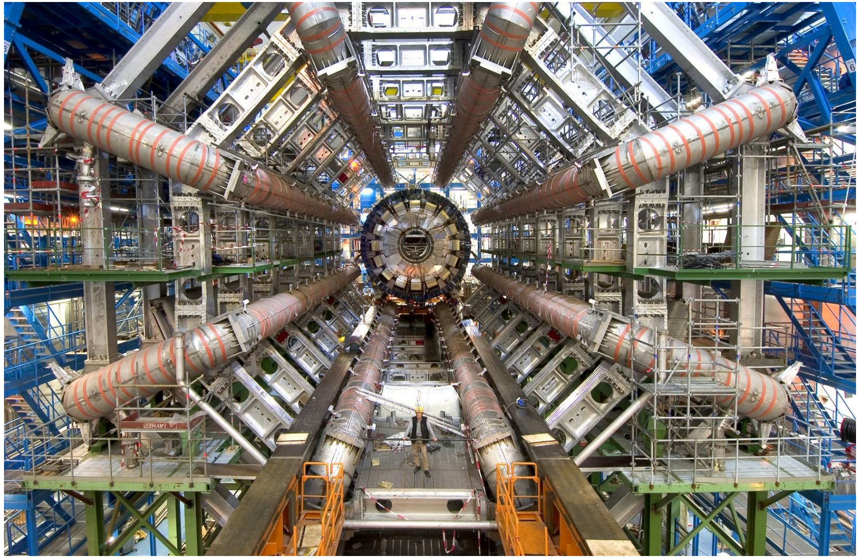
Detector Physics

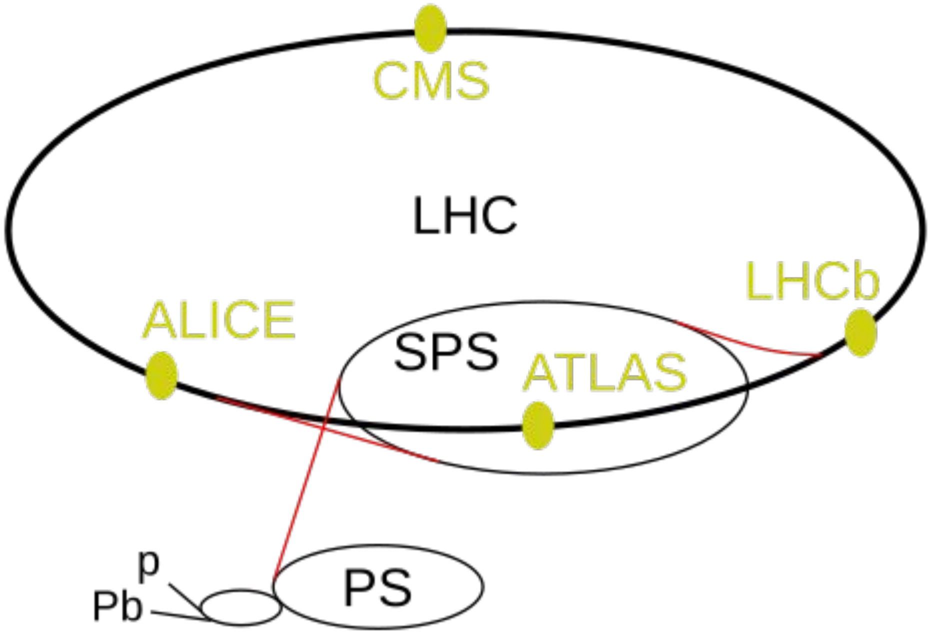
Jake Pfaller
Saba Faghih
University of Cincinnati
July 1, 2025



https://home.cern/resources/image/experiments/atlas-images-gallery

Accelerators

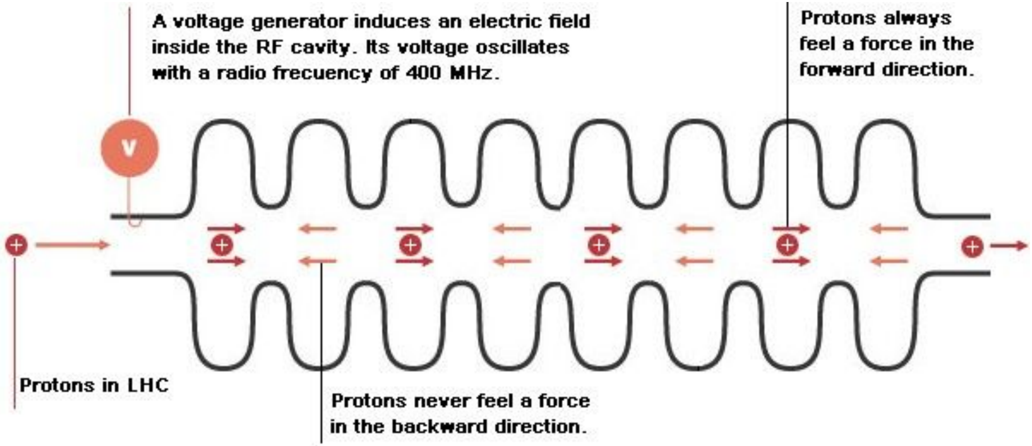
- For the physics we want to do, we need to collide particles at high energies (High energy = very fast)
- CERN uses a network of machines to accelerate particles for high-energy collisions
- Different components are used for:
  - Accelerating
  - Steering
  - Focusing



https://en.wikipedia.org/wiki/Large_Hadron_Collider

Accelerators - RF Cavities

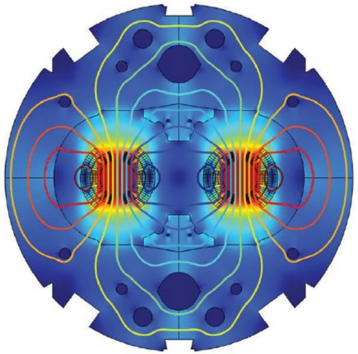
- Radio-frequency (RF) cavities accelerate the particles in a straight line
- Alternating electric fields pull the particles forward, but never push them backwards



