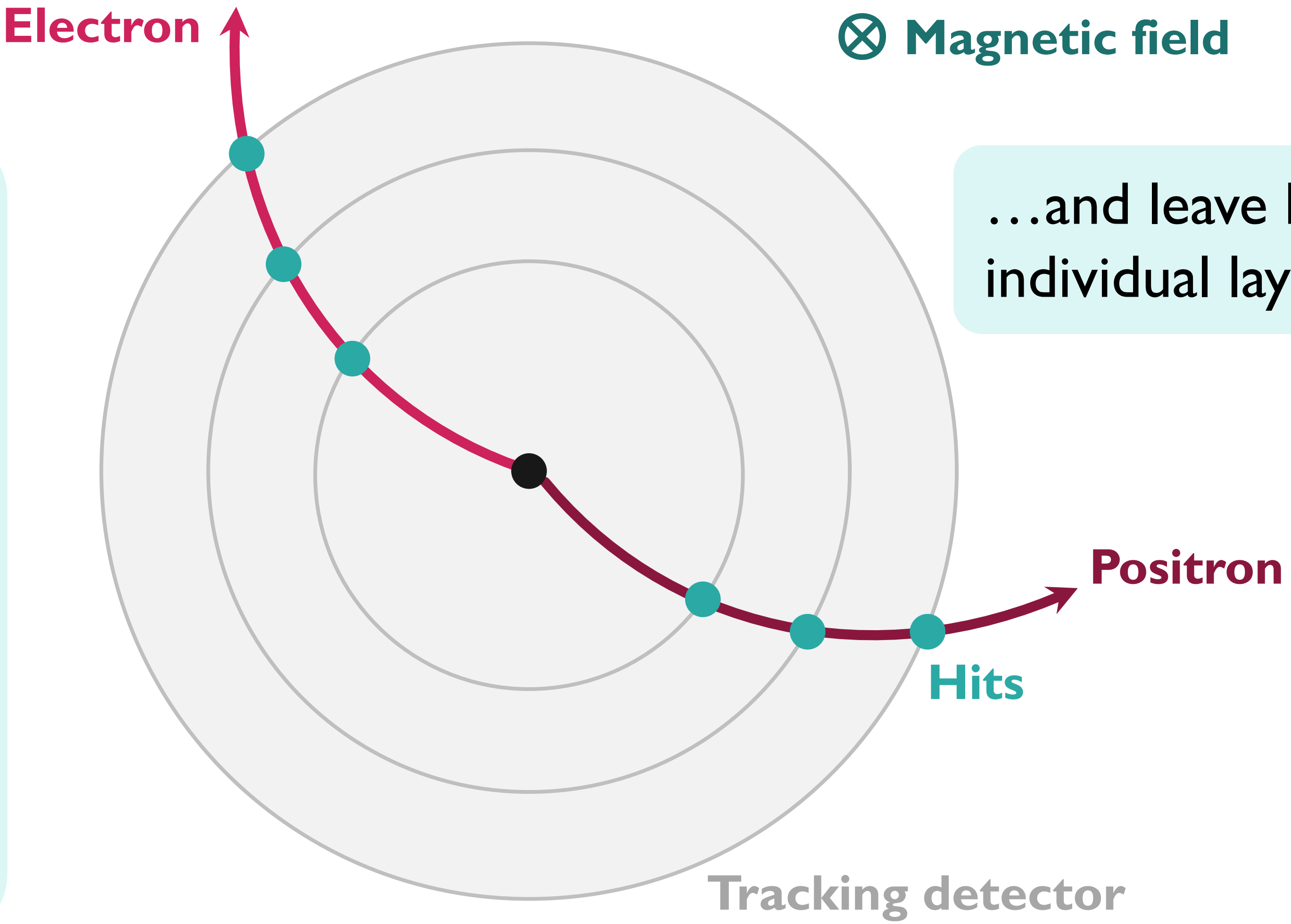
→ Charged particles bend in a magnetic field

**What does the curvature of the track depend on?**

→ Magnetic field

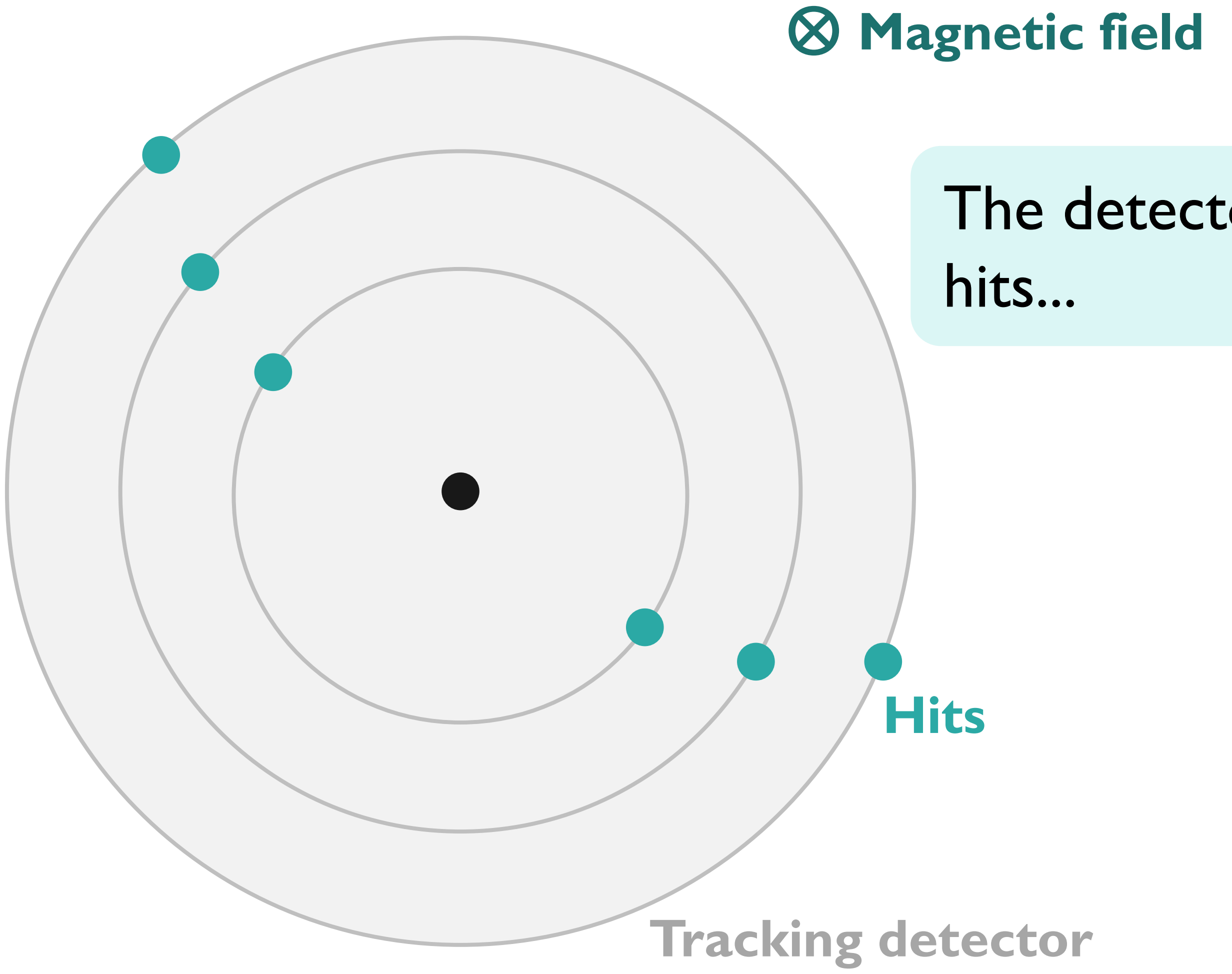
→ charge of the particle,

→ momentum/speed of the particle



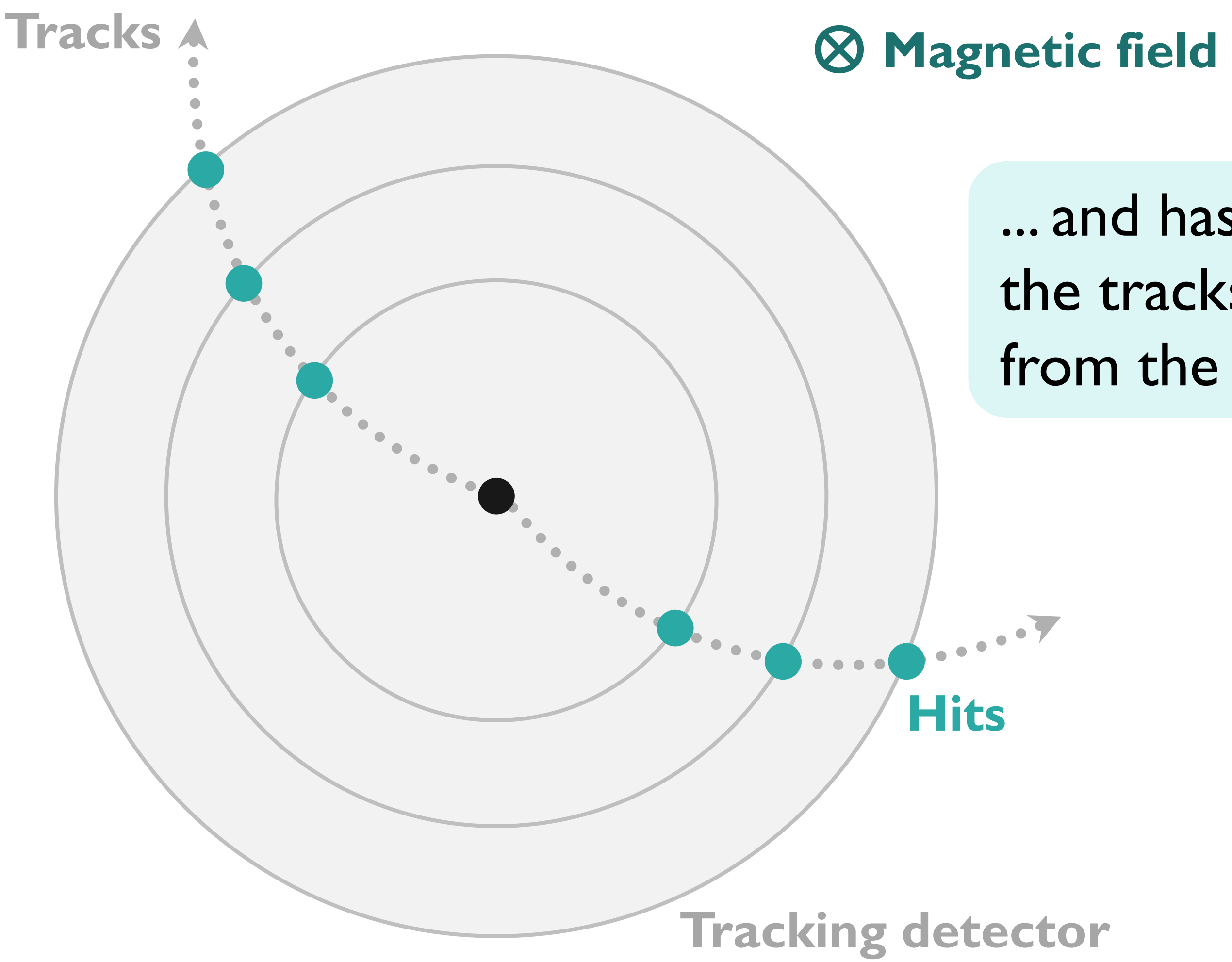

…and leave hits in the individual layers

# Tracking




The detector only sees the hits...

