What detectors measure

- As a particle goes through matter, it releases energy
- Detectors collect the released energy and convert it to electric signals recorded by DAQ
- Raw event record is a collection of hits
- Hit: a single measurement in the detector, characterized by its position (x,y,z), energy deposit ΔE, and time
  - Real events also have "noisy" hits (e.g. due to electronic noise) and "shared" hits (due to more than one particle)

Hit components (1)

- Position: can be precise (μm) or defined by the size of the detector element, also can be precise in one direction and coarse in another
  - known w.r.t. detecting element, needs to converted to the global reference frame
  - alignment: procedure of figuring out the actual location of detector elements

Hit components (2)

- Energy deposit: may or may not be available (analog vs digital readout)
  - tracking detectors: try to make it small to minimize the disturbance to the particle motion
  - calorimeters: make it close to the total particle energy
  - need to convert the readout to actual energy ("calibration")
- Time: determined w.r.t to some reference (accelerator clock, trigger), can be precise (tens of ps) or just a time window

What detectors tell about the particle

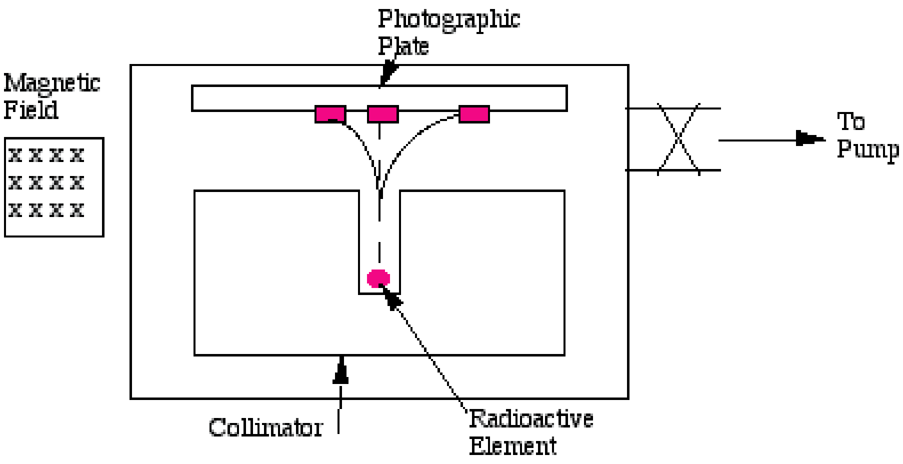
- That it's there (detectors that can just establish the particle's presence are called counters)
- Its momentum (by combining individual particles into trajectories)
  - a charged particle of momentum p in magnetic field B follows a helix of radius $R=p_T/qB$
  - luckily, we can almost always assume $|q|=e$
- Its type (→mass)
  - from the way it looks in the detector (e.g. RICH)
  - from time of flight
  - from energy deposit
- If a particle gives rise to a bunch of collinear particle products, it makes sense to measure all of the together as a single cluster (e.g. jets due to quarks/gluons)

The eye: a natural particle detector

- Detected particles: photons
- Sensitivity: high (single photons)
- Dynamic range: excellent ($1–10^{14}$)
- Energy range: poor (visible spectrum 400 – 700 nm)
- Energy discrimination: good (1 – 10 nm)
  - trichromats (humans): 10^7 colors
  - pentachromats (e.g. pigeons): 10^{10} colors
- Speed: low (~10 Hz, including processing)

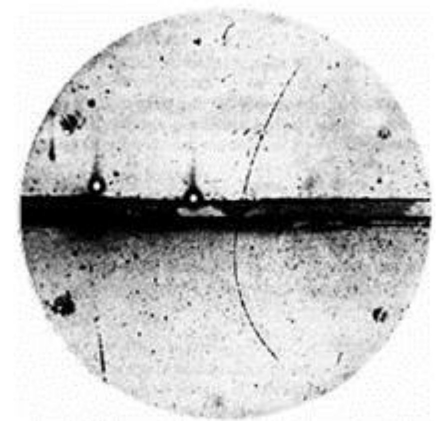
Photo emulsion

- The oldest particle detector
  - photographic plates helped Becquerel to discover radioactivity in 1896
- Good: spatial resolution (<1 μm)
- Bad: no time resolution, tricky readout



- Still used in modern experiments (OPERA)
  - used by DONUT to discover the τ-neutrino (2000)
- Used in personal dosimeters ("badges")

