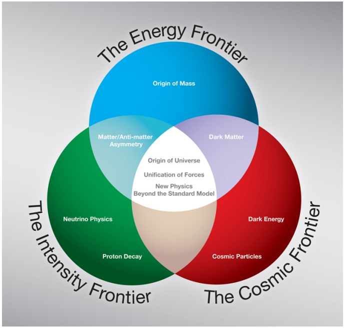
Physics 129: Particle Physics
Lecture 4: Accelerators and Detectors (Part I)

Sept 8, 2020

- Suggested Reading:
  - Thomson Sections 1.2-1.4
  - Perkins Chapter 11
  - PDG Reviews listed under *Experimental Methods and Colliders*

The 3 frontiers

- Energy Frontier
  - Use high energy colliders to discover new particles and new interactions and directly probe the fundamental forces
- Intensity Frontier
  - Use intense particle beams or large mass detectors to uncover the properties of neutrinos and to observe rare processes that involve other elementary particles
- Cosmic Frontier
  - Use underground experiments or telescopes to study Dark Matter and Dark Energy. Use high energy particles from space to search for new phenomena



- The “frontiers” describe experimental approaches
- Different approaches can often target the same physics questions

Particle Physics Strategies

- Create new particles through high energy collisions
  - $E = mc^2$
  - Examples: e^+e^- or hadron colliders
- Scatter particles (beam) from a target:
  1. Study structure of the target
     - eg Rutherford scattering or structure of proton
  2. Understand interaction between beam and target
     - eg Study weak neutral current using ν-p scattering
  - Sometimes the target can be another beam
- Study particle decays
  - Use decay rates and kinematics to:
    - Understand internal structure (spectroscopy)
    - Study symmetry properties of interactions
    - Confirm or refute detailed SM predictions
  - Search for unexpected decays that signal presence of new interactions
    - ie violation of a expected conservation law

Accelerator vs Non-accelerator Experiments

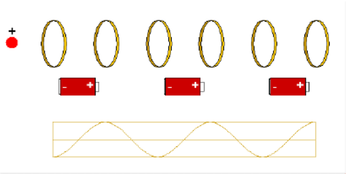
- Previous slide focused on discussion of beams
  - Often implies man-made beams from accelerators
- But can also use “beams” from nature
  - eg ν or Dark Matter particles from outer space

  or from other man-made sources
  - eg ν from reactors
- Experimeents without a beam possible
  - proton decay, neutrinoless double β-decay
  - astrophysical measurements

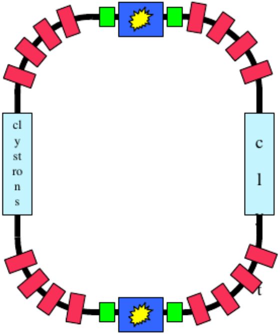
Today and Thursday, we’ll explore how experimental goals and strategies affect detector and accelerator design

Accelerators: Using particle beams to probe the energy and intensity frontiers

- Charged particles "surf" on EM waves produced from RF cavities



- Magnetic fields used to steer the beams



Will discuss how accelerators work in Thursday's lecture

Fixed Target vs Collider

- Colliding Beams:

Beams of equal and opposite momentum give;

$$E_{cm} = \sqrt{4E_1E_2}$$

  - Usually in center-of-mass
  - All energy available for hard scattering and/or creation of new particles

- Fixed Target:

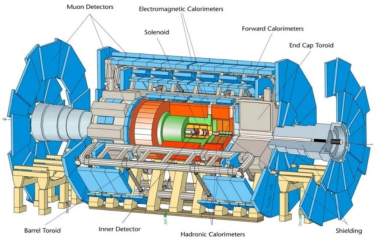
$$E_{cm} = \sqrt{2m_{target}E_{beam}}$$

  - Kinetic energy infinal state: available to produce particles
  - Variety of targets and beams possible
    - Including beams of unstable particles
    - Larger target mass, higher event rates

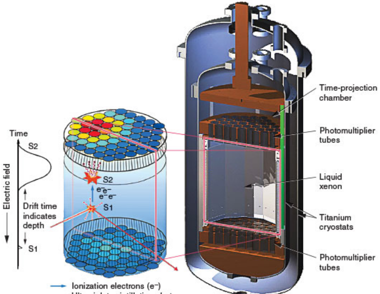
Configuration of multiple detector elements