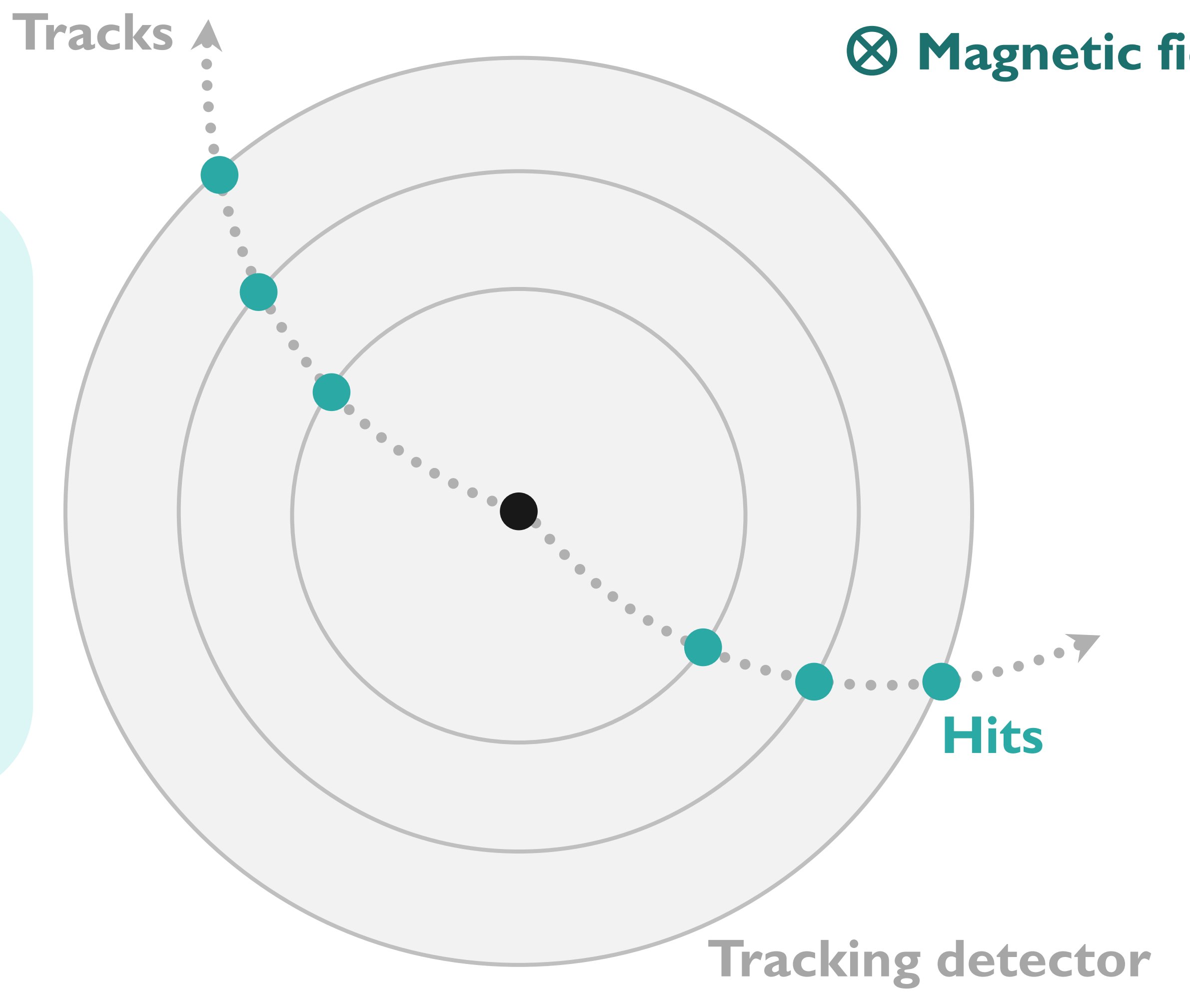
# Tracking




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

# Tracking

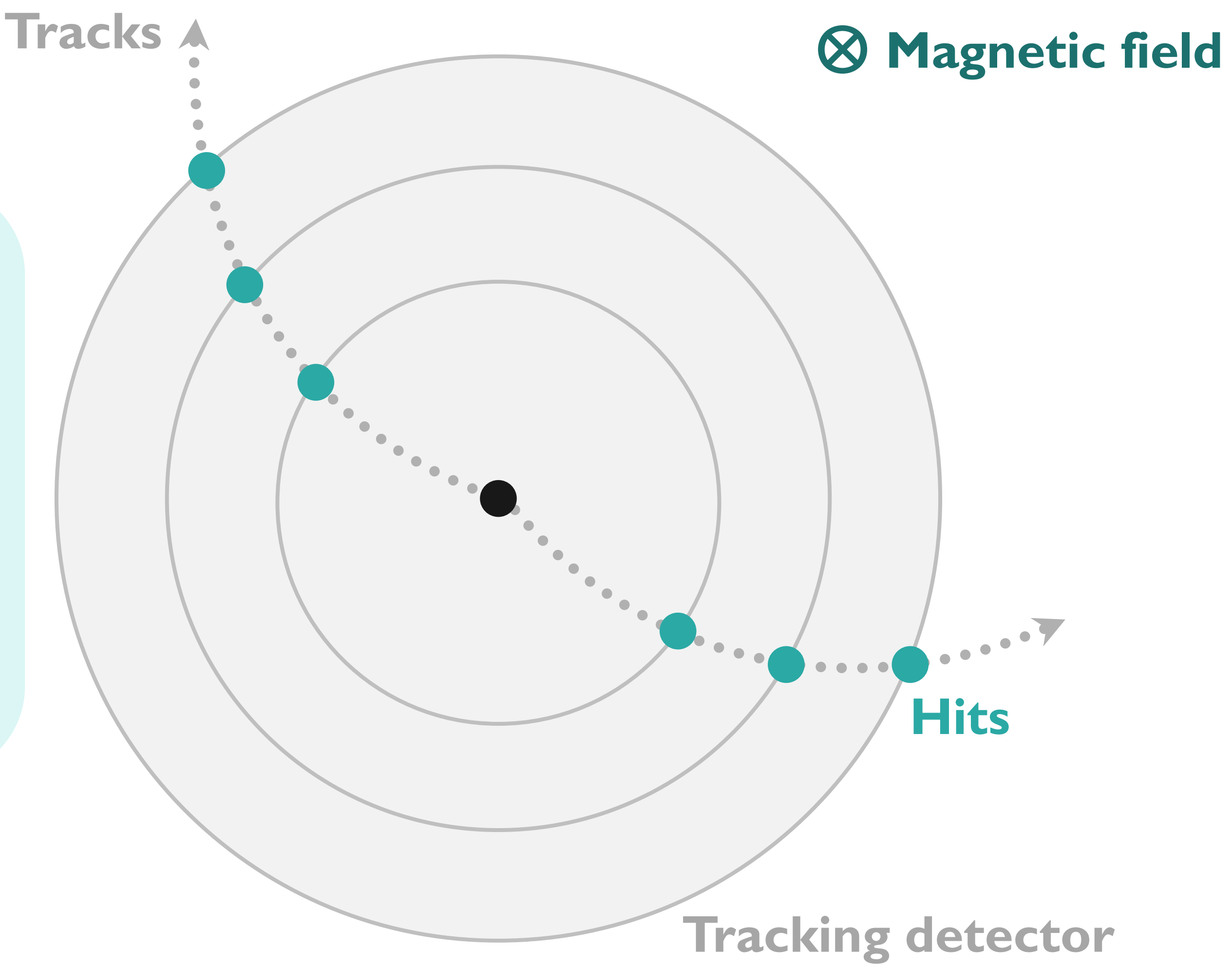
Tracking detector purposes



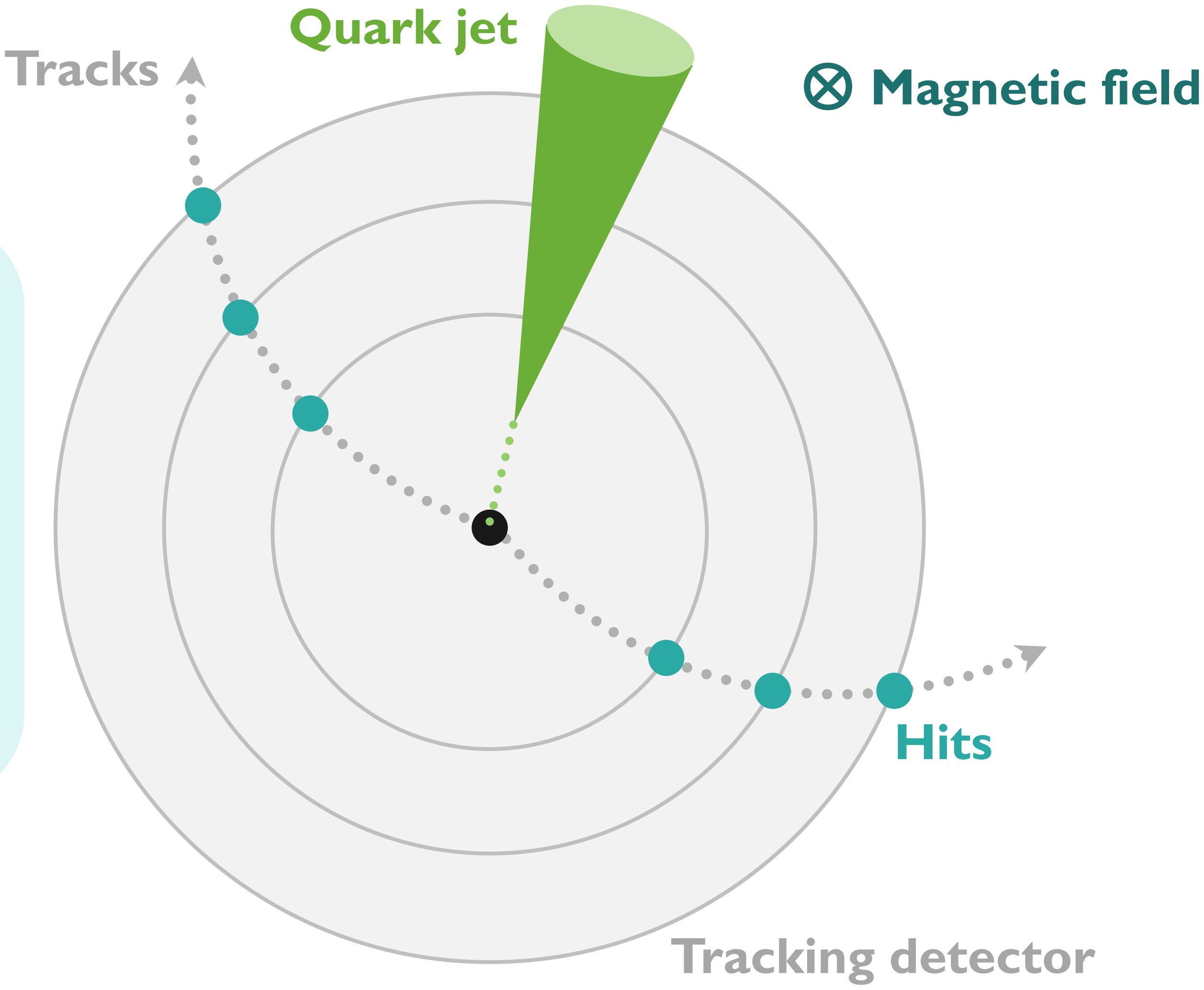
# Tracking

**Tracking detector purposes**

1. Measure tracks of particles to determine momentum



# Tracking



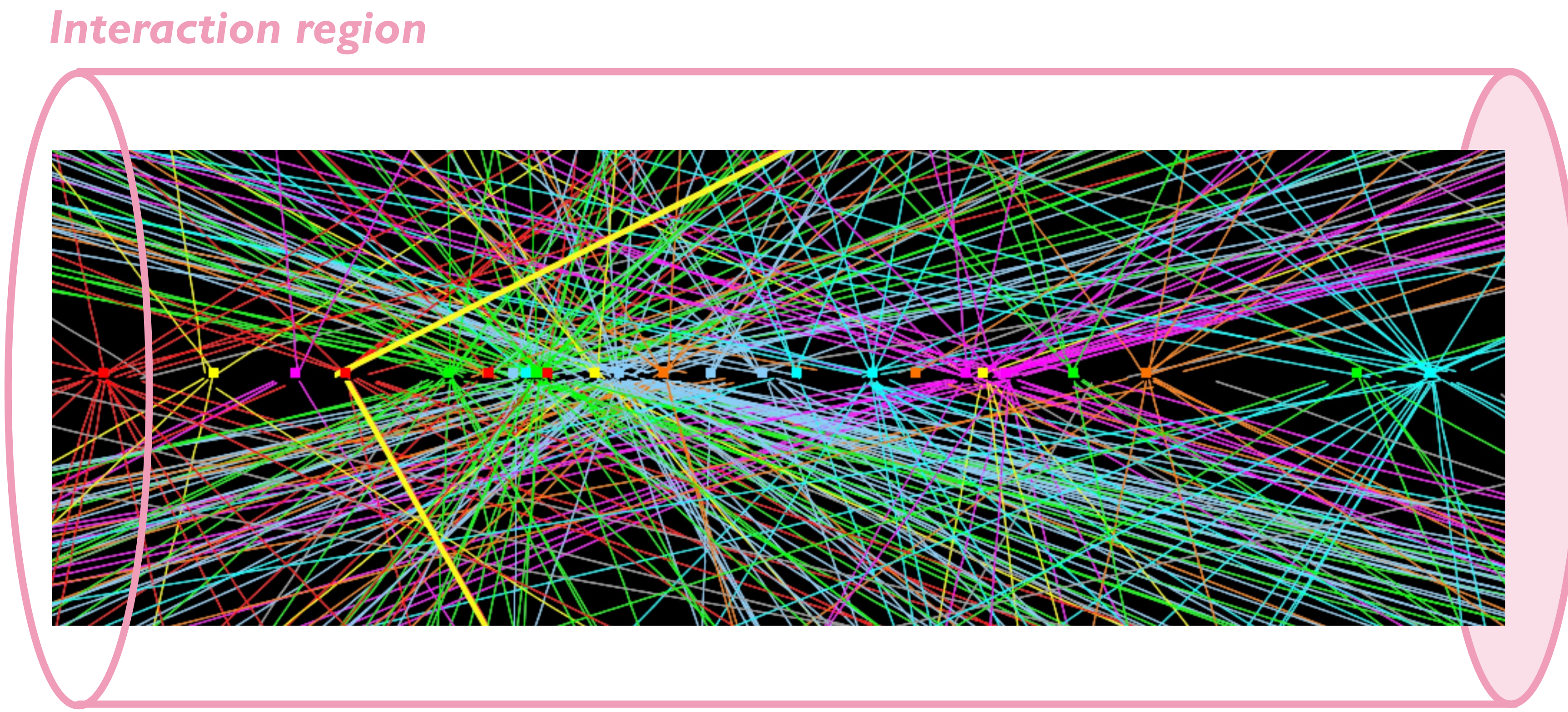

### Tracking detector purposes

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

# Tracking

**Tracking detector purposes**

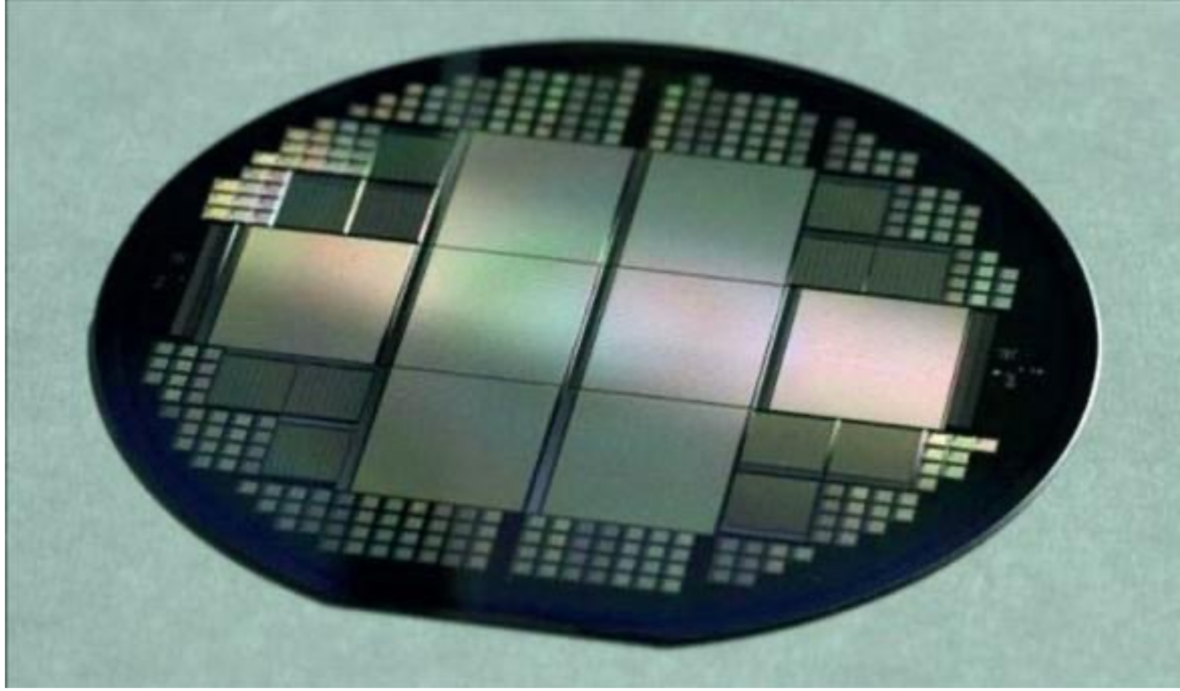
1. Measure tracks of particles to determine momentum
2. Measure "secondary vertices"
3. Distinguish multiple interactions in one event

