Physics of Particle Detectors

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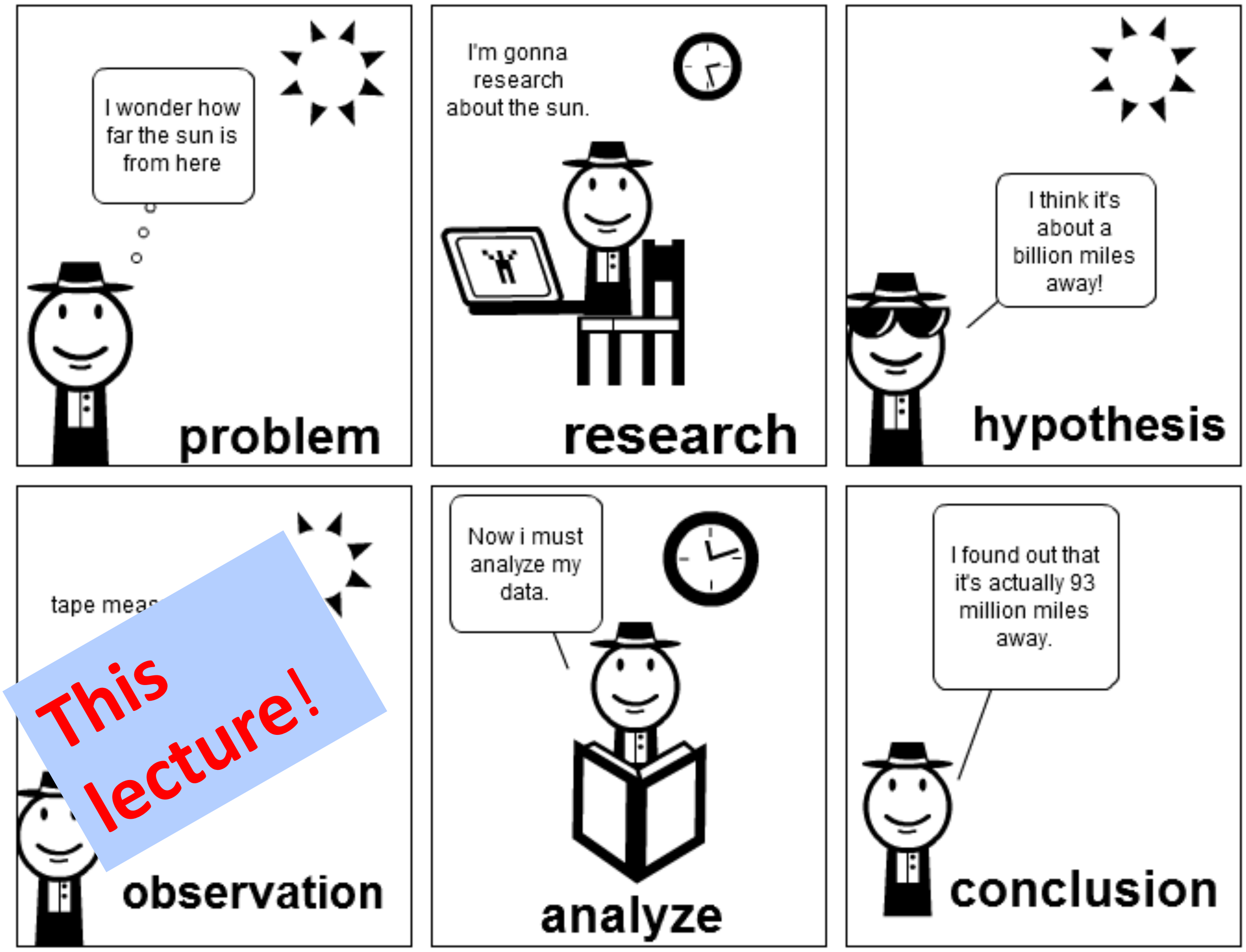
Saturday Morning Physics

24 October 2020

What are we trying to learn about?

- What are the building blocks of nature?
- How do particles interact?
- Why is there more matter than antimatter?
- What is dark matter?
- What is dark energy?

How are we going to answer these questions?