The cloud chamber



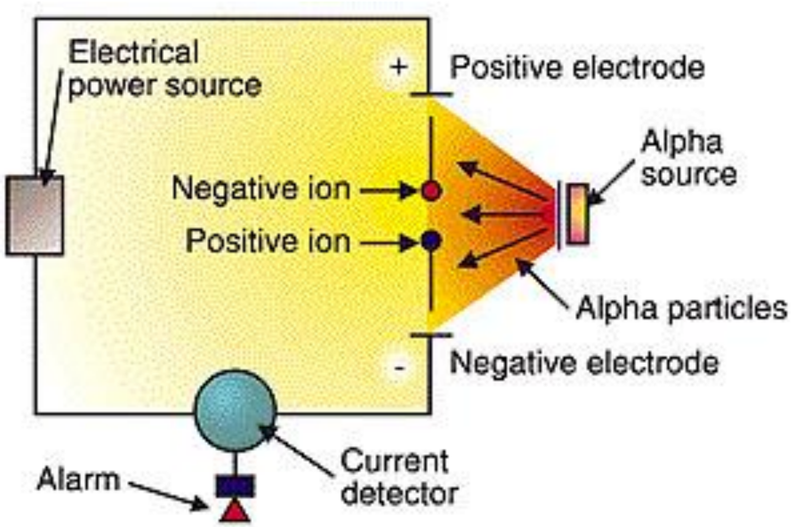
- C. T. R. Wilson (1911, Nobel prize: 1927)
  - Used by Anderson to discover the positron (1932, Nobel prize: 1936)
- Principle of operation:
  - an air volume is saturated with water vapor
  - pressure lowered to generate super-saturated air
  - charge particles cause saturation of vapor into small droplets that form a "track"
  - photographs allow longer inspection
- Spatial resolution is fair (0.1 – 1 mm)
- Time resolution is fair (seconds) but the detector can be used continuously!

The bubble chamber

- D. A. Glaser (1952, Nobel prize: 1960)
- An improvement over the cloud chamber
  - a liquid is heated near the boiling point
  - a pressure is suddenly dropped, so the liquid becomes superheated
  - particles entering the chamber create a track of micro bubbles
- Widely used in 1970's
  - Gargamelle: a 12 m^3 bubble chamber used to discover neutral currents (1973)

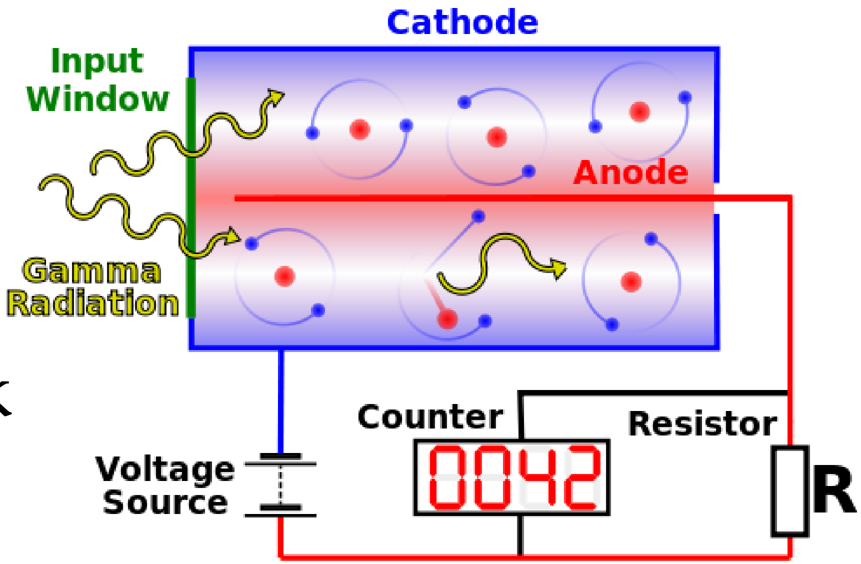
Ionization chamber

- When a charged particle crosses the gas volume it ionizes it (breaks atoms into ion—electron pairs)
- If placed inside electric field, ions and electrons drift towards electrodes and create current
- Example: smoke detector
  - radiation source (Am-241) emits α-particles
  - they pass through ionization chamber, creating current
  - smoke absorbs α-particles and interrupts current