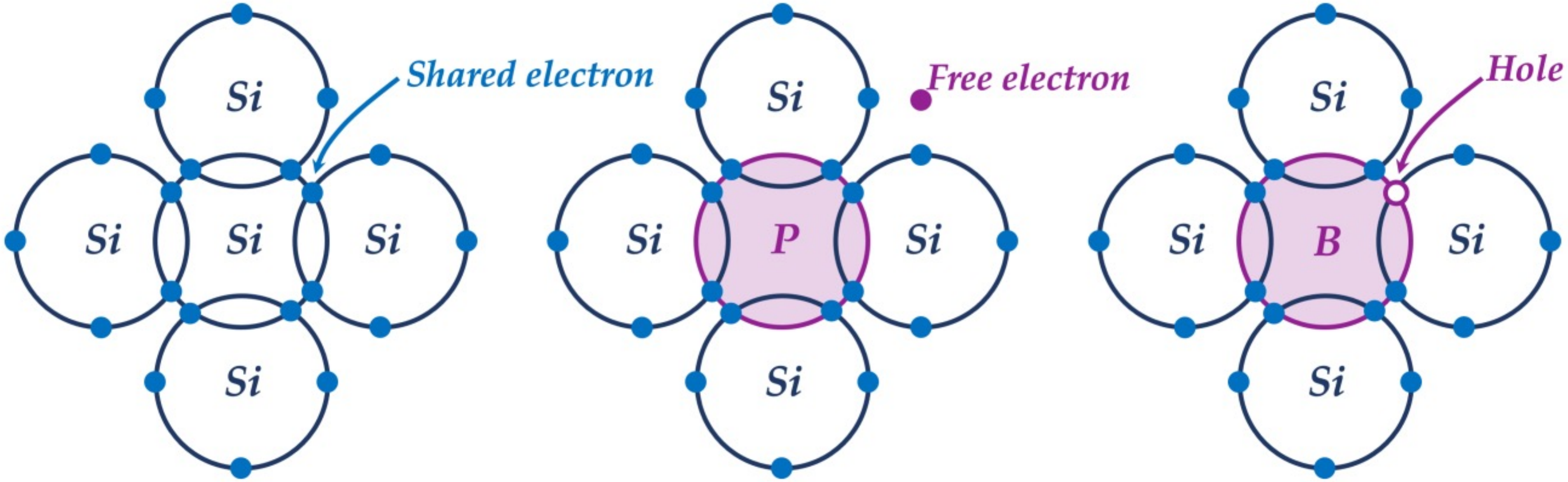


# Questions?

# 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

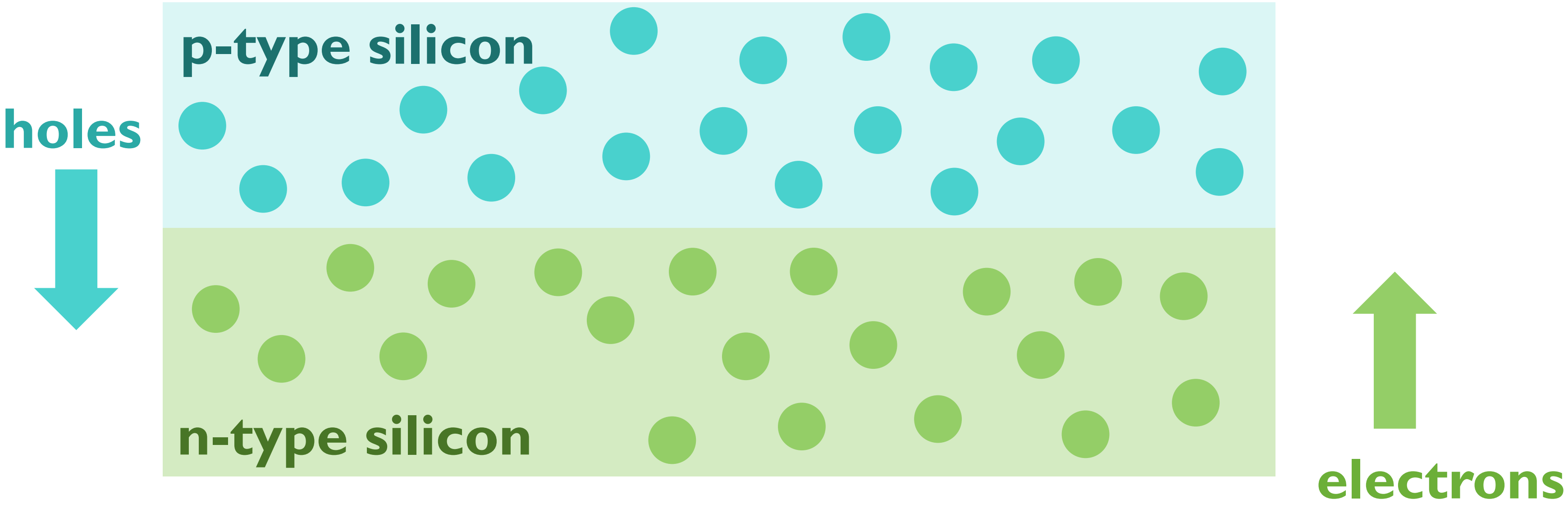





***Electronic structure of pure and doped silicon***

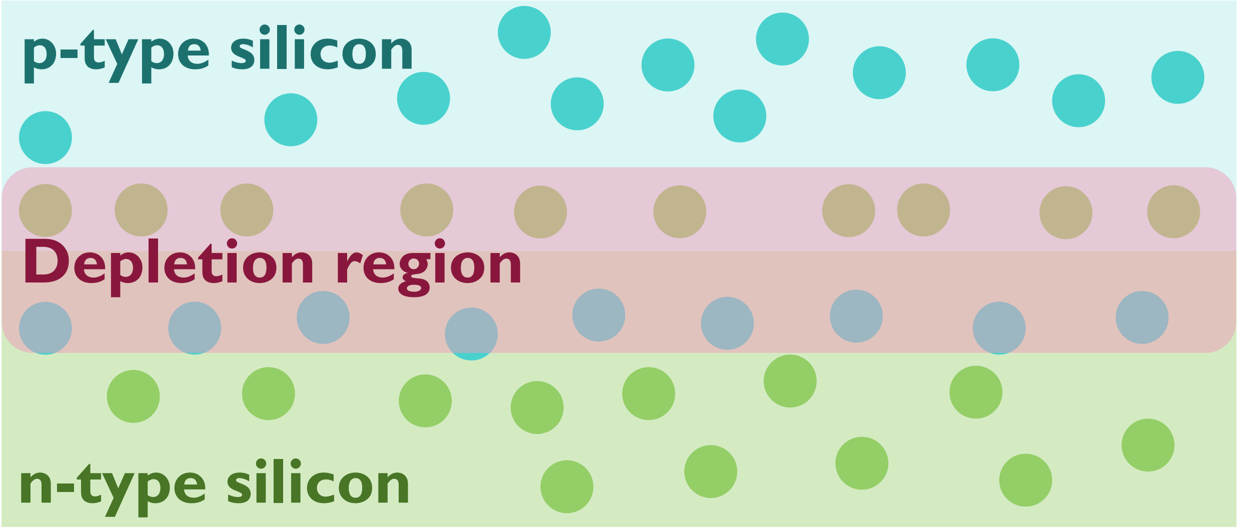
# Silicon detectors

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



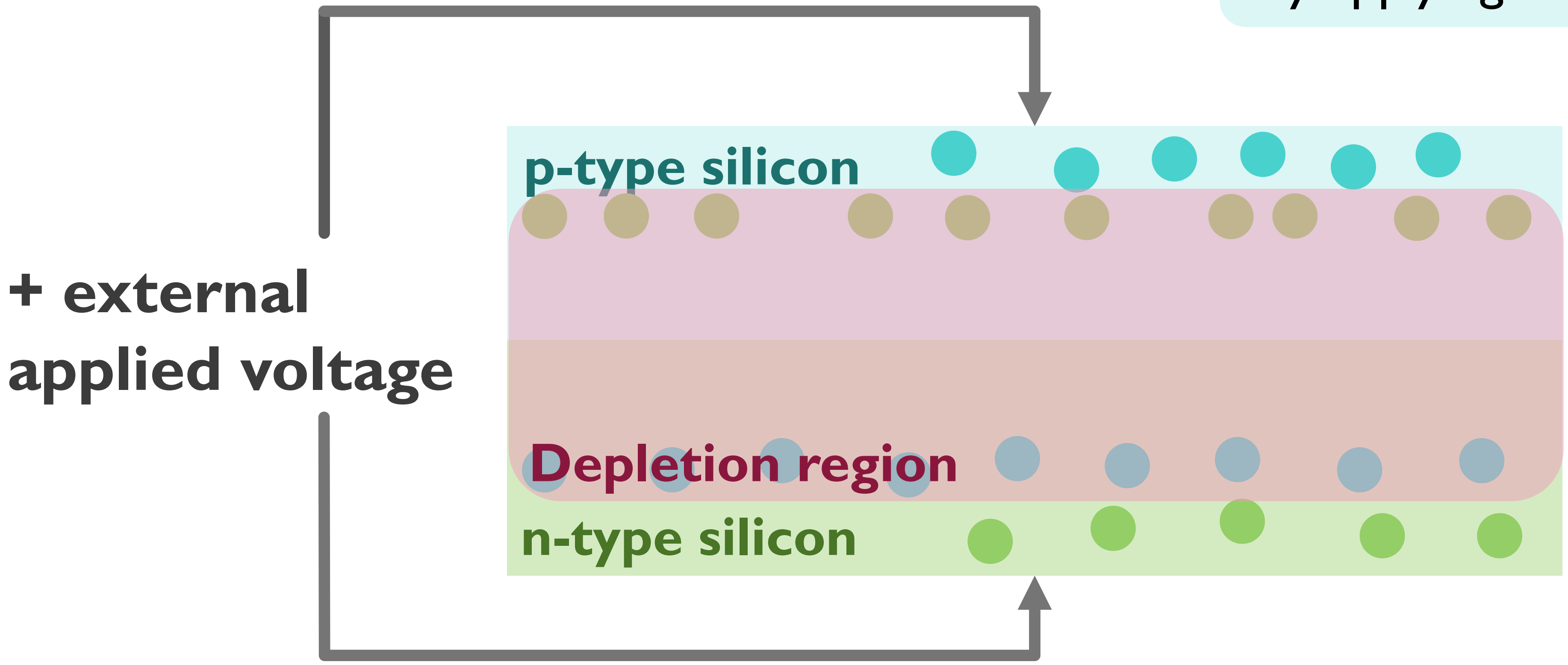
# Silicon detectors

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



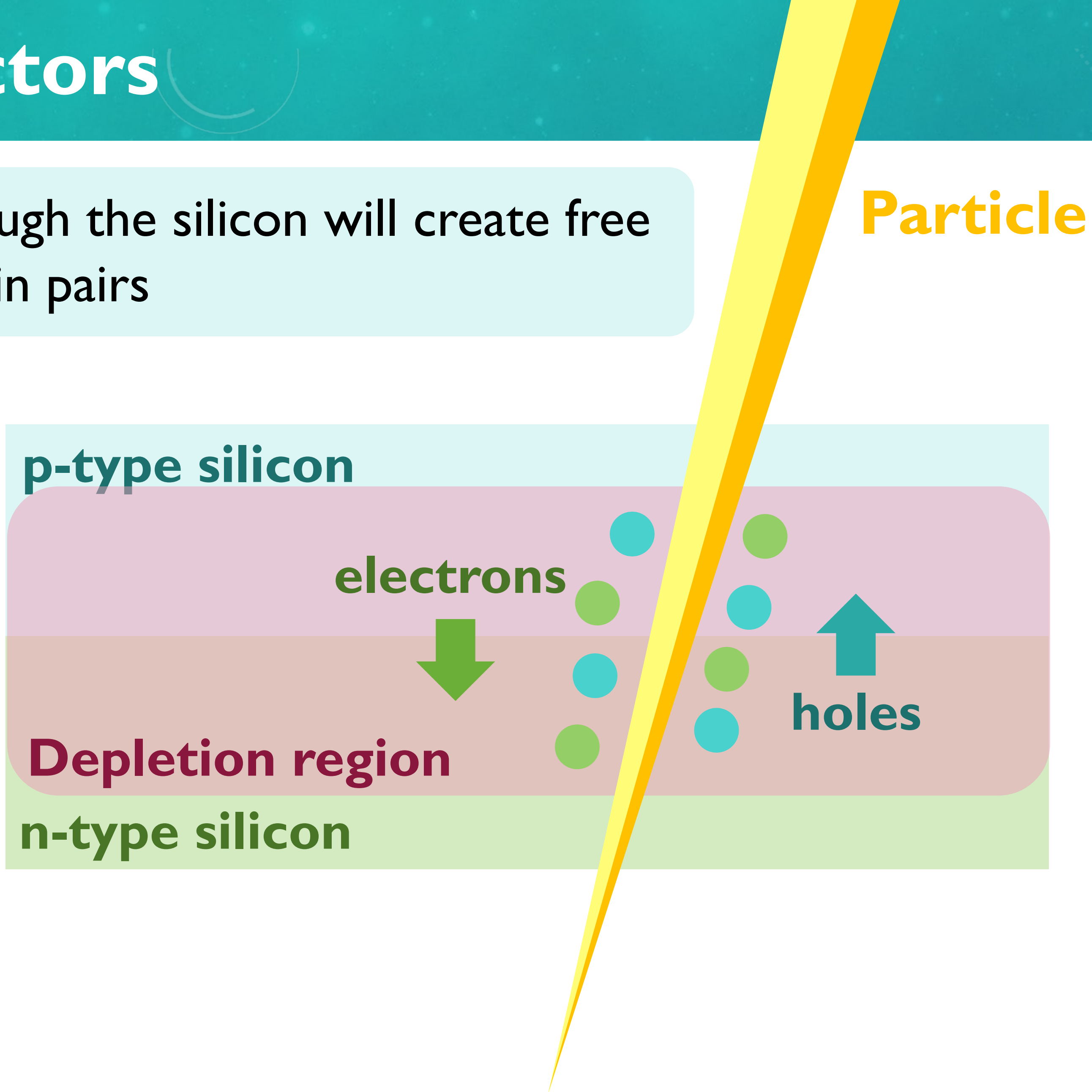