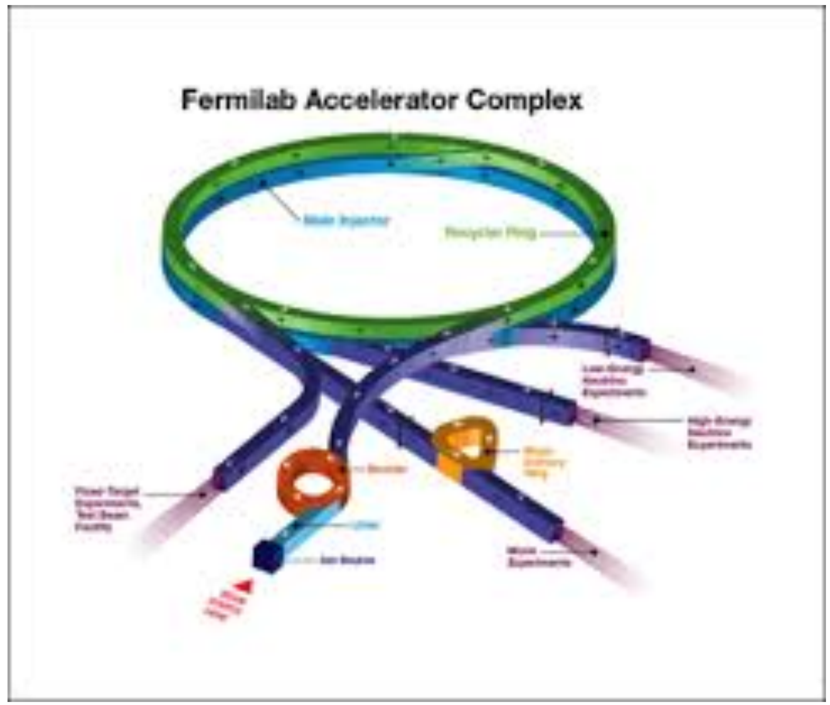
So – what is our tape measure?

- **We want to look at something very very small and see if it is made of smaller things. We also want to see how two small particles interact.**
- **Can we use a microscope?**
  - Best scanning electron microscope can see something as small as 0.2 nanometers (0.0000000002 meters)
  - Smallest object human eye can see is a few microns (0.000001 meters)
  - The Bohr radius of hydrogen atom is 0.000000000053 meters (53 picometers)

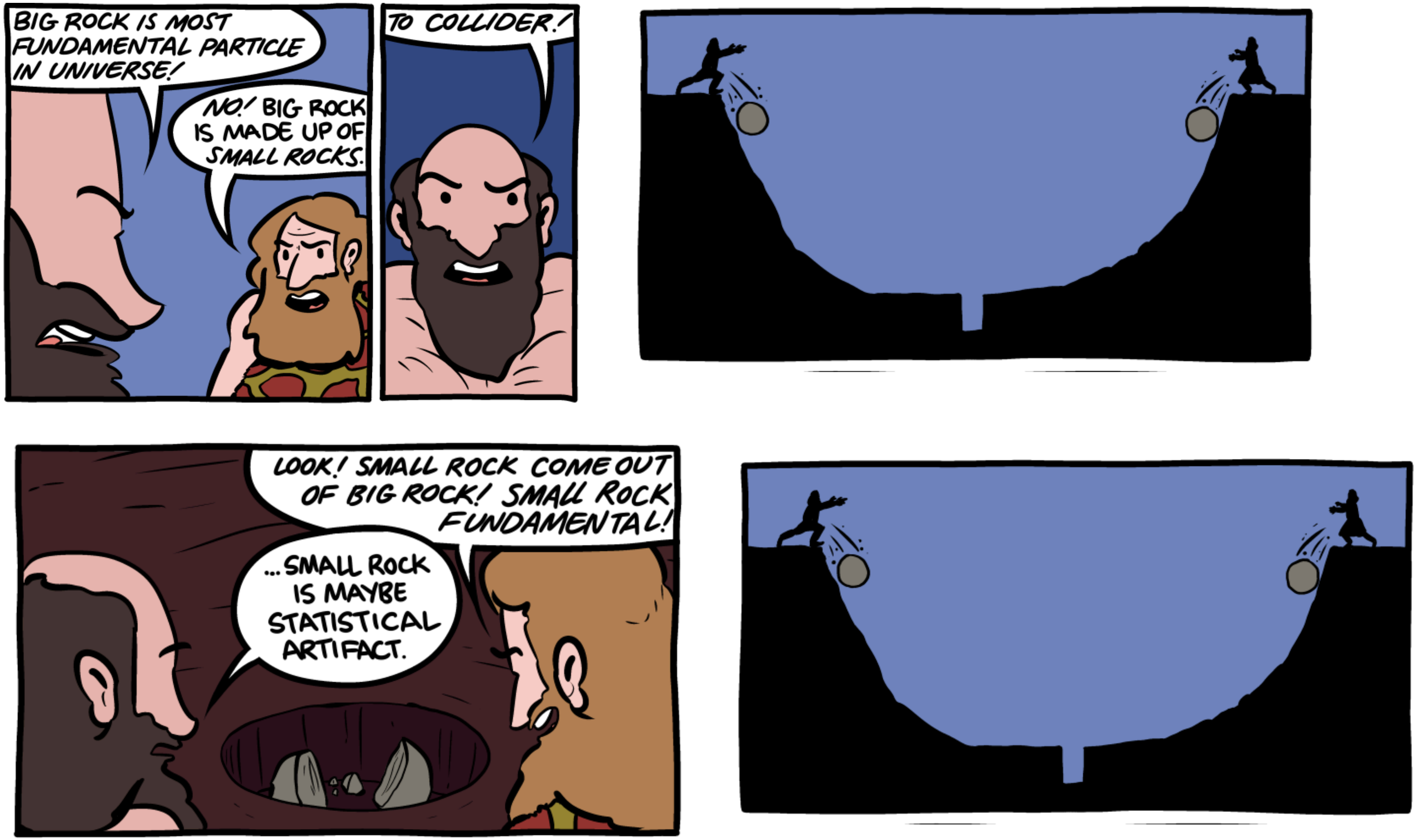
- **How do we look at such small objects?**