- Most experiments combine different detector technologies
  - Each emphasizes different type of measurement
- Geometry determined by type of "beam":
  - Collider, fixed target, non-accelerator
- Granularity determined by # particles per event
- Required resolution depends on
  - Momentum and energy of produced particles
  - Backgrounds to be rejected
  - Necessary precision

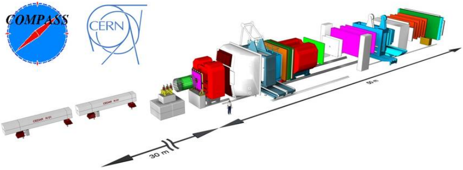
ATLAS (Collider)



LUX (Underground DM Detector)



Compass ν experiment (Fixed target)



Classification of particle detectors: What do we measure?

- Charged Particles
  - Momentum: Determine trajectory in B field
  - Mass: More difficult; Measurement of velocity and momentum
  - Energy: Deposited as particle stops.
    - Energy loss from ionization, bremsstrahlung

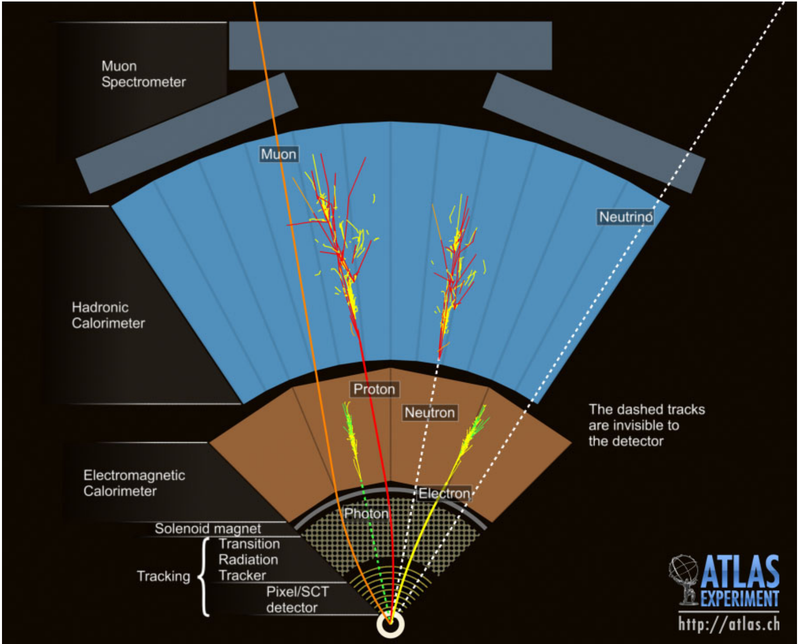
Tracking Detectors

- Strongly Interacting Particles (charged or neutral)
  - Energy: Deposited where particle stops
    - Energy loss from nuclear interactions
- Photons
  - Energy: Pair production followed by ionization

Calorimeters

- Muons
  - Momentum: As for other charged particles
  - No nuclear interactions
    - Can pass through lots of matter before stopping
    - Place additional tracking detectors after calorimeter
- Neutrinos
  - Often observed by their absence: missing momentum
  - Weak interactions, eg $\nu_\mu N^Z \to \mu^- N^{Z+1}$ or $\nu_\mu N^Z \to \nu_\mu X$

How it works:



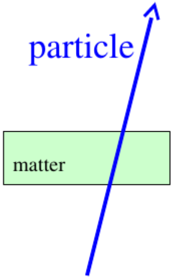
Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