# Silicon detectors

Depletion region can be extended by applying an external voltage



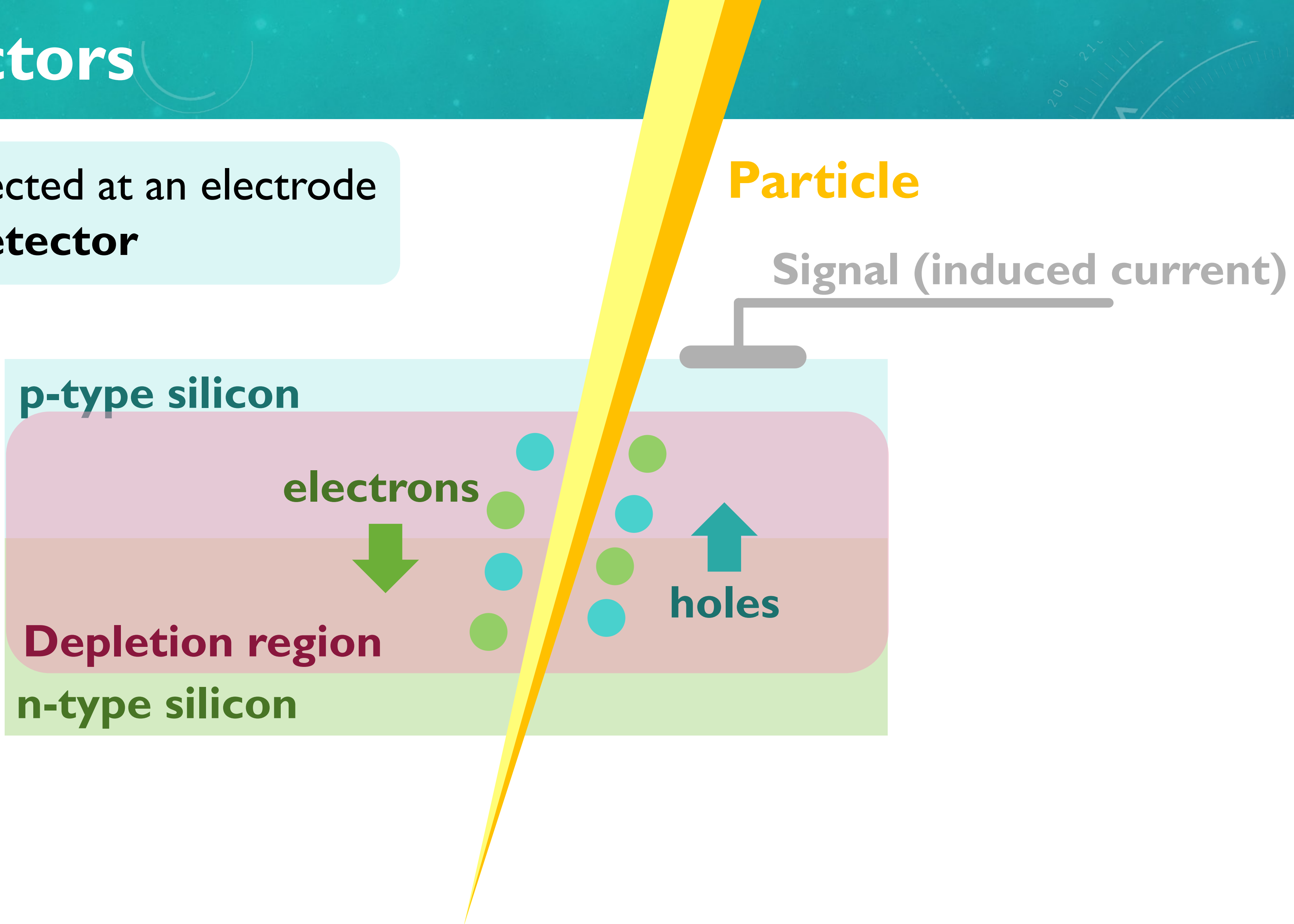
# Silicon detectors

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



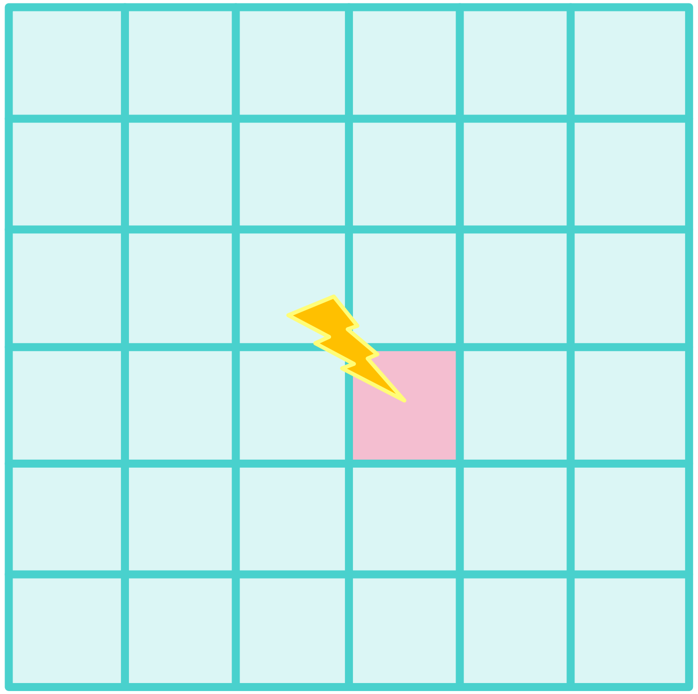
# Silicon detectors

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



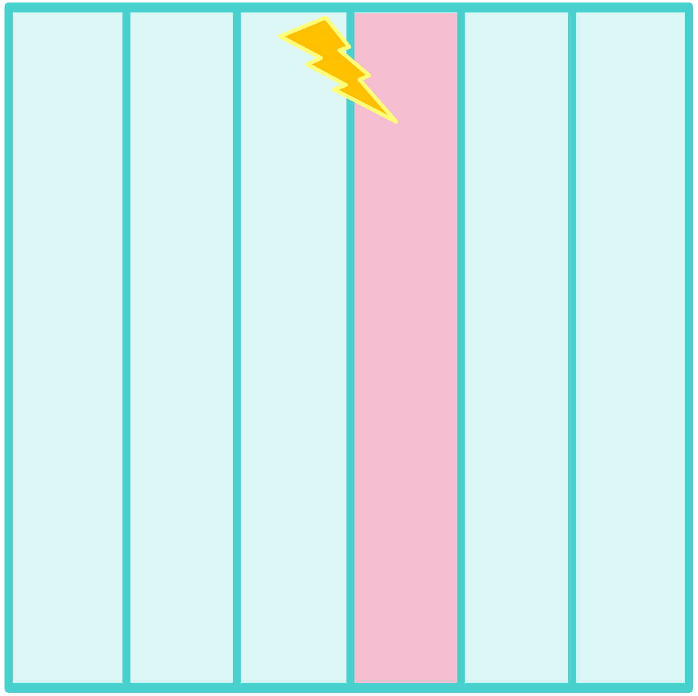
# Pixel vs strip detectors

**Pixel detector**



**Pixel pitch: 400 x 50 $\mu m^2$**

**Strip detector**



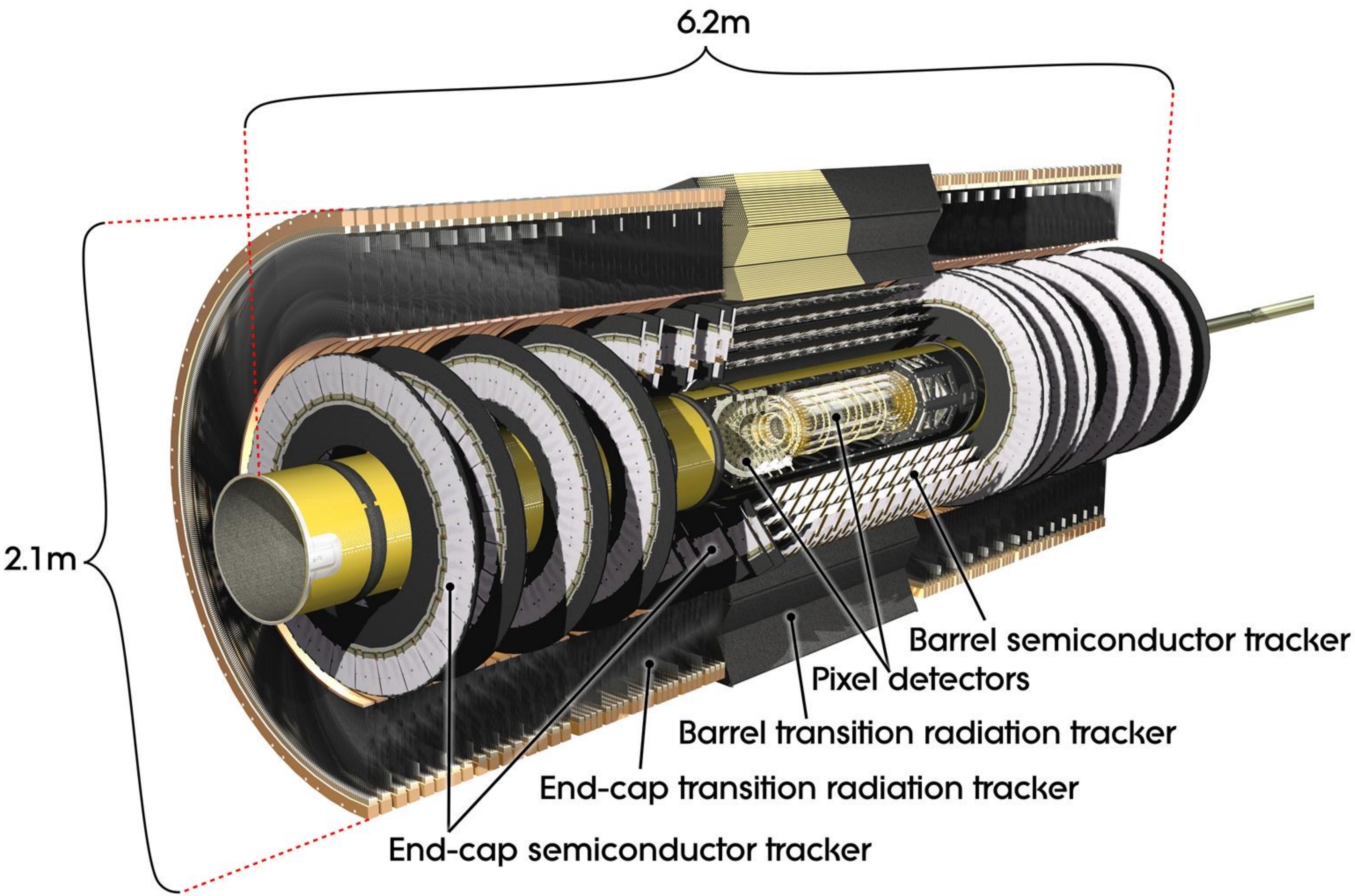