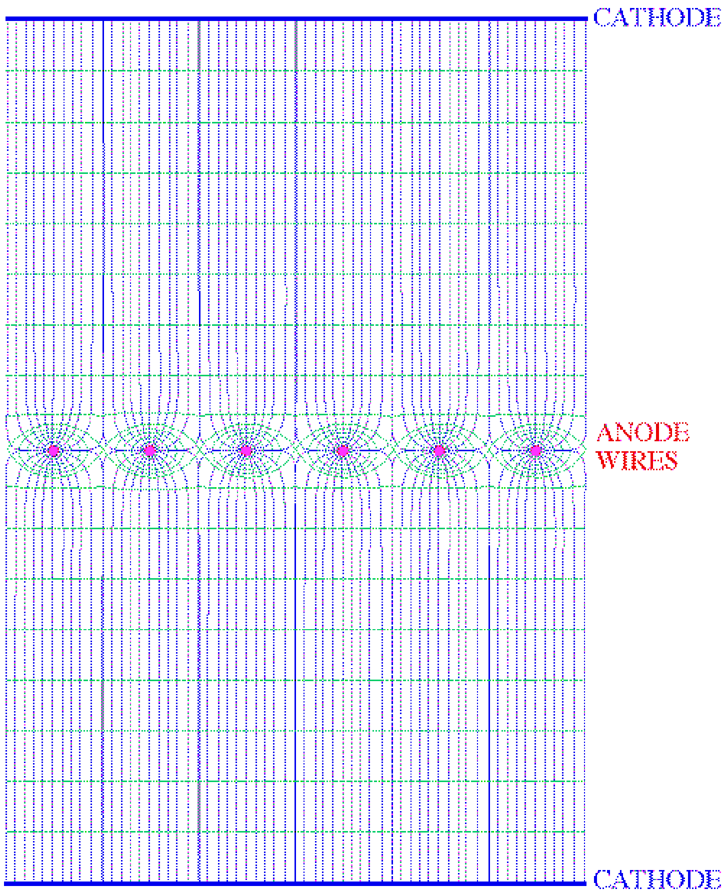
The Geiger counter

- H. Geiger (1908)
  - single ion-electron pairs are too difficult to be detected
  - if the electric field is strong, electrons cause multiple ionizations – a process known as “avalanche”
  - avalanches cause a strong electric pulse, recorded by electronics (and heard as a click!)
- Good: sensitive to single particles, fast response (microseconds)
- Bad: no spatial resolution, no dynamic range (one click for everybody)



Multiwire proportional chamber

- G. Charpak (1968, Nobel prize: 1992)
- MWPC fixed the lack of spatial resolution (by introducing multiple wires) and lack of dynamic range (by tuning the geometry and voltage to control the ionization)
- Revolution in data acquisition: MWPC was directly linked to a computer



Modern detector types

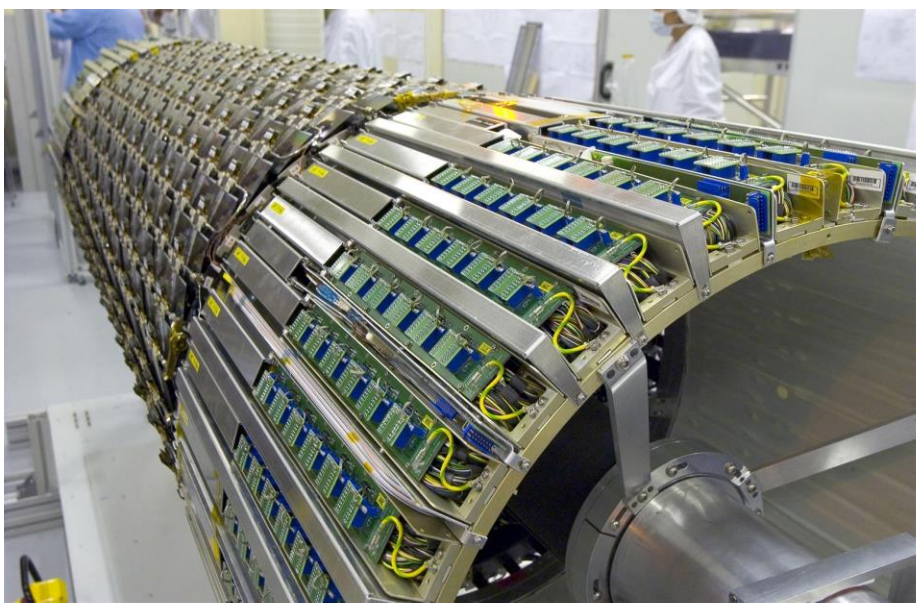
- Tracking detectors
  - detect charged particles
  - principle of operation: ionization
  - two basic types: gas and solid
- Scintillating detectors
  - sensitive to single particles
  - very fast, useful for online applications
- Calorimeters
  - measure particle energy
  - usually measure energy of bunches of particles ("jets")
- Particle identification systems
  - recognize electrons, charged pions, charged kaons, protons