How do we look at such small objects? Collisions

- To break down these particles, we also need a ton of energy and shoot them at each other or targets.
  - *Accelerator Lecture (Cindy Joe)*



In Other Words



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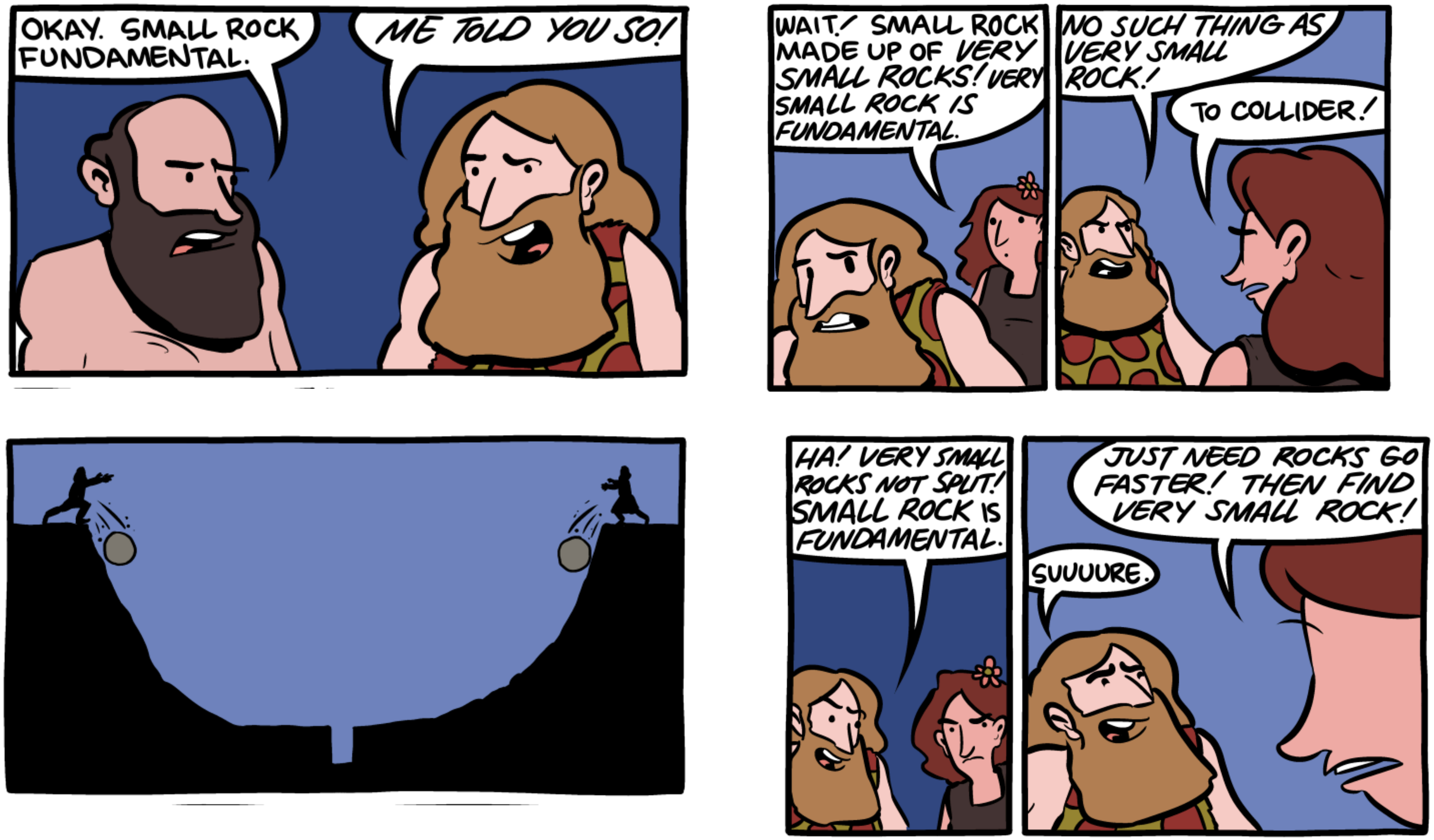