Interaction of particles with matter

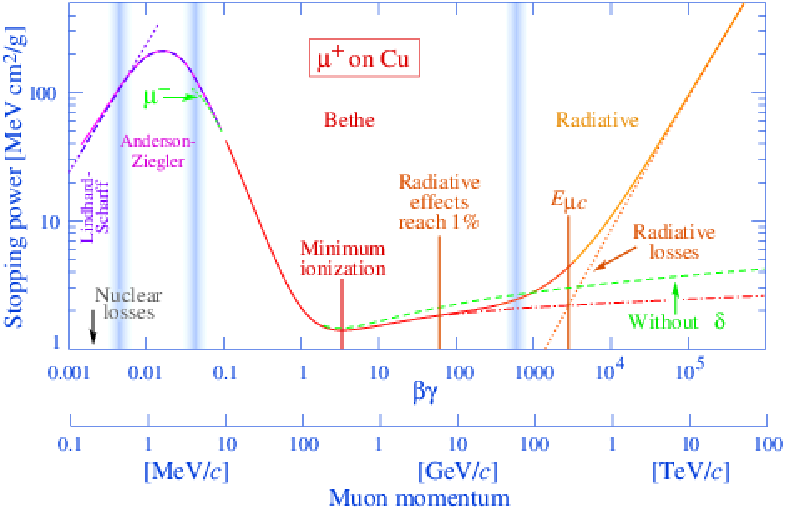
- Except for hadron calorimeters and ν-detectors, particle detection depends on EM interaction of the particle with a detector element
  - Even for these exceptions EM interactions dominate through detection of secondaries
- Charged particles leave ionization trail
  - Amount of ionization per unit length depends on velocity
  - Total ionization produced when particle stops measured from number of ionizing particles produced in "shower"
- Statistical description of ionization energy loss

Charge particle interactions with matter

- Charged particles deposit energy in matter
  - Ionization
    - Average ionization energy loss (dE/dx)
    - Fluctuations in ionization deposition
  - Light
    - Scintillation
    - Cerenkov radiation
    - Transition radiation
- Matter affects charged particles
  - Multiple scattering
  - Bremsstrahlung



Energy loss in Matter (particles heavier than electrons)



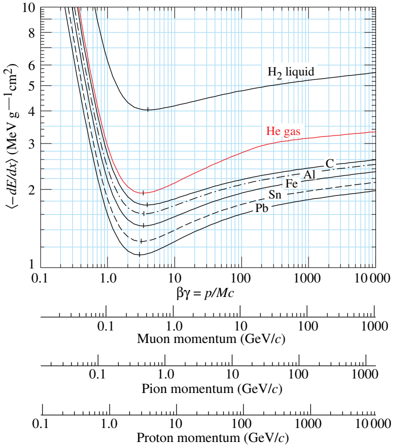
Energy loss at intermediate energies

- Bethe-Block Formula

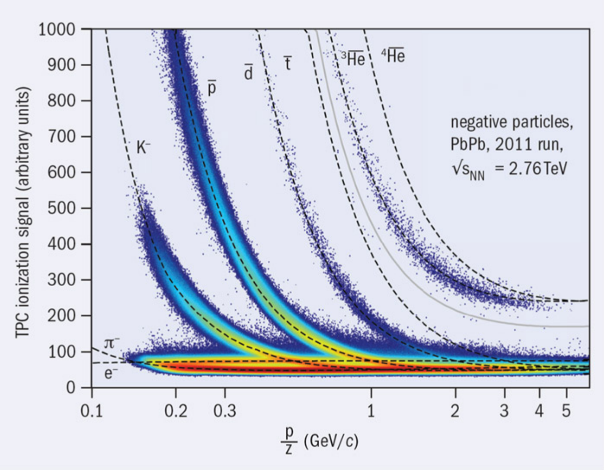
$$\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$\begin{aligned} K &= 4\pi N_A r_e^2 m_e c^2 \\ &= 0.307 \text{MeV mol}^{-1} \text{cm}^2 \end{aligned}$$

- m_e, m_N, α: universal constants: electron and nucleon masses, fine structure constant
- z, β, γ: Incoming particle charge, $\beta \equiv v/c$, $\gamma = 1/\sqrt{1 - v^2/c^2}$
- Z, A, ρ, I: properties of medium
- W_{max}: maximum energy that can be transferred
- $\delta(\beta\gamma)$: Correction due to polarization of medium



dE/dx for particle identification



ALICE experiment, Heavy Ion collisions at the LHC

- dE/dx depends on $\beta\gamma$ and p : $\Rightarrow$ depends on mass
- Can distinguish between e, π, K, p at low momentum

Multiple Coulomb Scattering

- Rutherford scattering

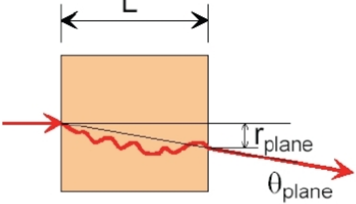
$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\left(\frac{zZ\alpha}{\beta p}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