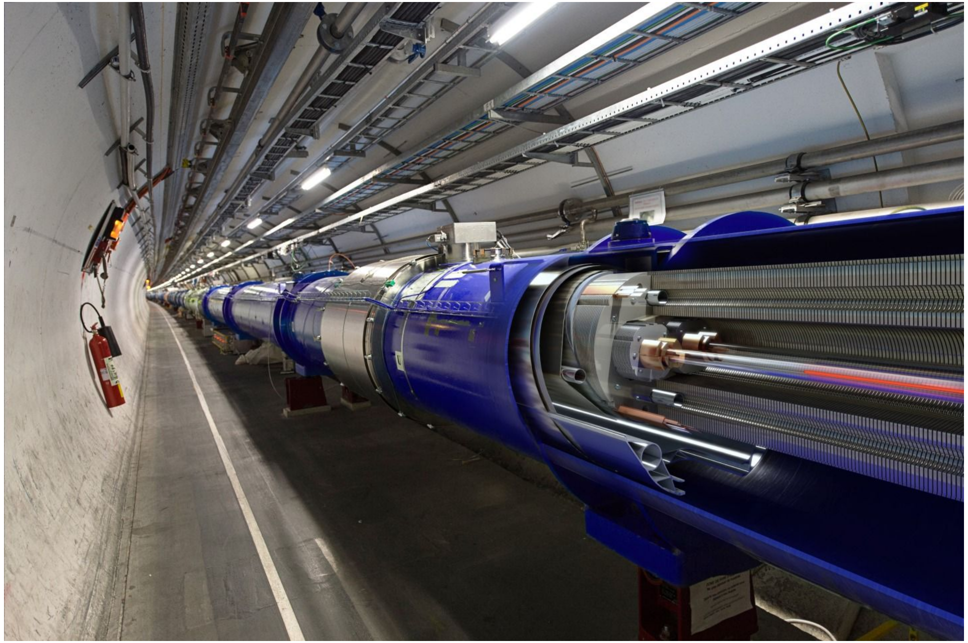
https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.rf_cavities

Accelerators - Magnets

- Magnetic dipoles steer the particles around in a circle
- More complicated magnetic fields, quadrupoles and octopoles, are used to focus the beam of particles



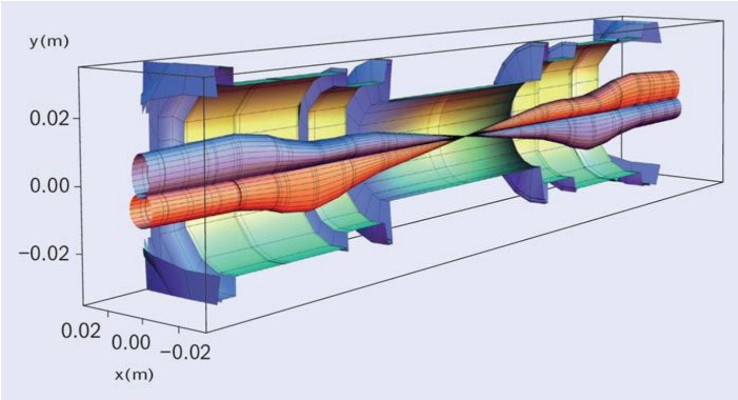
https://spectrum.ieee.org/analyzing-the-lhc-magnet-quenches



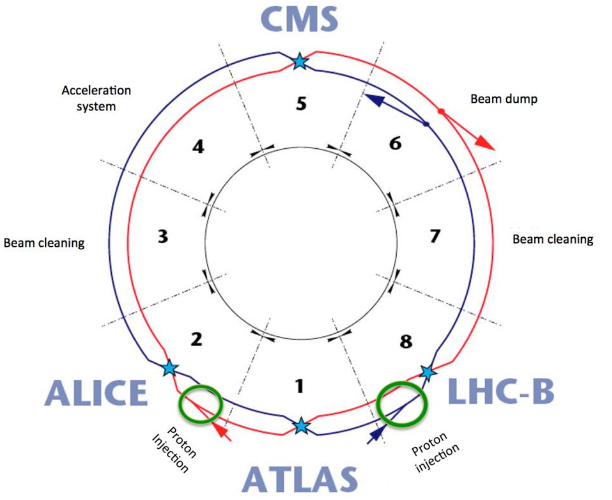
https://www.bnl.gov/newsroom/news.php?a=111785

Collisions at the LHC

- Protons are grouped into "bunches" of ~10^{12} protons
- Beams of protons circulate the LHC in opposite directions
- Bunches cross each other at 40,000,000 times per second
- Bunches "collide" at 4 points around the LHC, where experiments measure the outcome
- Terminology:
  - collision = interaction = bunch crossing
  - Event = 1 or more proton collisions at the same time



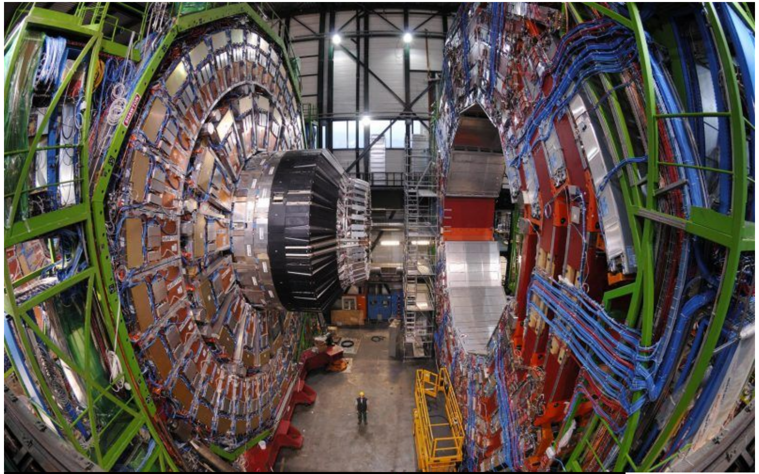
https://cerncourier.com/a/the-lhcs-first-long-run-2/