**Strips pitch: 75 µm x 5 cm**

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

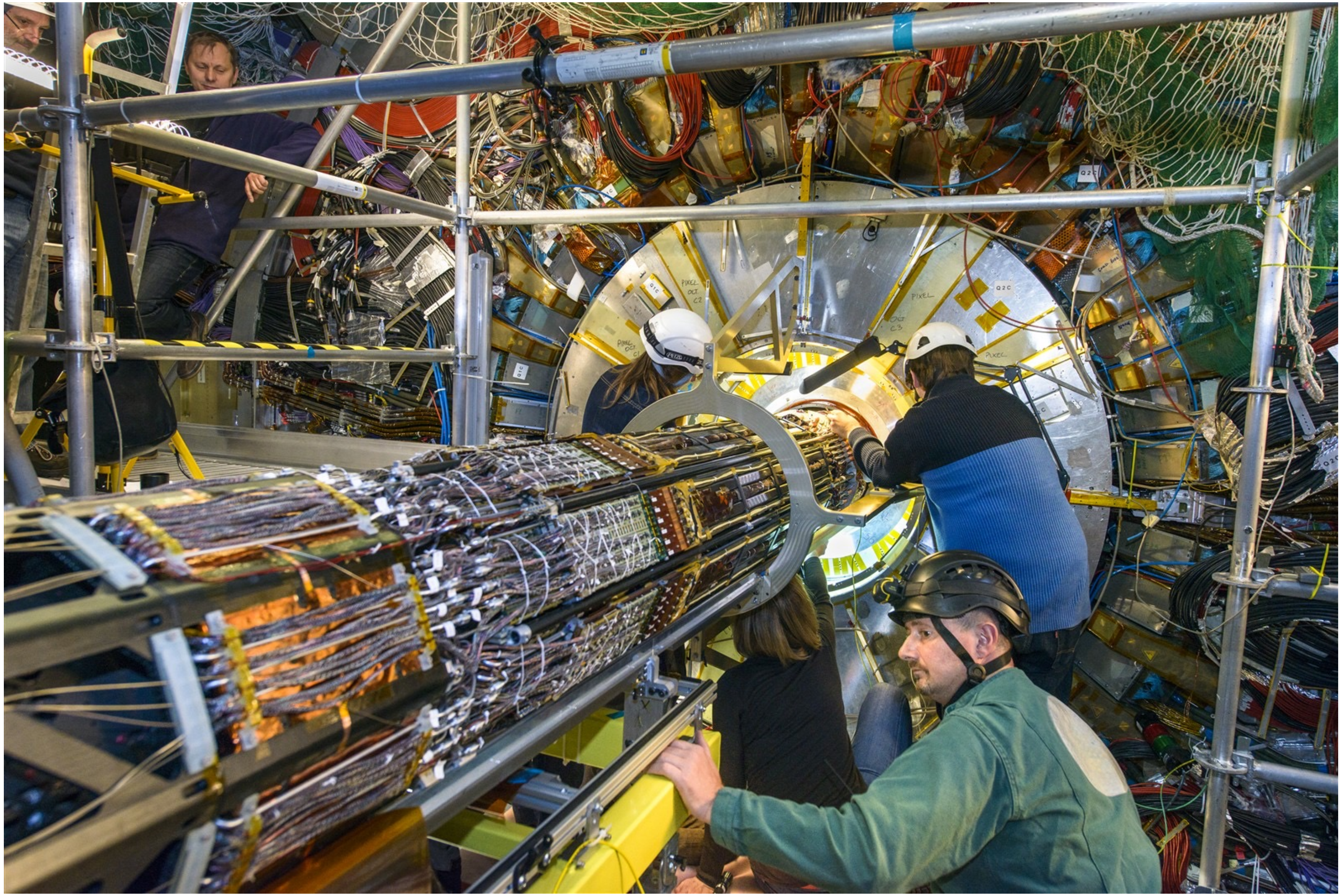
→ **Pixel and strip detectors**

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

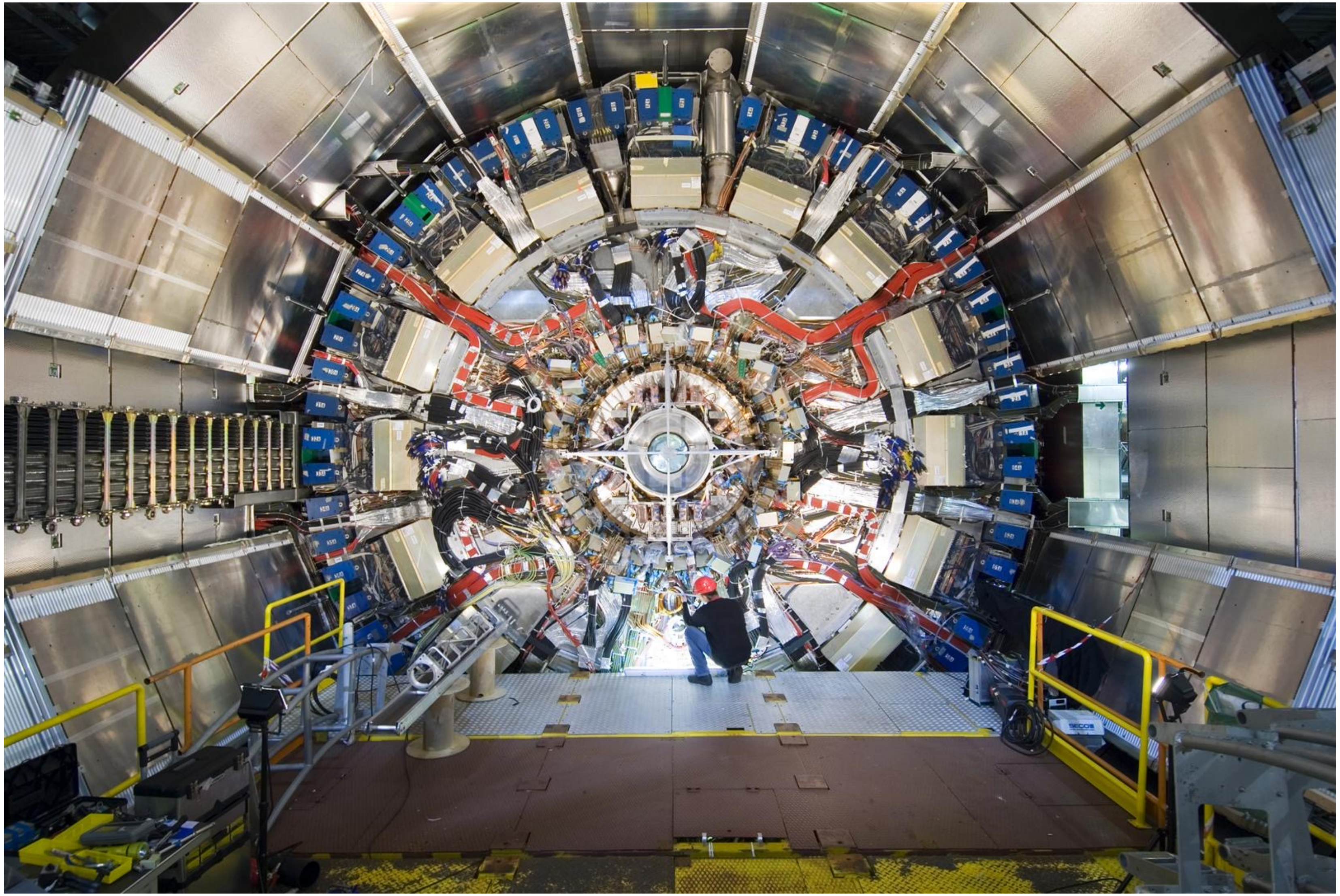
# ATLAS Tracking Detector



# ATLAS Pixel Detector



# ATLAS Tracking Detector



# Questions?

# How to build a pixel detector

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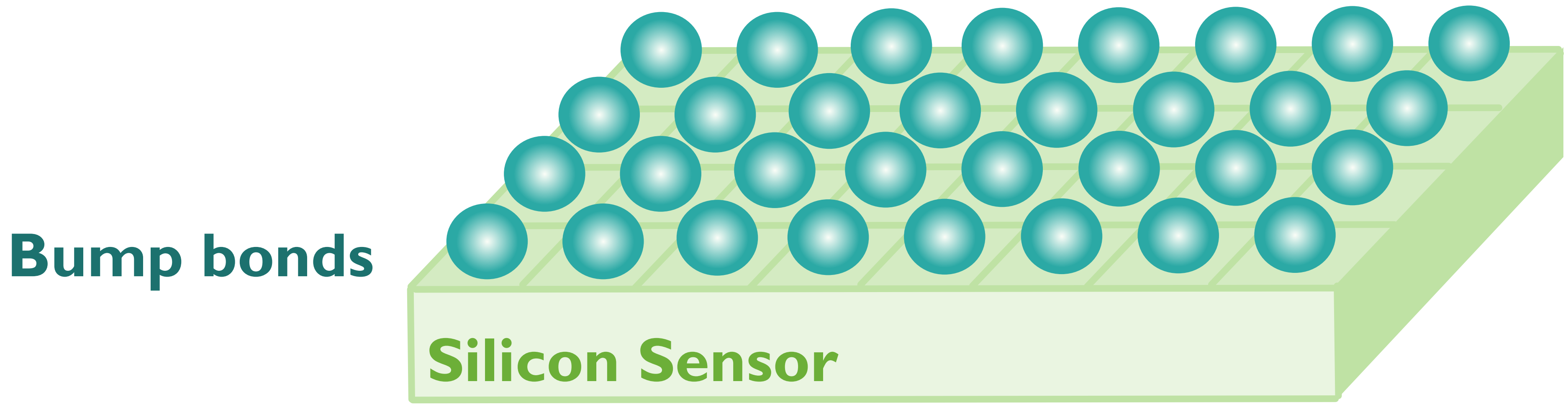