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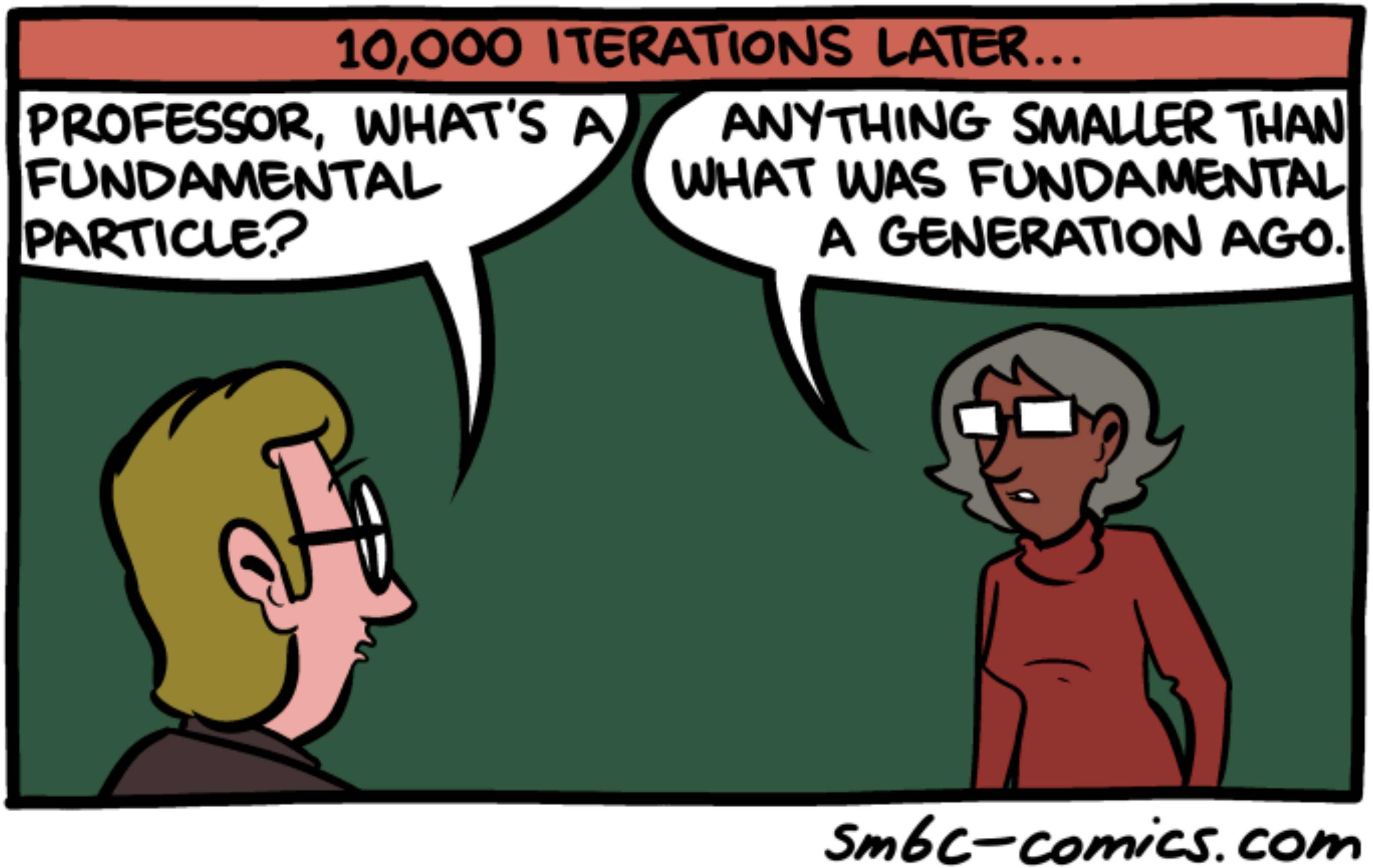
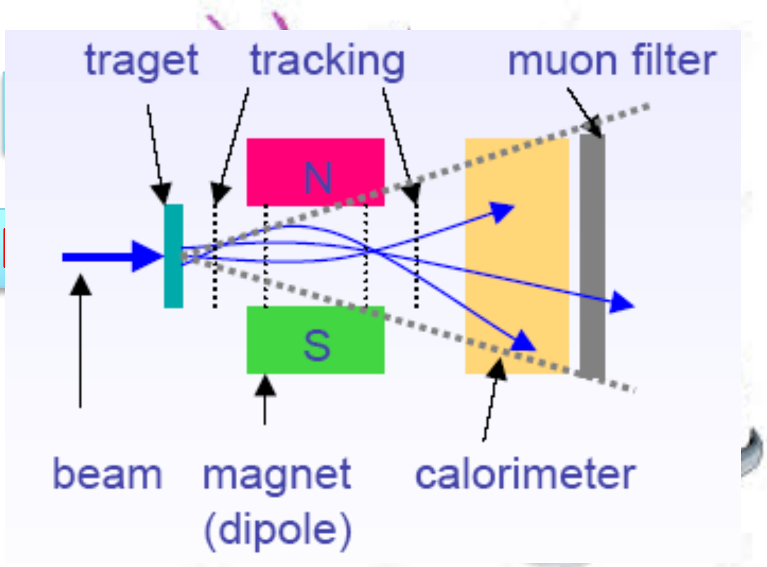
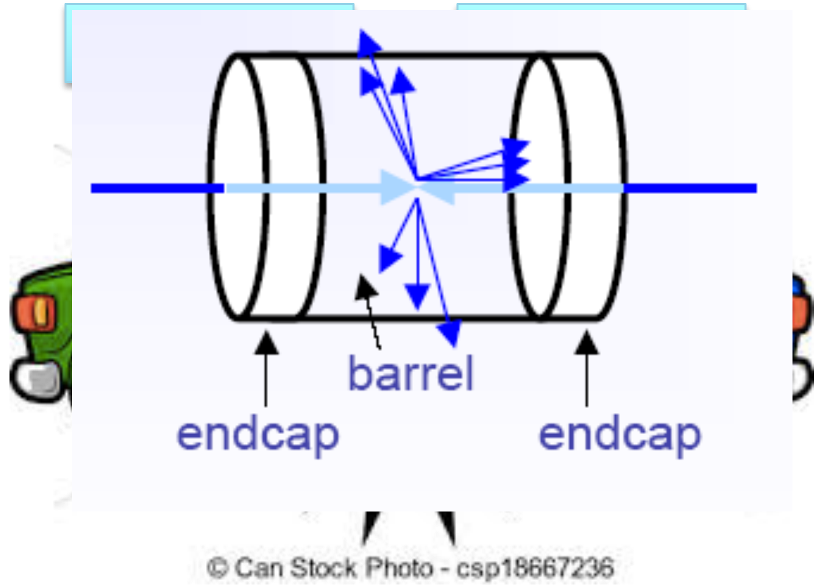