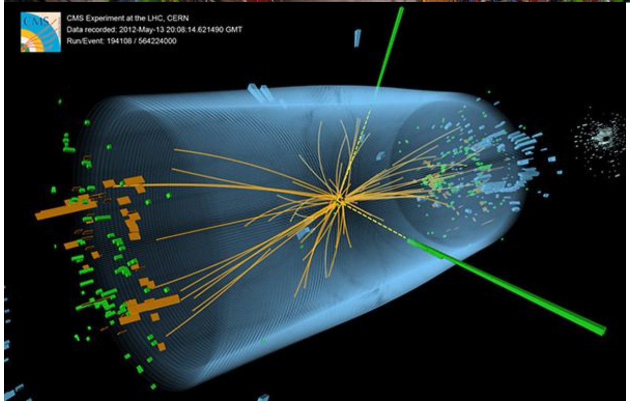
https://cds.cern.ch/record/1706606

Detectors

- Array of instruments around the interaction point to measure the particles resulting from a collision
- Some are general purpose, meant to gather as much information on the event as possible (ATLAS, CMS)
- Some are specialized to do more specific physics (LHCb, ALICE)
- What would we want to measure?
  - Position?
  - Momentum?
  - Type of particle?
  - Anything else?

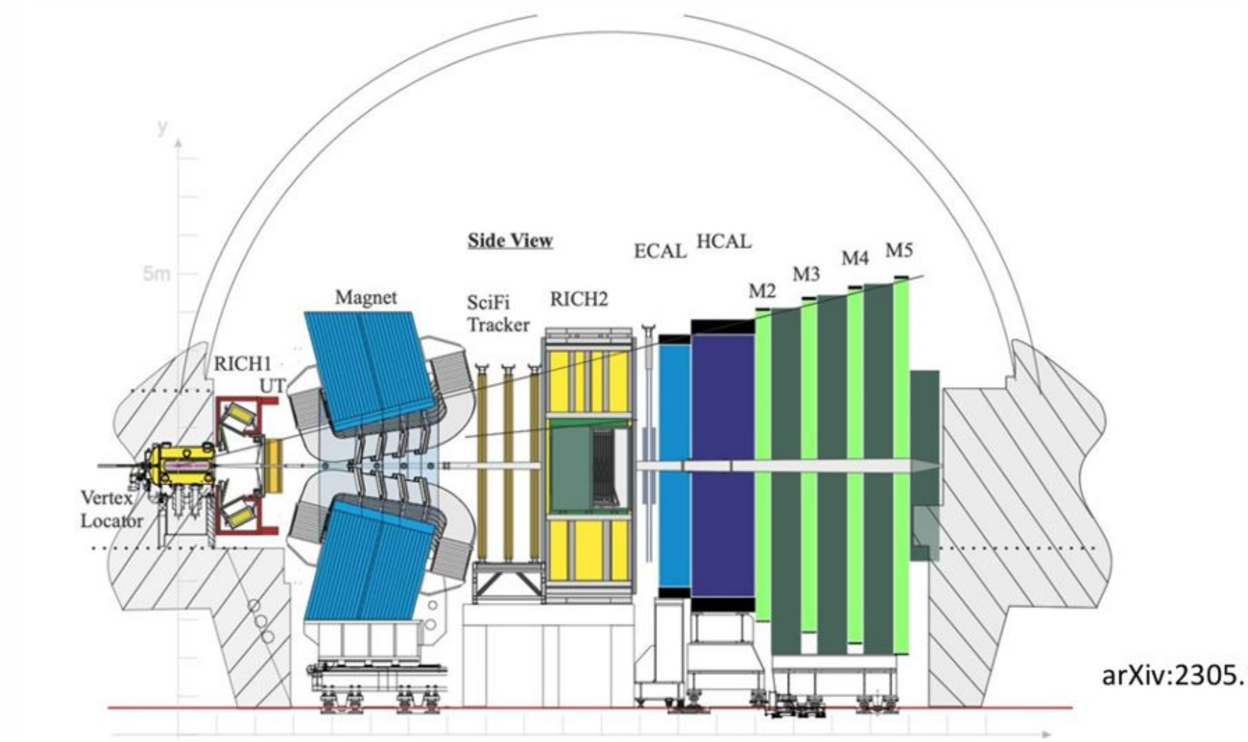


https://cms.fnal.gov/about-cms/



https://www.classe.cornell.edu/Research/CMS/

LHCb Detector



arXiv:2305.10515

LHCb Detector

Everything that we want to know about a particle

Position and Momentum(Tracking)

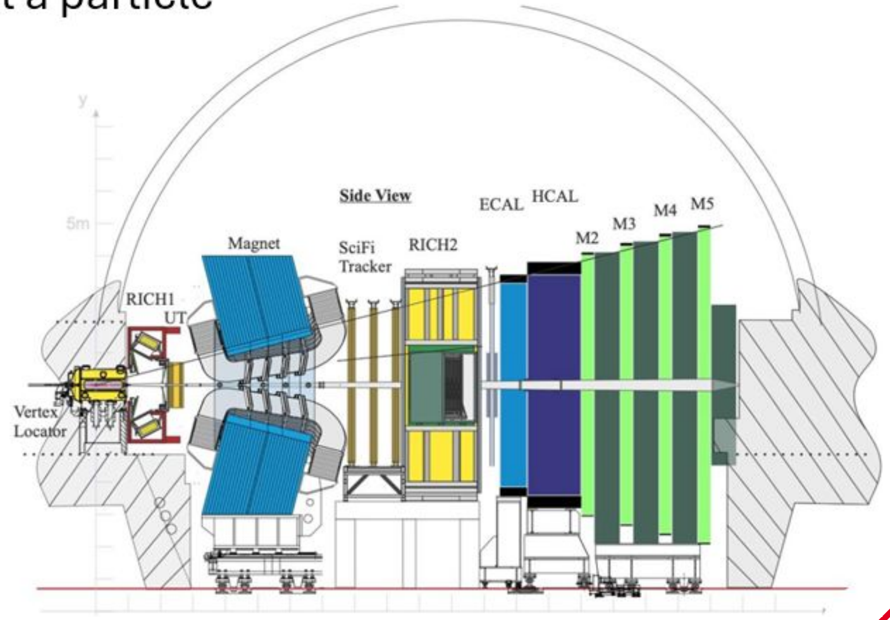
- -Vertex Locator(VELO) (7mm from LHC beam)
- -Upstream Tracker(UT)
- -Scintillating Fiber Tracker(SciFi)