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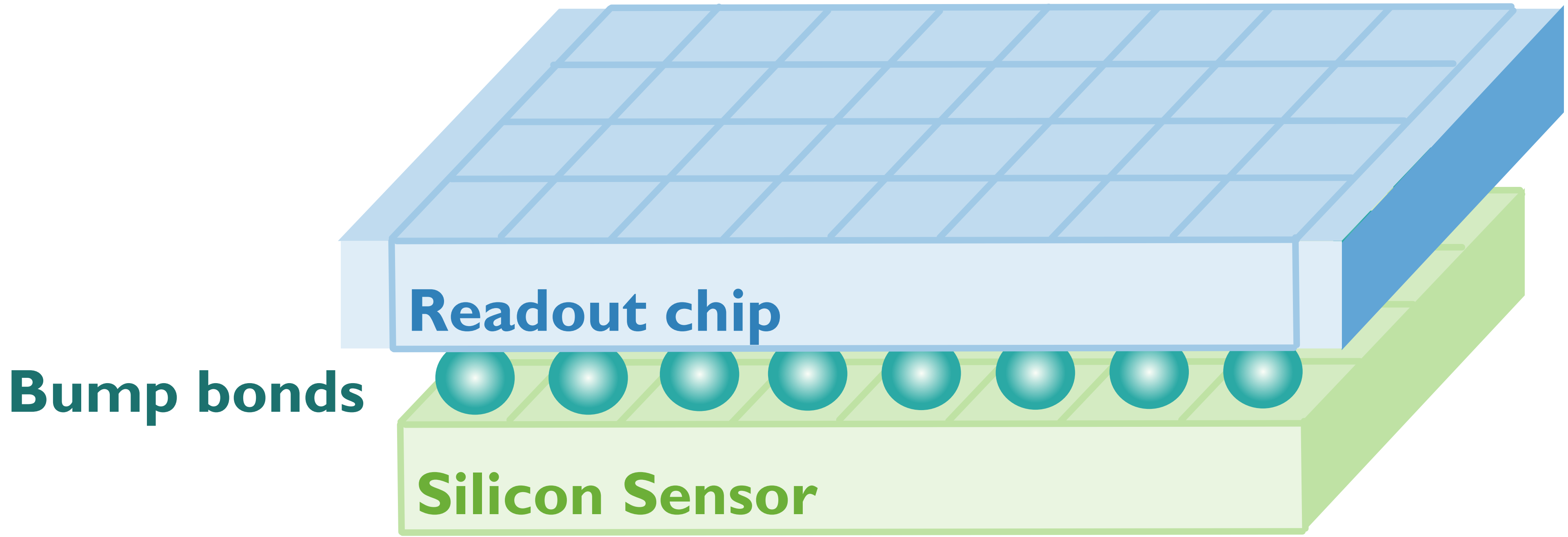

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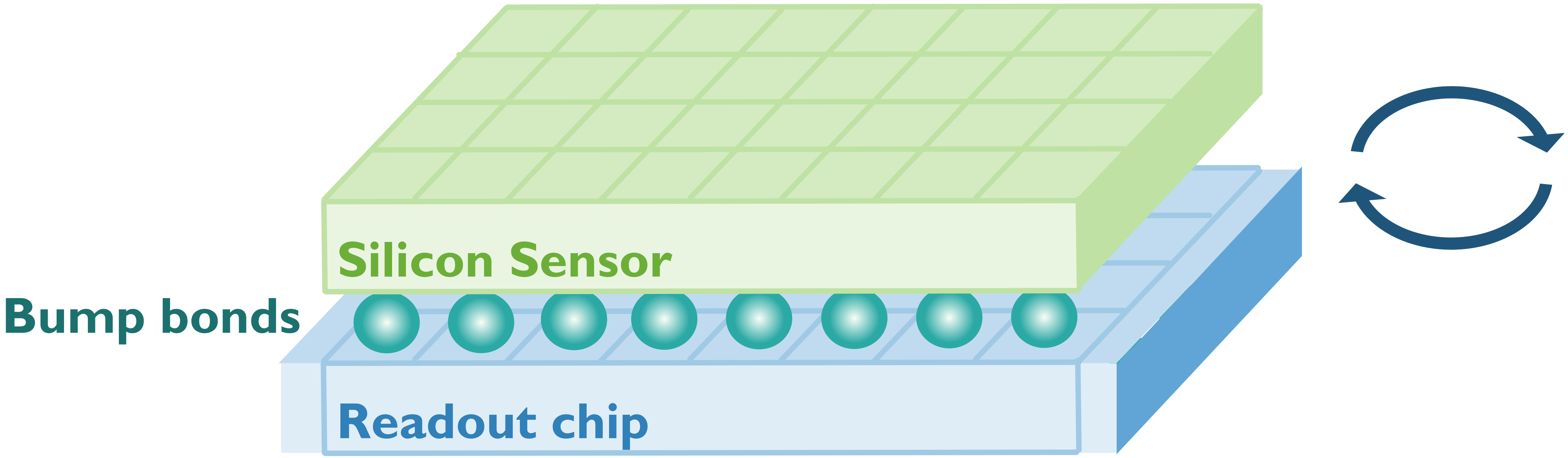

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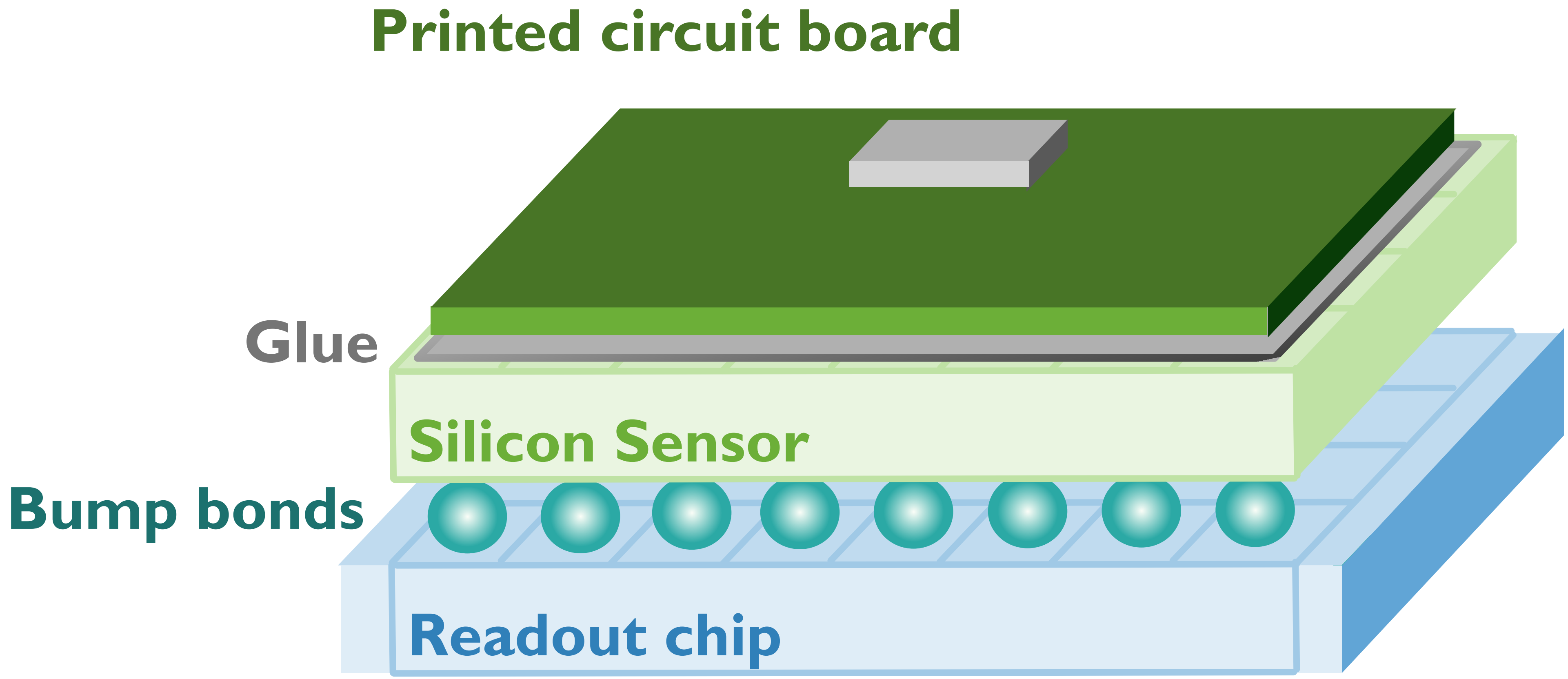

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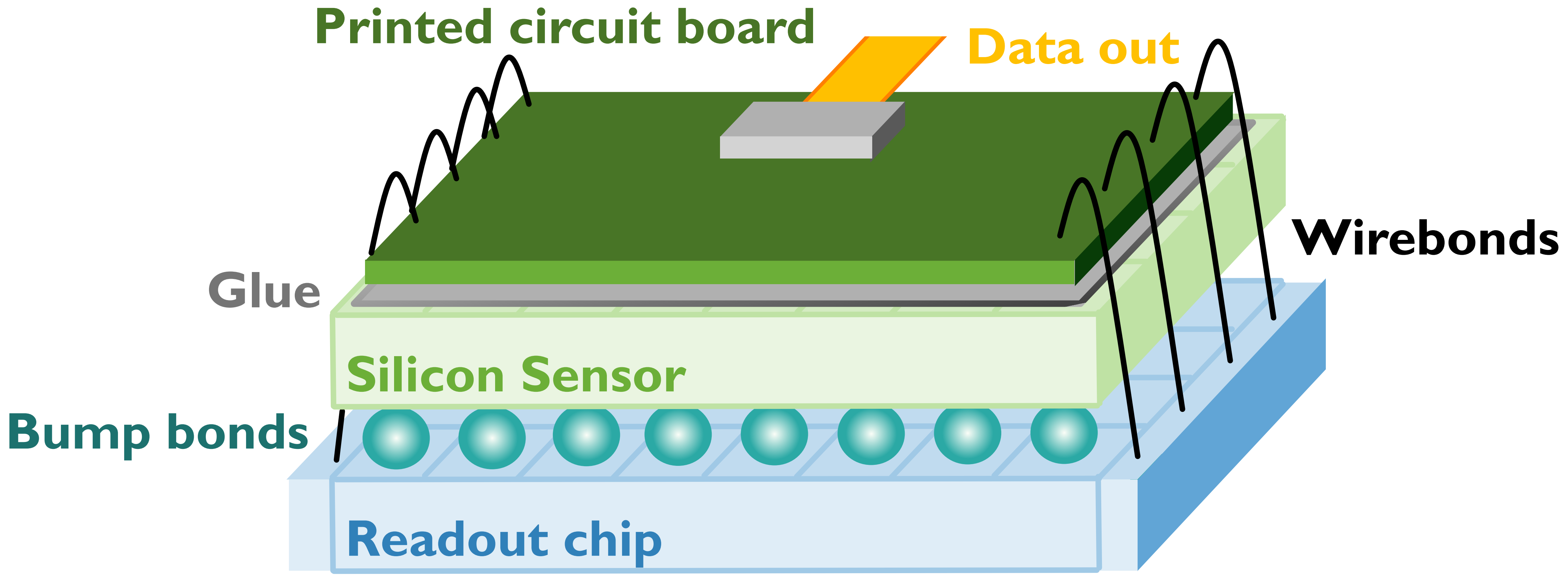
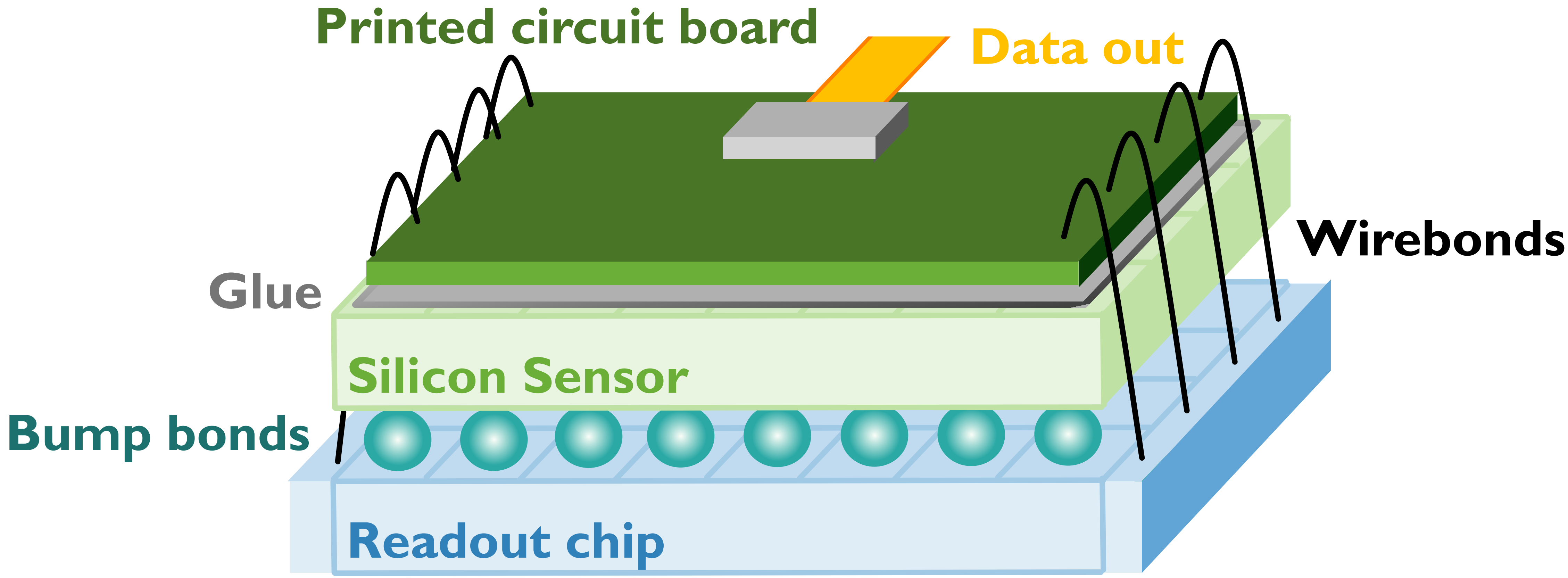