We only see the end products of the collision

Fixed Target Geometry



Collider Geometry

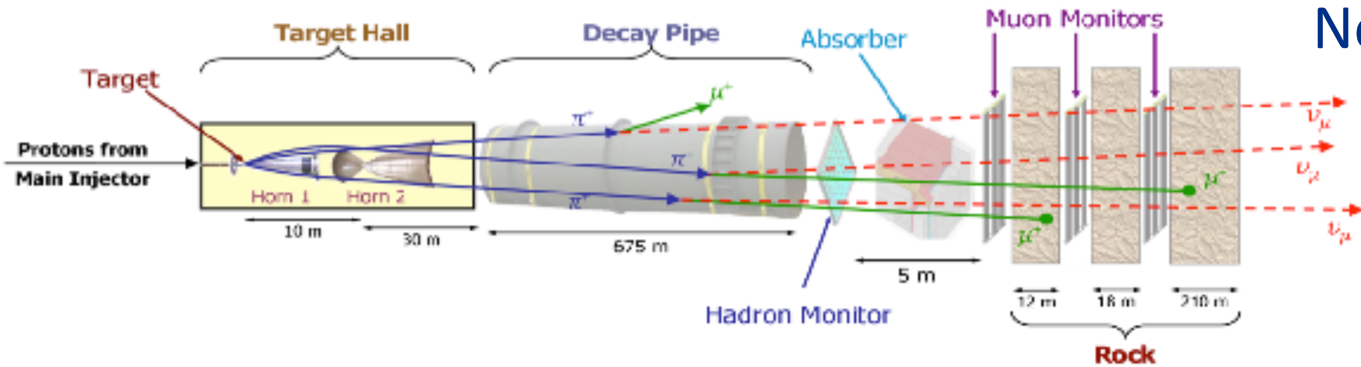


Detector

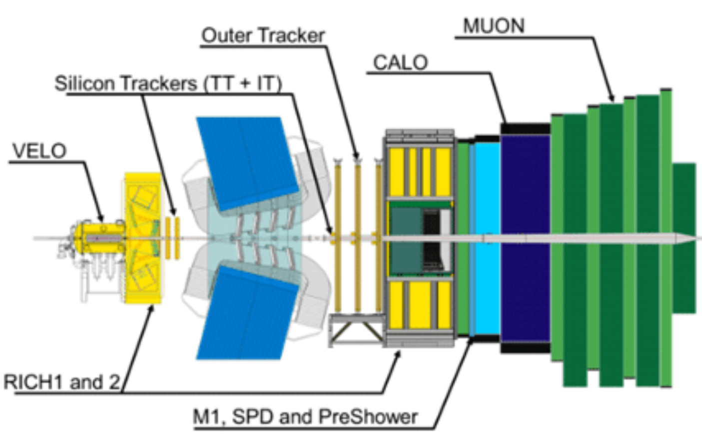
Detector

You've seen these!