Energy(Calorimetry)

- -Electron Calorimeter(Ecal)
- -Hadron Calorimeter(Hcal)

Charge, Mass and... (Particle Identification)

- -Ring Imaging Cherenkov Detector(RICH1&2)
- -Muon ID (Muon Chamber)



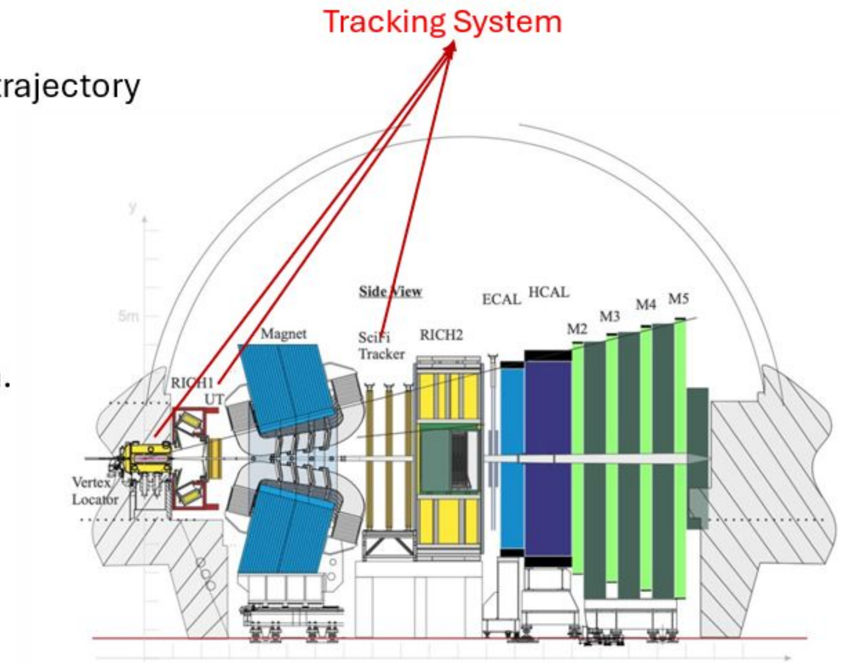
LHCb Detector

Tracking

The goal of the tracking system is to reconstruct the trajectory of particle's going through the LHCb detector.

Here we are able to do measurements on particle's Momentum and position.

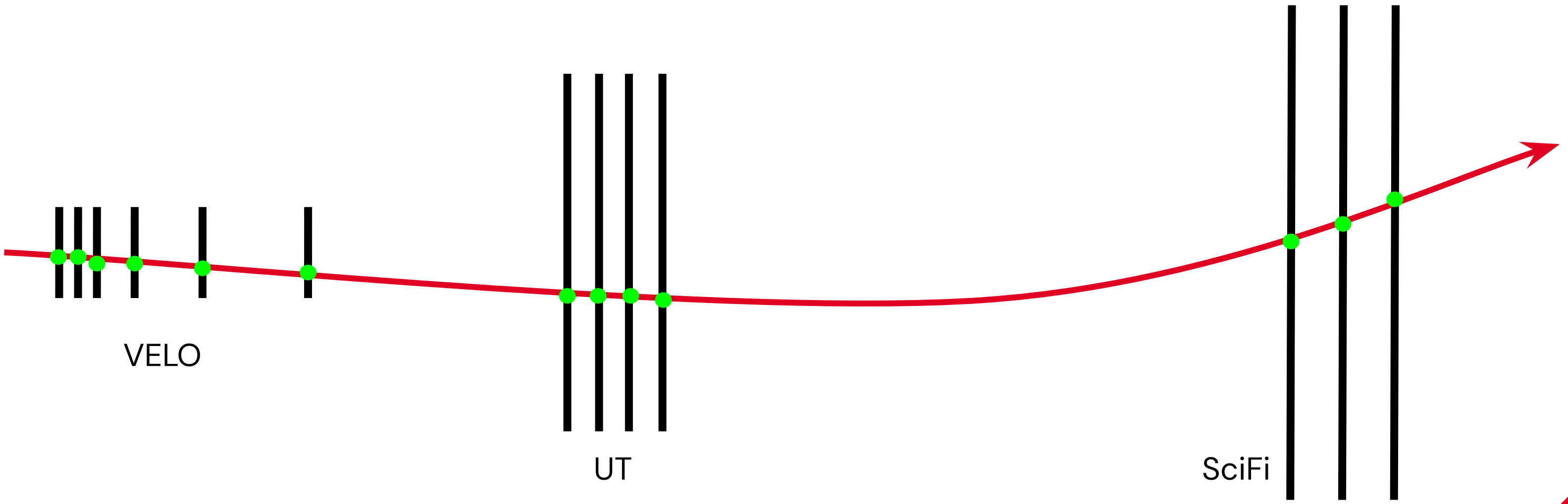
By putting all this data together in a computer algorithm now we can reconstruct the particle's path.