- Random walk: N steps of size d: Total deviation is Gaussianly distributed with width D:

$$D \sim \sqrt{dN}$$

- Resulting angular spread

$$\begin{aligned} \theta_{rms} &= (14\ MeV)\frac{z}{\beta l}\sqrt{L/X_0} \\ r_{rms} &= \frac{1}{\sqrt{3}} L\theta_{rms} \end{aligned}$$

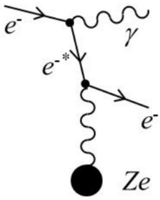


- where X_0 is the "radiation length" of the material

(see next page)

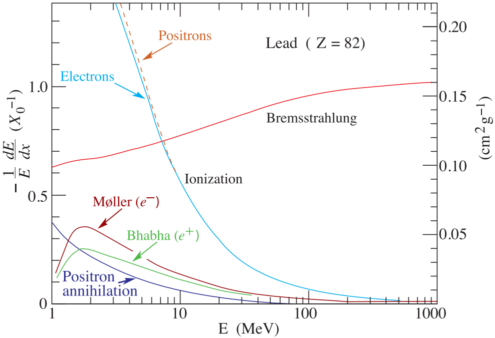
Bremsstrahlung

- Radiation of photons from charged particles
  - Can carry away a large fraction of energy
  - Energy loss increases with incident energy



For electrons $\frac{dE}{dx} = -\frac{E}{X_0}$

- Radiation length X_0 is both:
  1. Mean distance over which a high-energy electron losesall but $1/e$ of its energy by bremsstrahlung
  2. 7/9 of the mean free path for pair production by a high-energy photon



- Critical energy
  - Energy where losses from brem equal those from ionization
    - Electrons: 20 MeV in iron
    - Muons: ~ 1 TeV in iron

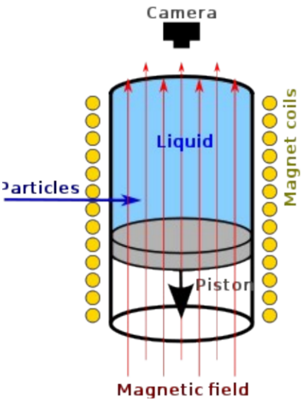
Tracking Detectors

- Tracking Detectors observe and measure the properties of charged particles
- Goal is to determine:
  - Trajectory
  - Momentum
  - Sometimes, species or mass
- Often placed in magnetic field; curvature to find momentum
- Often measure ionization trail (although other possibilities as well)
- Combination of tracks originating from one spot can be used to isolate a vertex from interaction or decay of particles

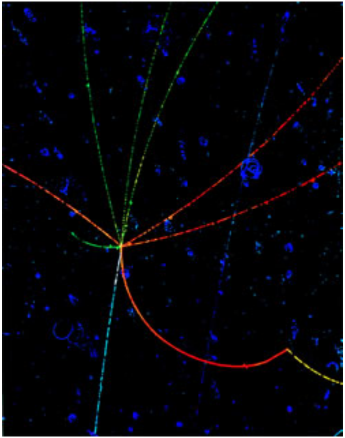
Bubble Chambers

- Large cylindrical tank of liquid heated to just below boiling point
- Piston suddenly desceases pressure ⇒ liquid in superheated phase
- Charged particles leave ionization track; liquid vaporises around track
  - Bubbles!
  - Bubble density proportional to dE/dx
- Drawbacks:
  - Photographic readout
  - Difficult to "trigger" on events
  - Cannot reset quickly

Don Glaser Nobel Prize 1960



Bubble Chamber Picture of Proton-Antiproton Annihilation



http://www2.lbl.gov/Science-Articles/Archive/sabl/2005/October/01-antiproton.html

An antiproton (cyan) enters a bubble chamber from bottom left and strikes a proton.

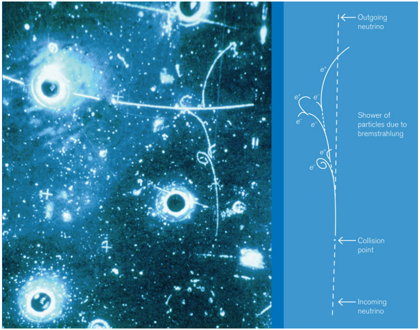
The released energy creates four positive pions (red) and four negative pions (green).

The yellow streak at the far right is a muon, a decay product of the adjacent pion.