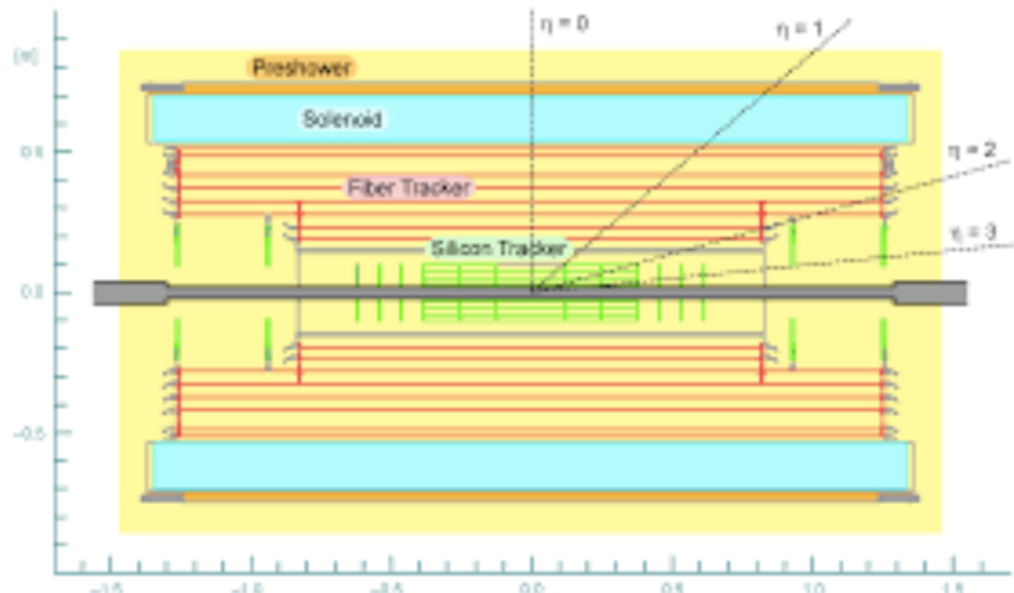
Neutrino Campus



LHCb @ CERN

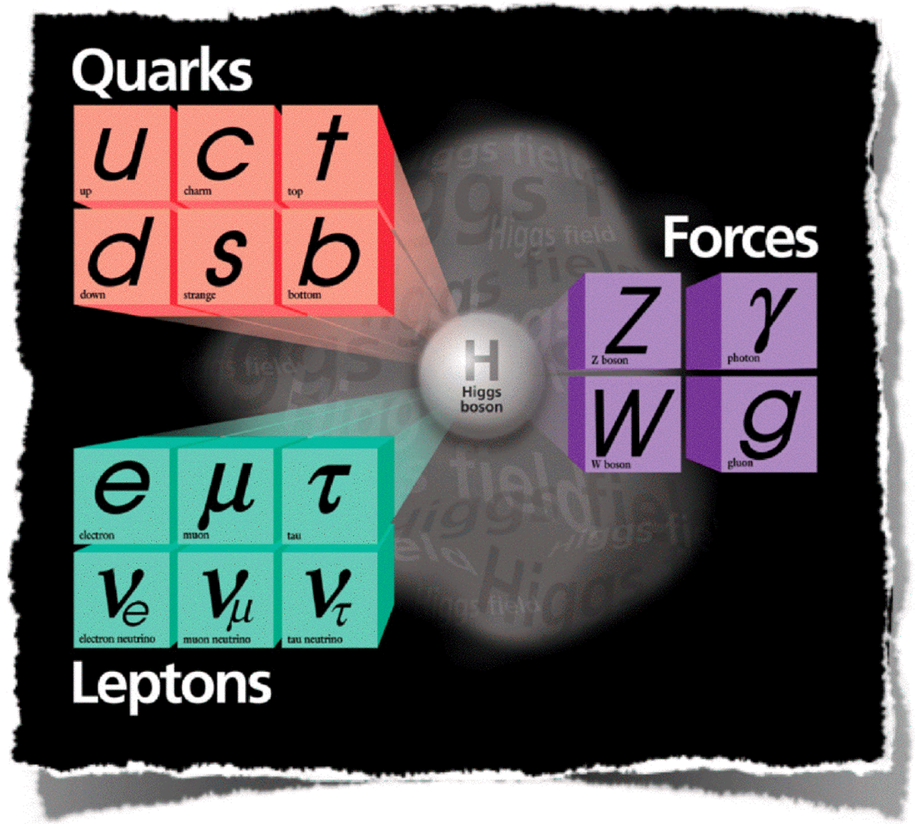


D0 Detector



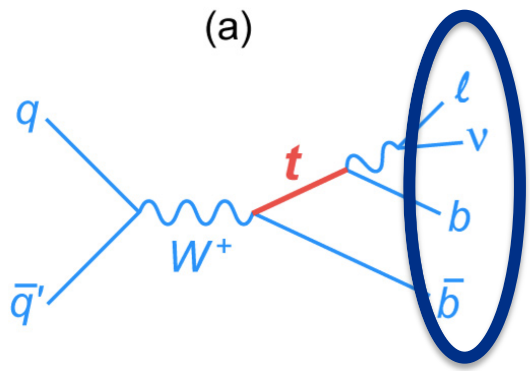
What will be in those collisions?

- **Full Intro Lecture on 10/17**
- **Standard Model**
  - Matter is made of quarks and leptons