Tracking

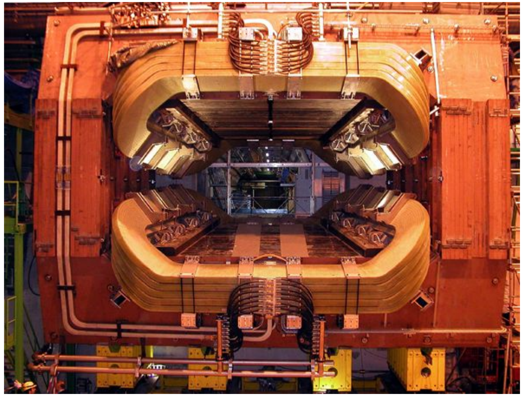
We want to reconstruct the path, or track, of a particle as it moves through the detector

This involves making precise measurements of its position at different points, which we can connect together with computer algorithms to form a track

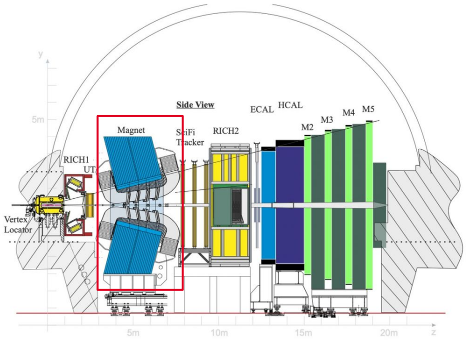


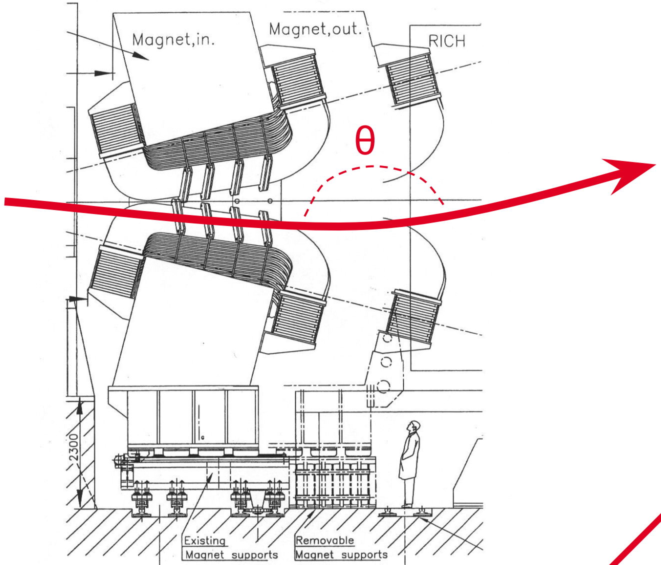
The LHCb Magnet

- Magnets allow us to measure the momentum of charged particles
- The path of charged particles bends in a magnetic field, just like in the LHC
- If we know the strength of the magnetic field and measure the degree of the bend, we can calculate the momentum of the particle



https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.magnets___detectors_ii