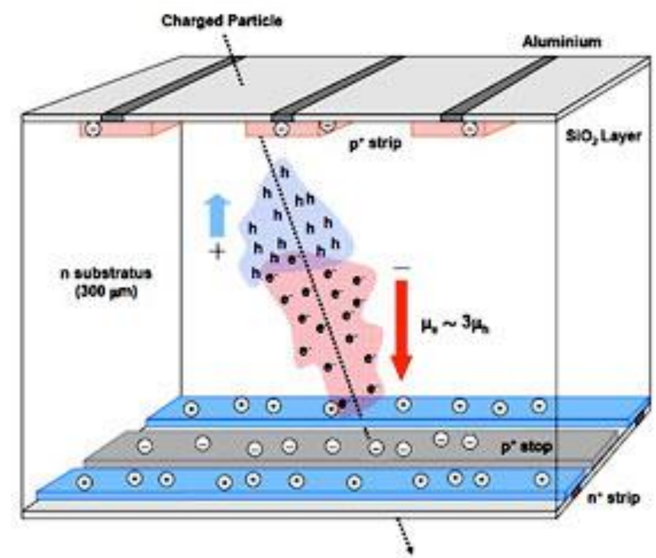
Tracking detectors

- A charged track ionizes the gas
  - $10-40$ primary ion-electron paris
  - multiplication $\times 3-4$ due to secondary ionization)
- The same principle (ionization + avalanche) works for solid state tracking detectors
  - dense medium → large ionization (32,000 electron-hole pairs per 300 μm thick detector due to a minimum ionizing particle)
  - more compact → put closer to the interaction point

Tracking detectors

- Solid state detectors = diodes at reverse bias
  - strip detectors: divide the large-area diode into many small strip-like regions and read them out separately
  - can achieve resolutions of several μm
  - pixel detectors: a matrix of read-out regions, 3d measurements





Calorimetry

- The idea: measure energy by total absorption
  - also measure location
  - the method is destructive: particle is stopped
  - detector response proportional to particle energy
- As particles traverse material, they interact producing a bunch of secondary particles ("shower")
  - the shower particles undergo ionization (same principle as for tracking detectors)
- It works for all particles: charged and neutral

Electromagnetic calorimeters

- Electromagnetic showers occur due to
  - Bremsstrahlung: similar to synchrotron radiation, particles deflected by atomic EM fields
  - pair production: in the presence of atomic field, a photon can produce an electron-positron pair
  - excitation of electrons in atoms
- Typical materials for EM calorimeters: large charge atoms, organic materials
  - important parameter: radiation length

Hadronic calorimeters

- In addition to EM showers, hadrons (pions, protons, kaons) produce hadronic showers due to strong interaction with nuclei
- Typical materials: dense, large atomic weight (uranium, lead)
  - important parameter: nuclear interaction length
- In hadron shower, also creating non detectable particles (neutrinos, soft photons)
  - large fluctuation and limited energy resolution

Muon detection

- Muons are charged particles, so using tracking detectors to detect them
  - Calorimetry does not work – muons only leave small energy in the calorimeter (said to be "minimum ionization particles")
  - Muons are detected outside calorimeters and additional shielding, where all other particles (except neutrinos) have already been stopped
  - As this is far away from the interaction point, use gas detectors

Detection of neutrinos

- In dedicated neutrino experiments, rely on their interaction with material
  - interaction probability extremely low → need huge volumes of working medium
- In accelerator experiments, detecting neutrinos is impractical – rely on momentum conservation
  - electron colliders: all three momentum components are conserved
  - hadron colliders: the initial momentum component along the (anti)proton beam direction is unknown

Multipurpose detectors

- Today people usually combine several types of various detectors in a single apparatus
  - goal: provide measurement of a variety of particle characteristics (energy, momentum, flight time) for a variety of particle types (electrons, photons, pions, protons) in (almost) all possible directions
  - also include "triggering system" (fast recognition of interesting events) and "data acquisition" (collection and recording of selected measurements)
- Confusingly enough, these setups are also called detectors (and groups of individual detecting elements of the same type are called "detector subsystems")

Generic HEP detector