  - Particles communicate through the 4 force bosons shown
- Four forces
  - Electromagnetic
  - Weak
  - Strong
  - Gravity



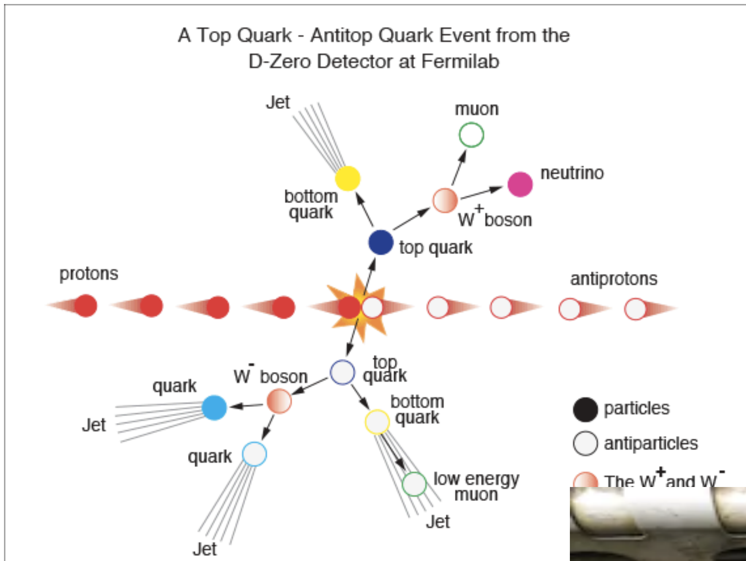
What theory tells us

- Theory tells us that a quark and antiquark interact via a W boson and produce a set of particles.