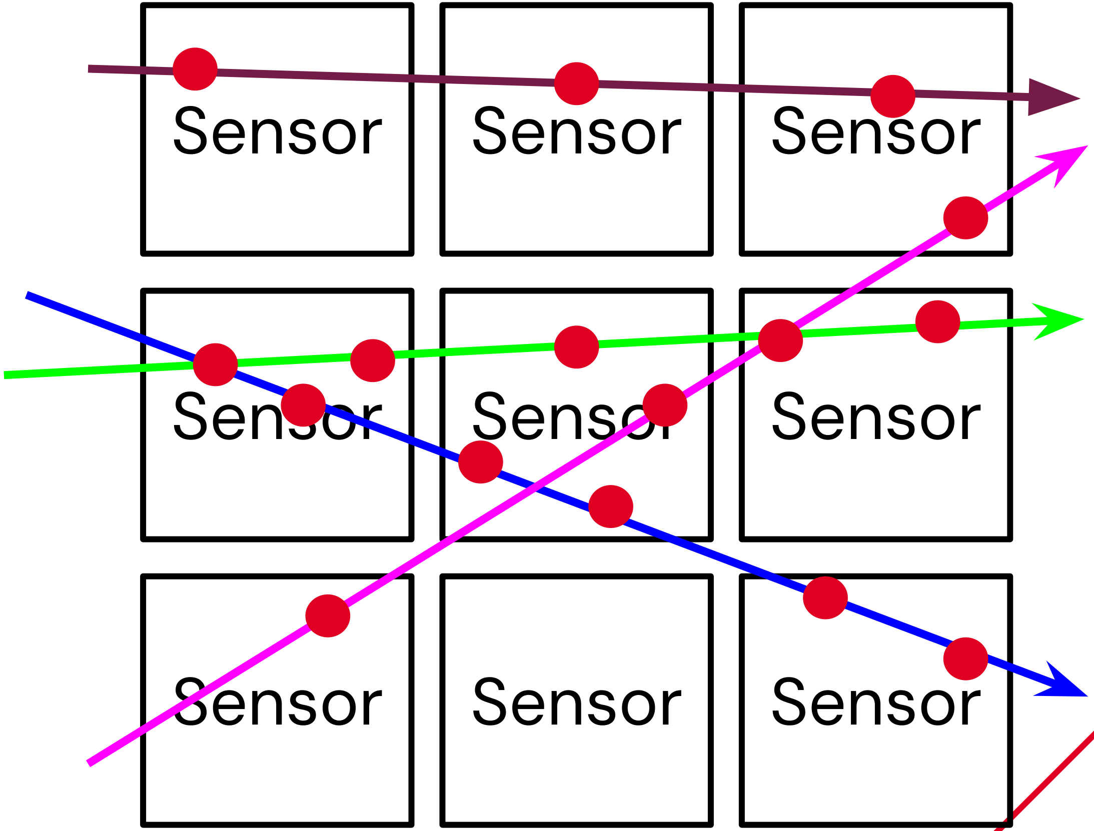




https://lhcb-magnet.web.cern.ch/TDRdrafts/html/draft3fi.html

Track Reconstruction

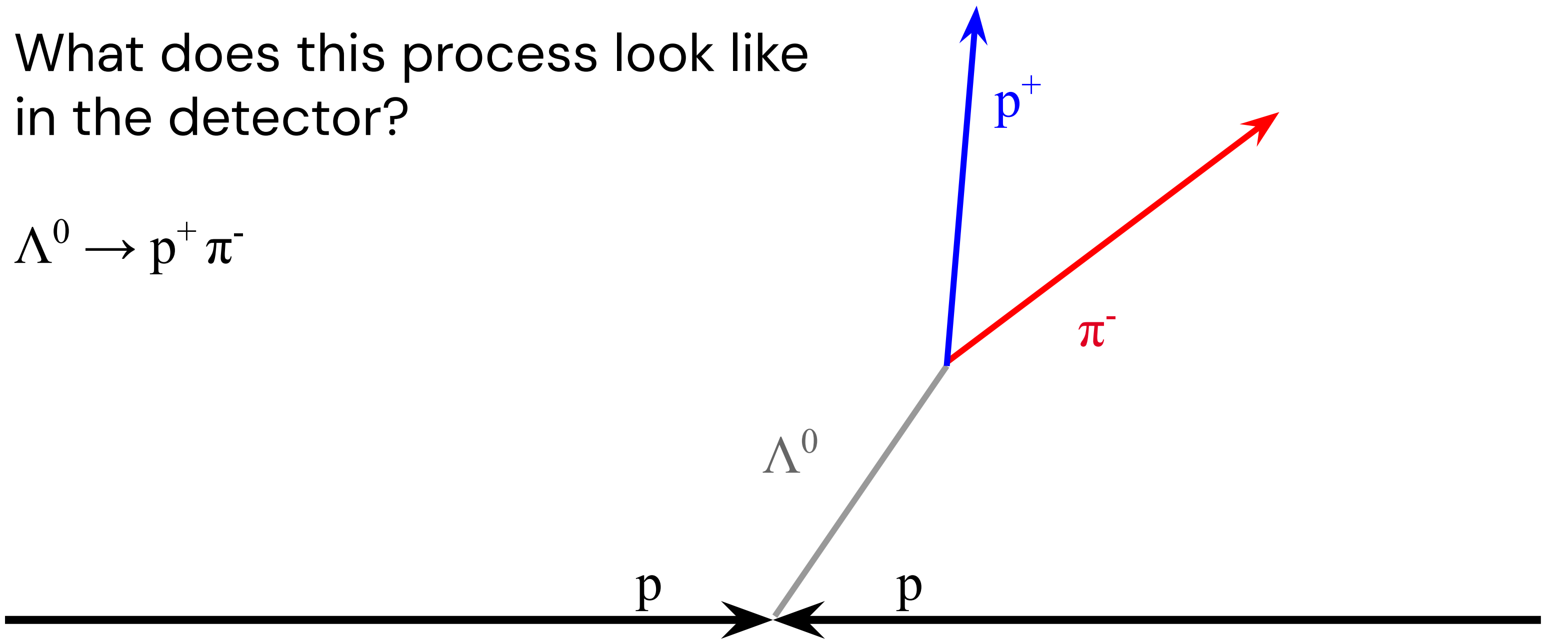
- Particles interact with sensors in the detector, leaving "hits" where they pass through
- Hits can be combined together to form tracks, and particle trajectories start to take shape
- Computer algorithms are needed, as the complexity scales with the number of particles in the detector



Track Reconstruction

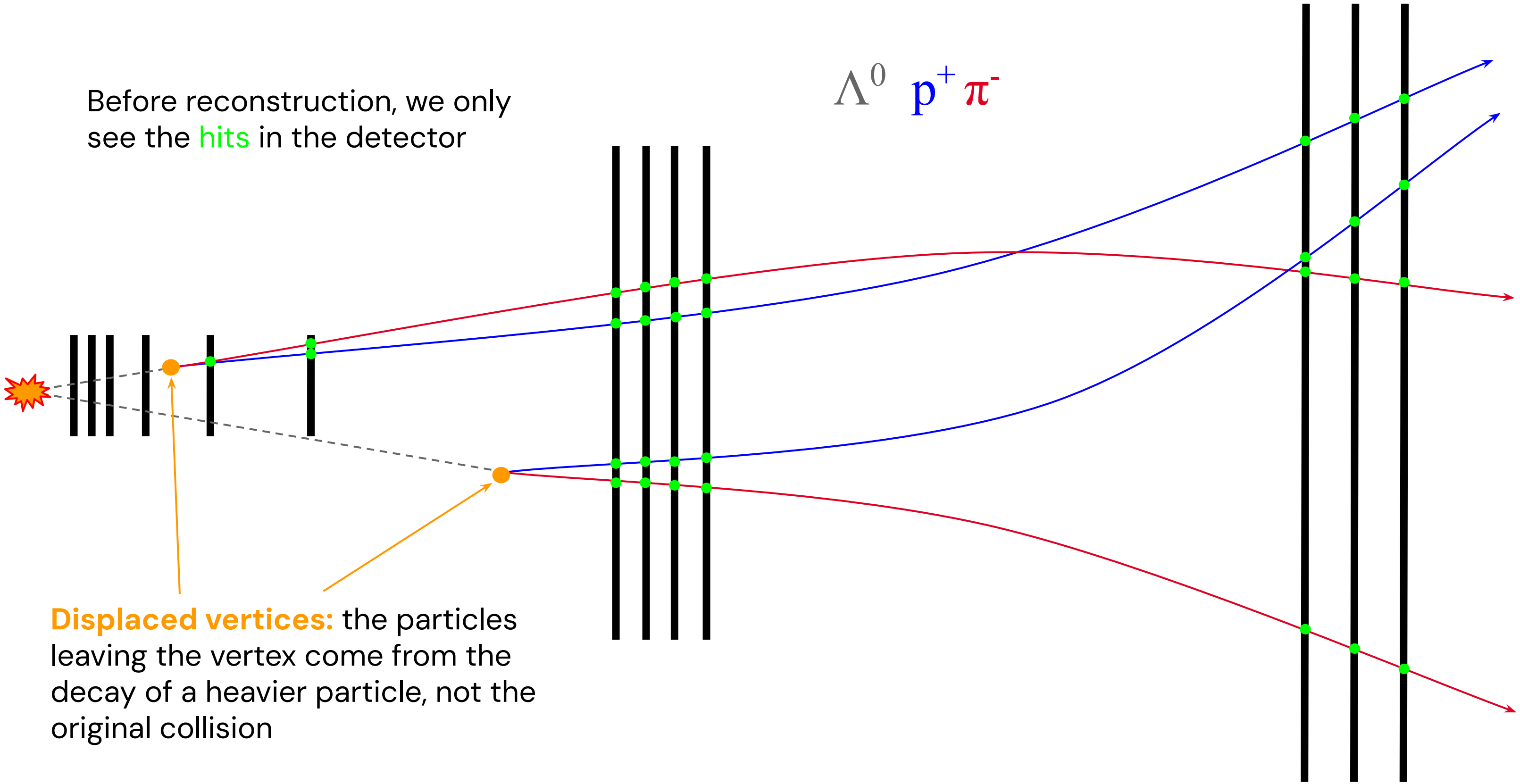
What does this process look like in the detector?