# Pixel detector requirements




*Detector requirements*

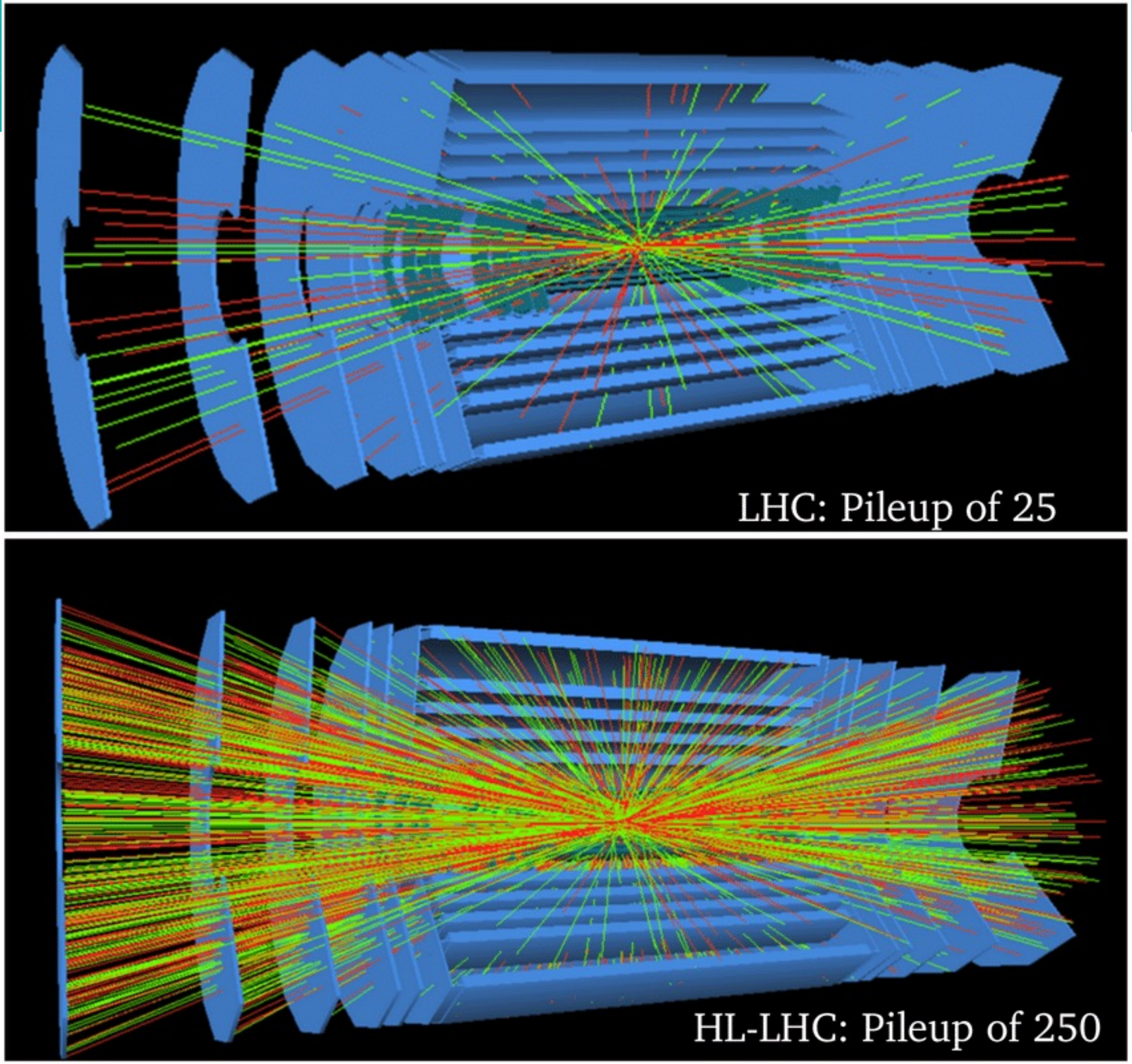
- Get the best resolution possible → **small pixel size** (400 x 50 μm$^2$)
- Fast enough to cope with collision rate at LHC (40 MHz) and large volume of data → **readout speed**
- Survive in a high-radiation environment → **radiation tolerance**

# High Luminosity LHC

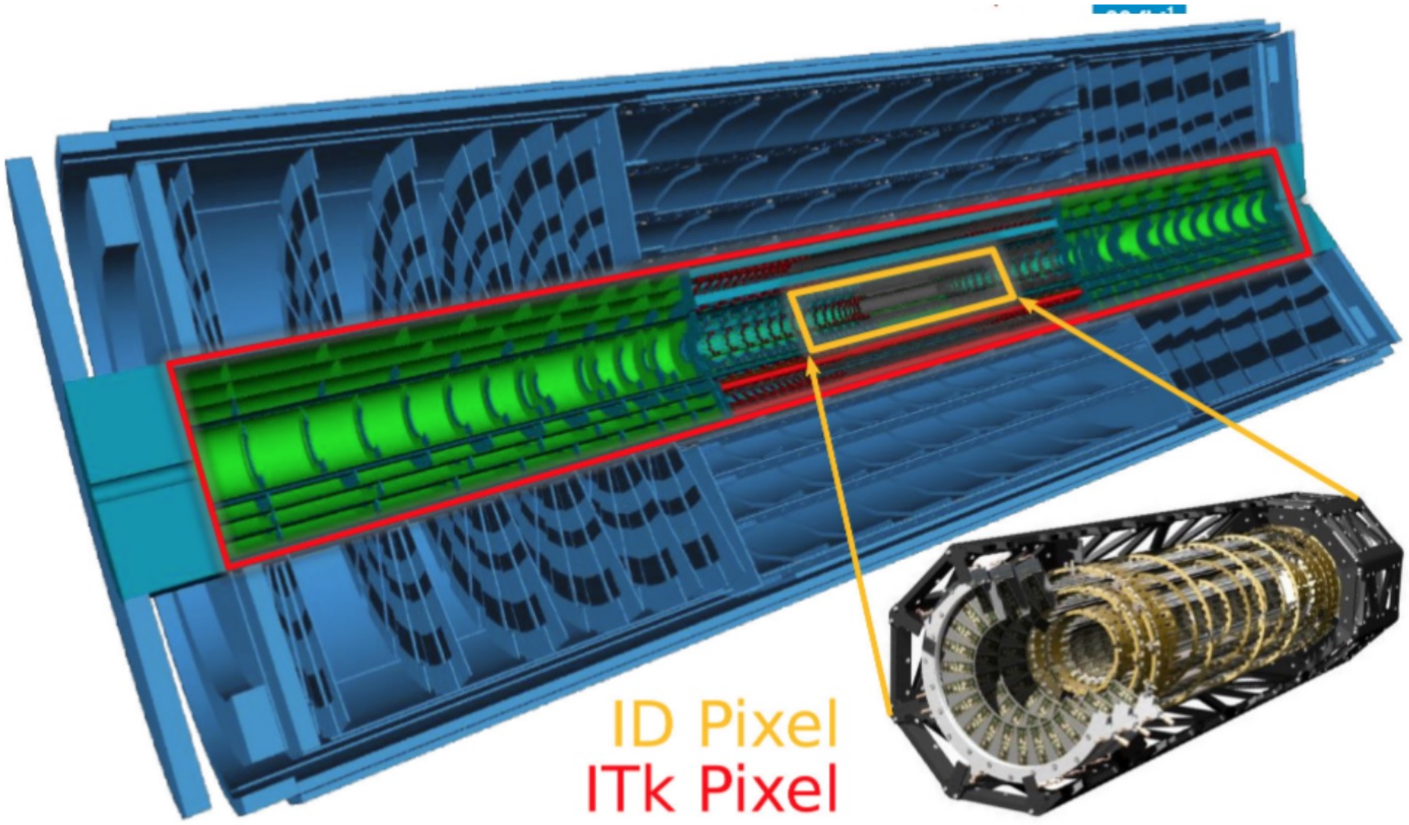
- Will upgrade LHC accelerator around 2025 to collect a 10 x larger dataset than we currently have