Gargamelle and the Discovery of Neutral Currents

Gargamelle at CERN

Diameter: 2m, Length 4.8m



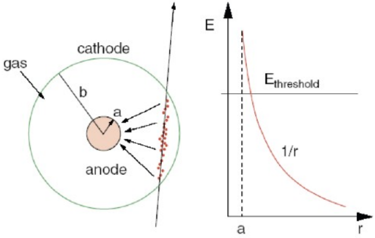
- Discovery of neutral weak currents in 1973
- Critical for establishing electroweak theory

$$\nu_\mu + e^- \to \nu_\mu + e^-$$

Gaseous Wire Chambers

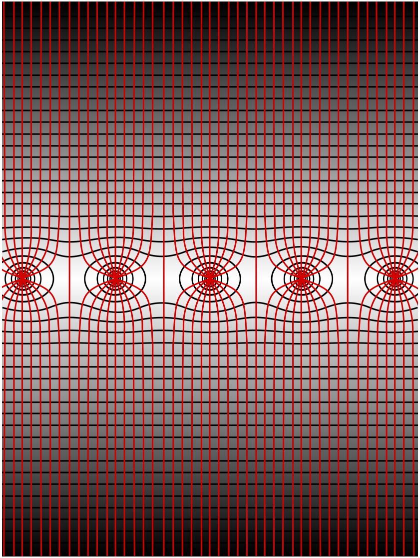
- Ionization signal in gas leaves ~ 100 electrons/cm
  - Too few to detect
- Solution:

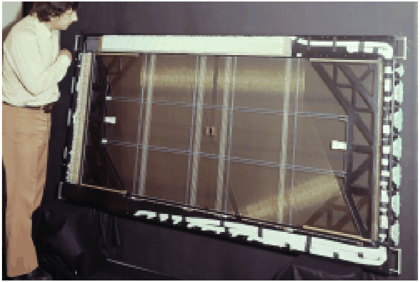
  Introduce thin wires (20-100μm) at positive HV (few kV) for gas multiplication
  - Field $E \sim 1/r$
  - Ionization electrons accelerate, ionizing more atoms
  - Avalanche develops with overall multiplication (gas gain) controllable by adjusting voltage



Example: Geiger counter

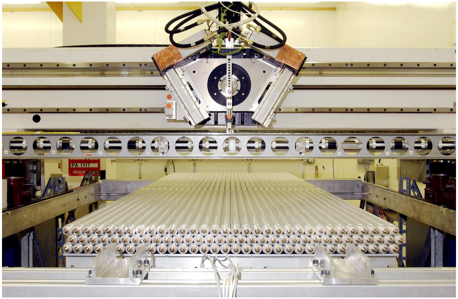
Multiwire Proportional Chambers

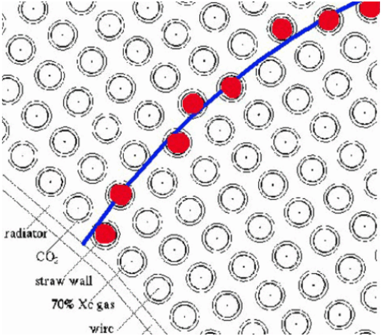




- For many years, a mainstay in HEP experiments
- Position resolution determined by wire spacing (few mm)
- Some chambers have etched pads on the cathode to provide measurement along wire direction

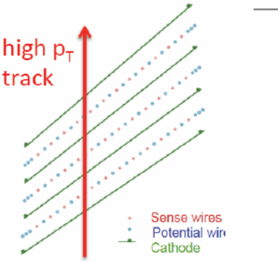
Drift Tubes

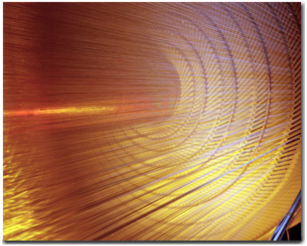




- Know when particle goes through detector (t_0)
- Measurement drift time $\Delta t = t - t_0$
  - Drift distance: $x = f(\Delta t)$
- Typical resolution: 100-200 μm