$\Lambda^0 \rightarrow p^+ \pi^-$



Track Reconstruction

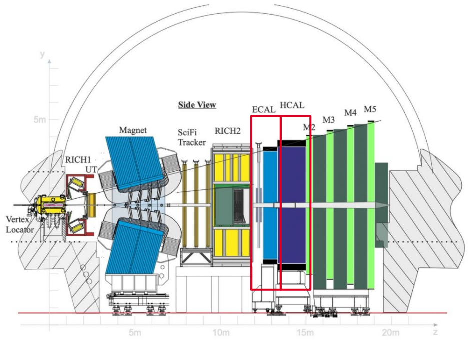
Before reconstruction, we only see the hits in the detector

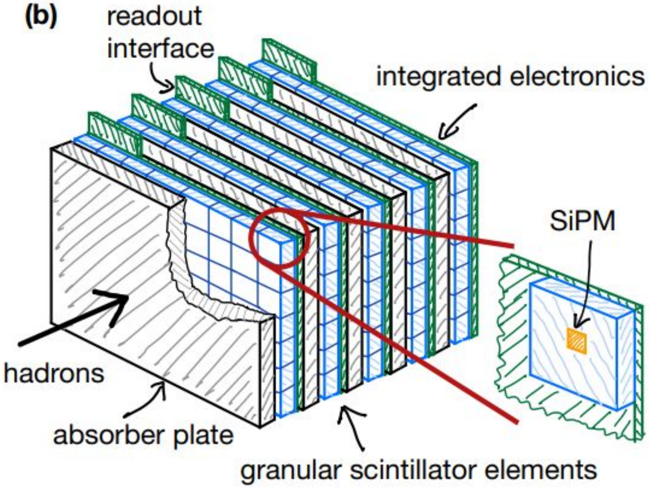


Displaced vertices: the particles leaving the vertex come from the decay of a heavier particle, not the original collision

Calorimeters

- Calorimetry, in the general science world, means to measure the energy of something
- Calorimeters in particle physics are used to measure the energy of particles by causing them to stop
- Stopping a particle causes it to deposit its energy in the material, which can be measured
- Electromagnetic Calorimeters (ECAL) measure primarily electrons and photons
- Hadronic Calorimeters (HCAL) measure hadrons not stopped by the ECAL