→ Increased number of interactions per collision of proton bunches

→ **High-Luminosity LHC (HL-LHC)**



# ATLAS detector upgrade



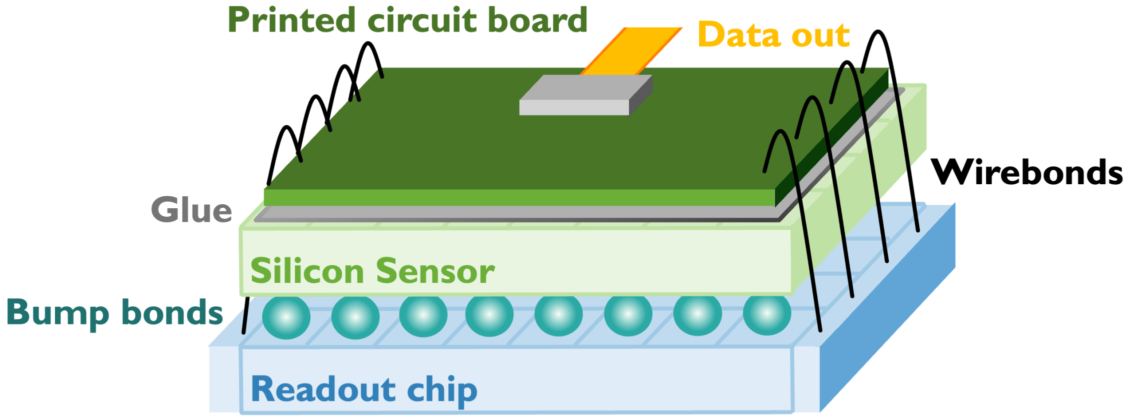

All-silicon upgraded tracking detector (ITk) for HL-LHC

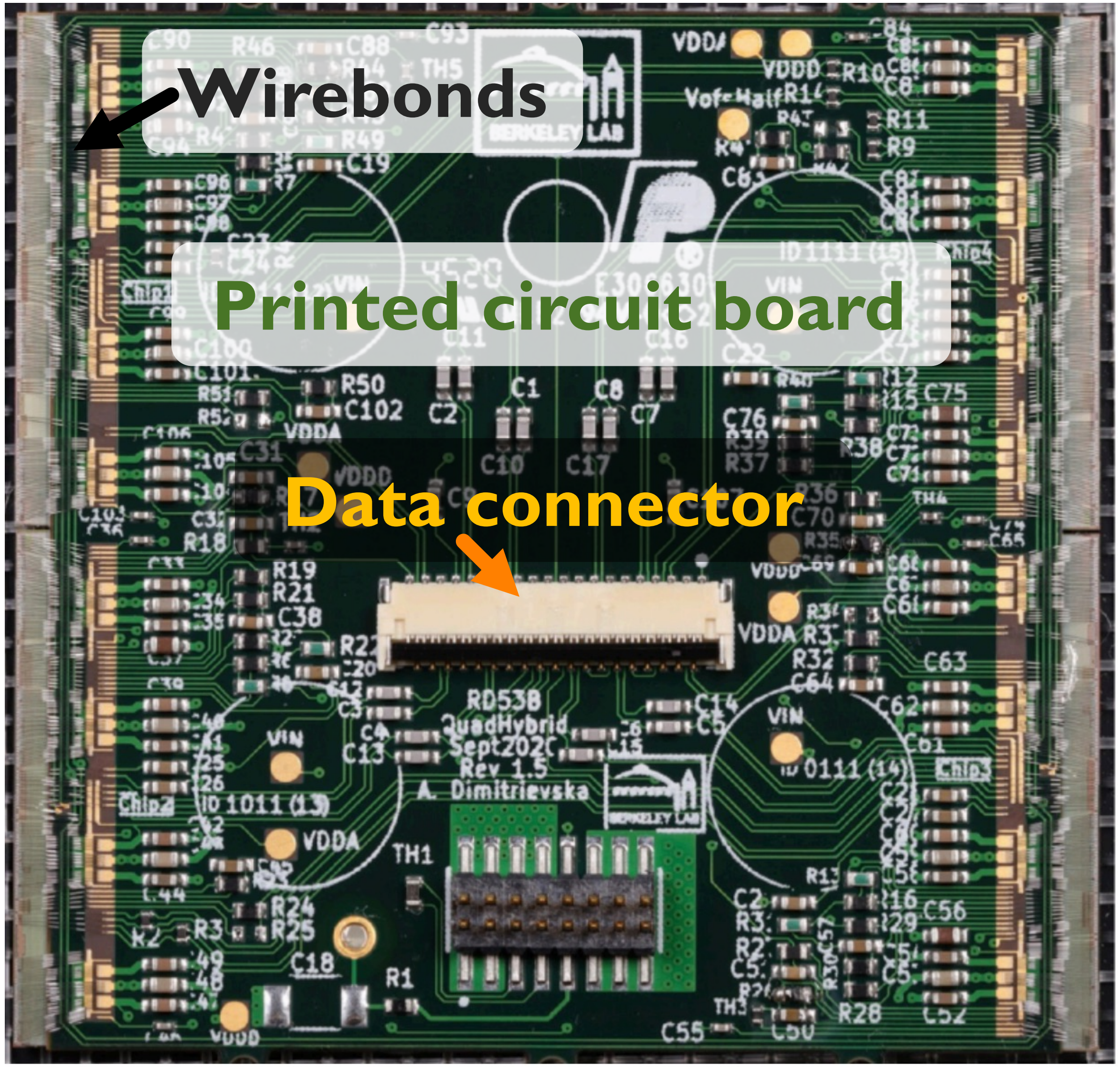
Upgraded pixel detector:

- 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 $\mu m^2$ → 50 x 50 $\mu m^2$
- **New readout chip** to cope with higher data rates and increased radiation

# Pixel modules for the ATLAS pixel upgrade



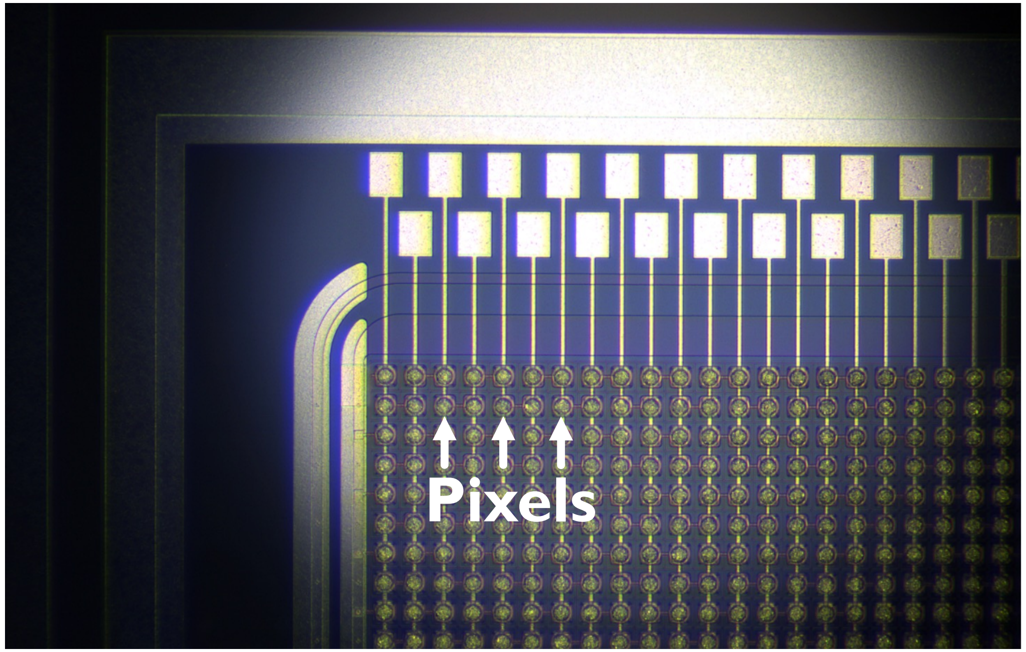



# Pixel sensors for the ATLAS upgrade

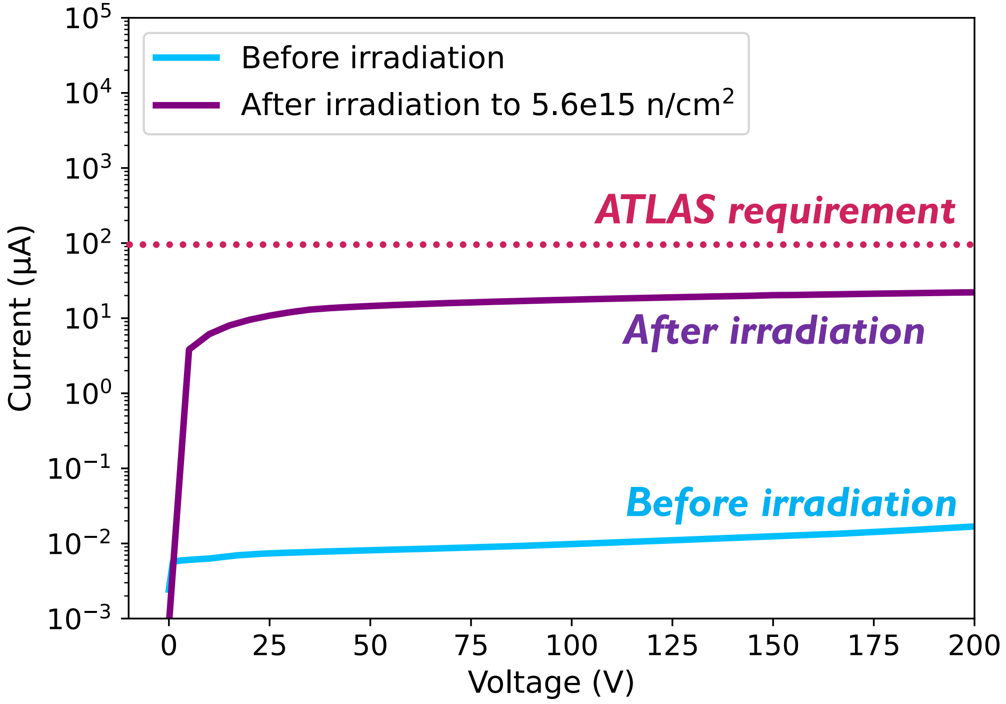
- Pixel sensors for ITk produced by industry → **need to check they meet the requirements for ATLAS**
- For example: Current flowing through the sensor must stay low throughout operation

→ check current before and after irradiation of the sensor

***Close-up of silicon sensor***



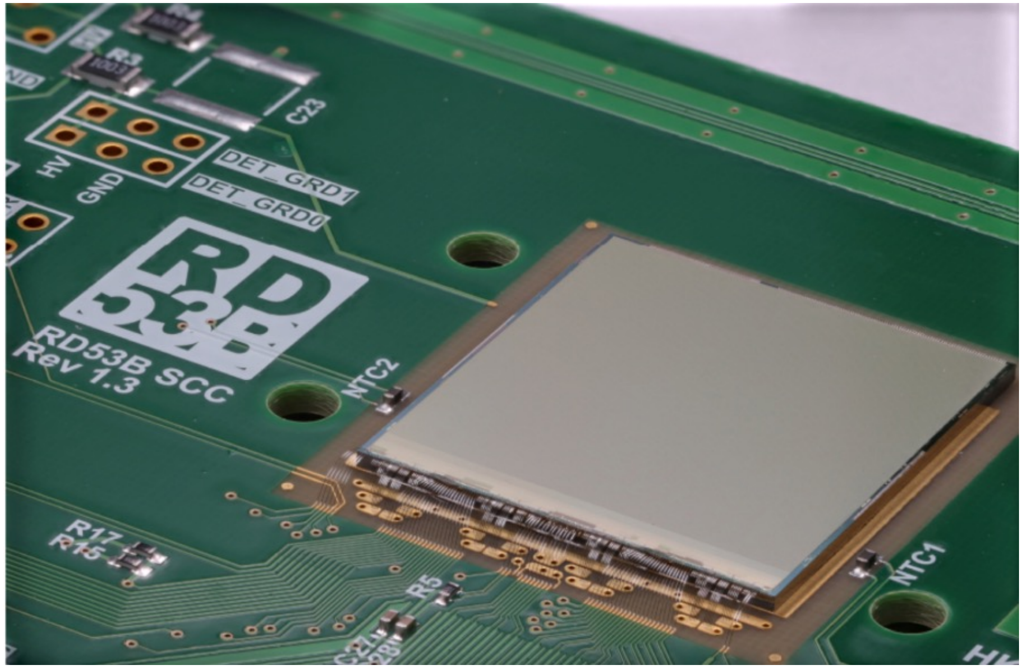

***Measurement of current of silicon sensor***



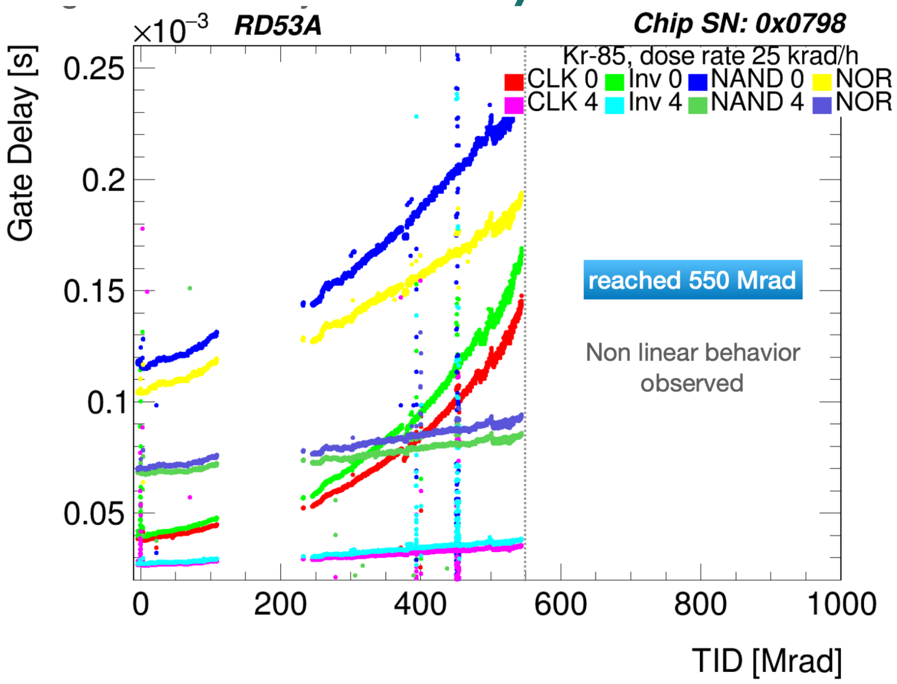
# Readout chips

- 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?