Multiwire Drift Chambers



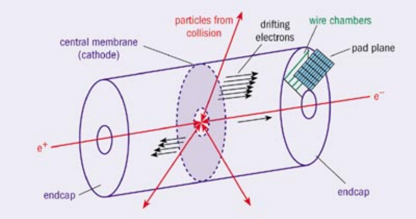


CDF Drift Chamber

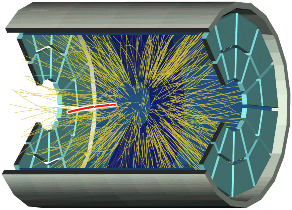
96 radial layers of gold wires spaced 3.9 mm from each other

- Similar to drift tubes but without individual tubes
- Both flat-plane and cylindrical geometries possible
- Can cover large surface areas

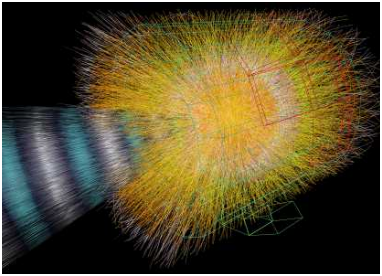
Time Production Chamber (TPC)



STAR TPC



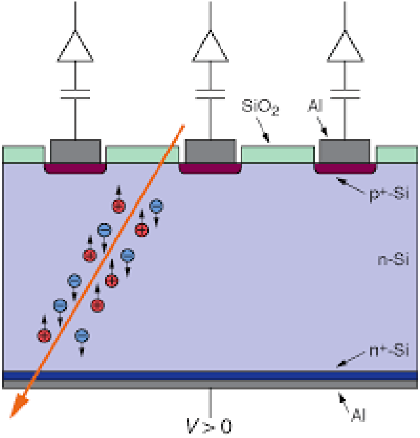
ALICE TPC



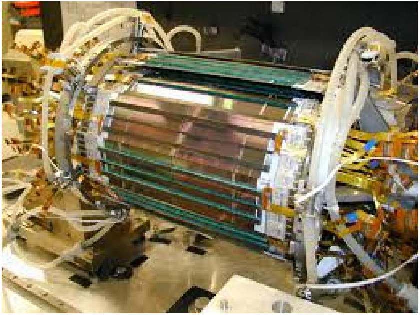
- Long drift distance
- Ionization collected at ends
- Very little material in tracking volume
- Good two-track resolution

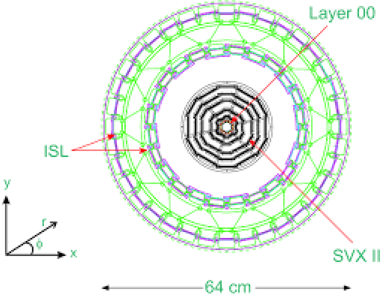
Solid State Detectors: Semiconductor Devices

- Inverse potential applied to p-n junction (reverse bias) in Si creates large volume depleted of charge carrier
  - Semiconductor behaves as insulator with no current flowing
- Ionization (from charged particles traversing sensor) release electron-hole pairs that drift apart and are collected on either side of sensor

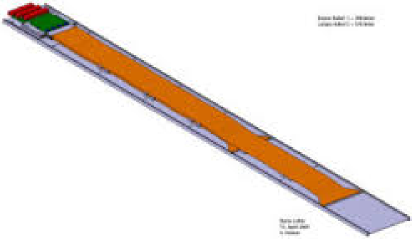


Silicon Strip Detectors

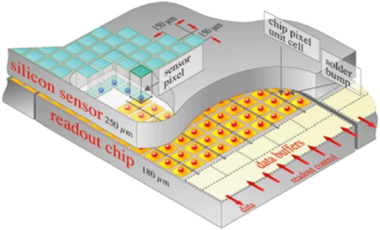


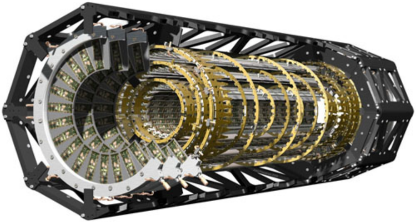


- Strips etched onto silicon waifer
  - Typical size of waifter: 3cm x 6 cm
  - Typical strip pitch: 50-100 μm
- One amplifier per strip
  - Only hit strips sent to data acquisition system



Pixel Detectors: Same idea, more channels





- Instead of long strips, 2D rectangles
- Electronics mounted on top of each pixel
- Example: ATLAS pixel detector
  - 1744 modules
  - 80 million pixels
  - Pixel size: 50μm x 400μm
  - Resolutiion 10μm in bending plane