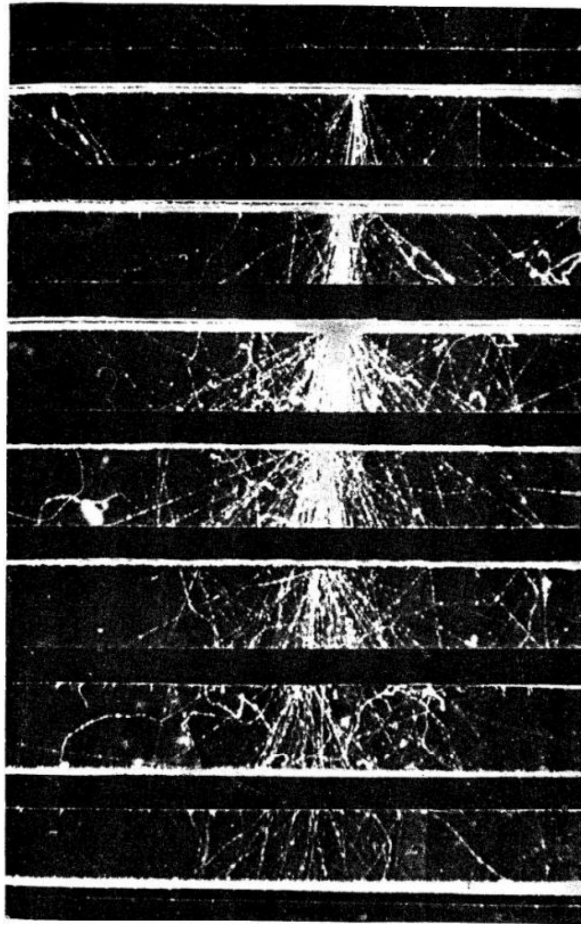




https://pdg.lbl.gov/2024/reviews/rpp2024-rev-particle-detectors-accel.pdf

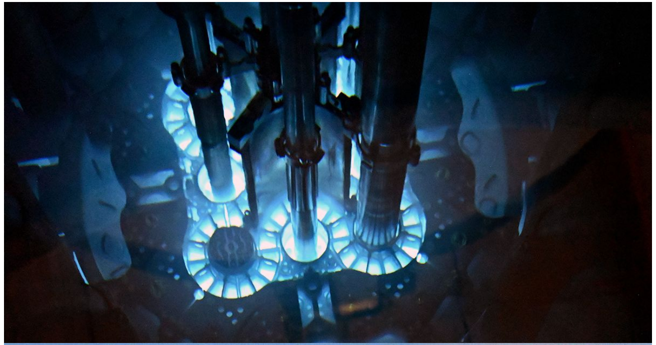
Calorimeters

- Particles deposit energy in the calorimeter via a shower (shown on the right)
- Absorber layers (dense material) interact with the particle, releasing more particles in a cascading fashion
- Active layers measure the particles created in the shower
- By measuring the energy deposited in the shower, we can measure the energy of the original particle



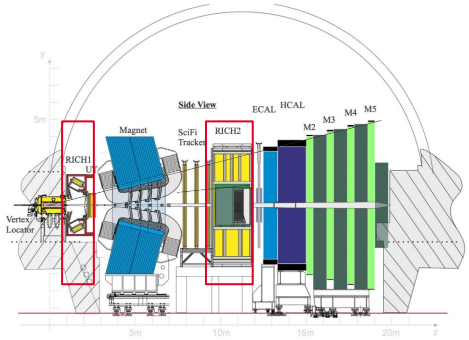
RICH Detectors

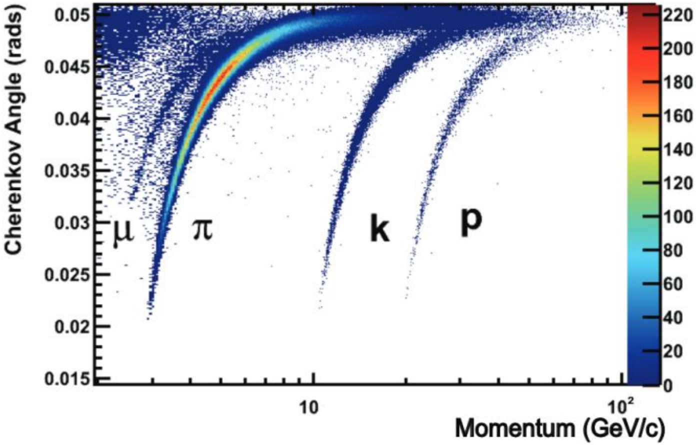
- Speed of light in materials is slower than in a vacuum, dependent on material properties
- Cherenkov Effect: particles traveling faster than the speed of light in a material emit light in a cone around them
- Seen in nuclear reactors (top), analogous phenomenon to sonic booms (bottom)
- We can use this effect to determine the type of particles
- RICH detectors fit into the broader category of Particle Identification (PID) detectors



RICH Detectors

- The angle of the Cherenkov light cone is determined by:
    - The material the particle is traveling through
    - The particle's momentum
    - The particle's mass
- Given that we know the material, and we can measure the light cone angle and momentum, we can calculate the particle's mass
- Different types of particles behave differently in the RICH detector (see plot on the right)

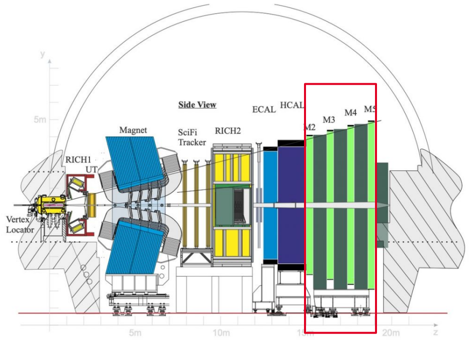


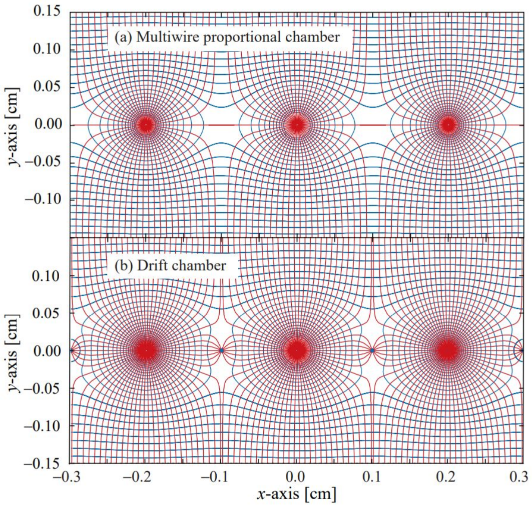


arXiv:2305.10515

Muon Detectors

- Muons are hard to stop, will pass through calorimeters and other dense material
- Muon detectors are also tracking detectors
- Typically are gaseous detectors, because they can occupy a large area at relatively cheap cost
- Muon detection layers are interspersed with steel
- If a track is formed in all layers of the muon system, we can say with good certainty that the particle is a muon
- Tracks can be combined with other tracking subdetectors (SCIFI, UT, VELO)





Triggers

- LHC delivers $4x10^7$ collisions per second
- If we kept all the data, we'd be storing ~4 Tb per second - way too much to store everything
- We need a way to filter events to choose what data to keep
- This process is called **Triggering**

Triggers

- Experiments that expect more data have a hardware trigger — a signal from their detector to signal a potential event before even reaching the software
- LHCb trigger system operates completely on software
- HLT1 (High-Level Trigger) is the first stage of the trigger, partially reconstructing the event and making decisions based on broader criteria
- HLT2 reconstructs more of the event and makes decisions based on more selective criteria
- Events that pass both trigger levels are saved for offline processing