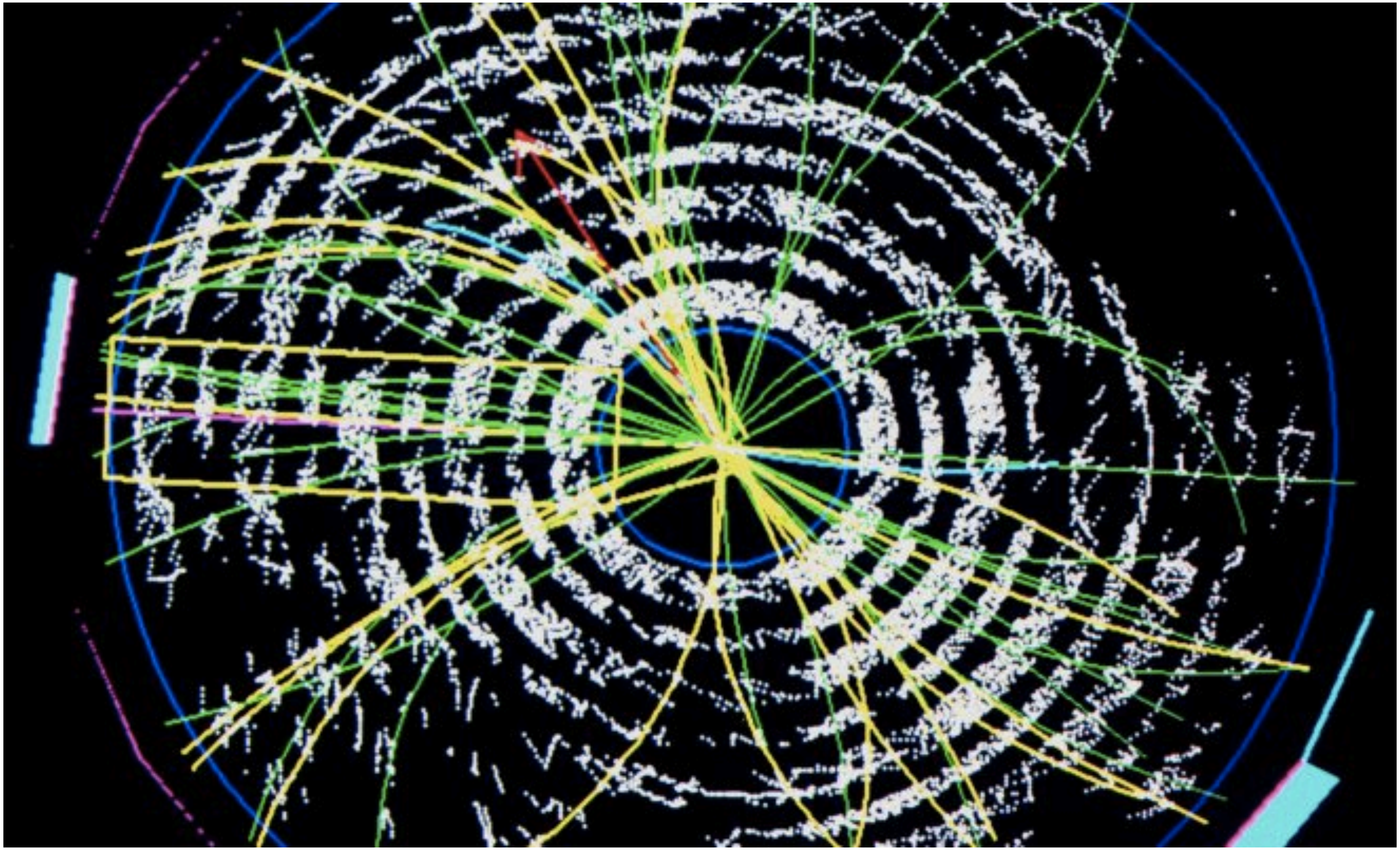


A little more realistic picture

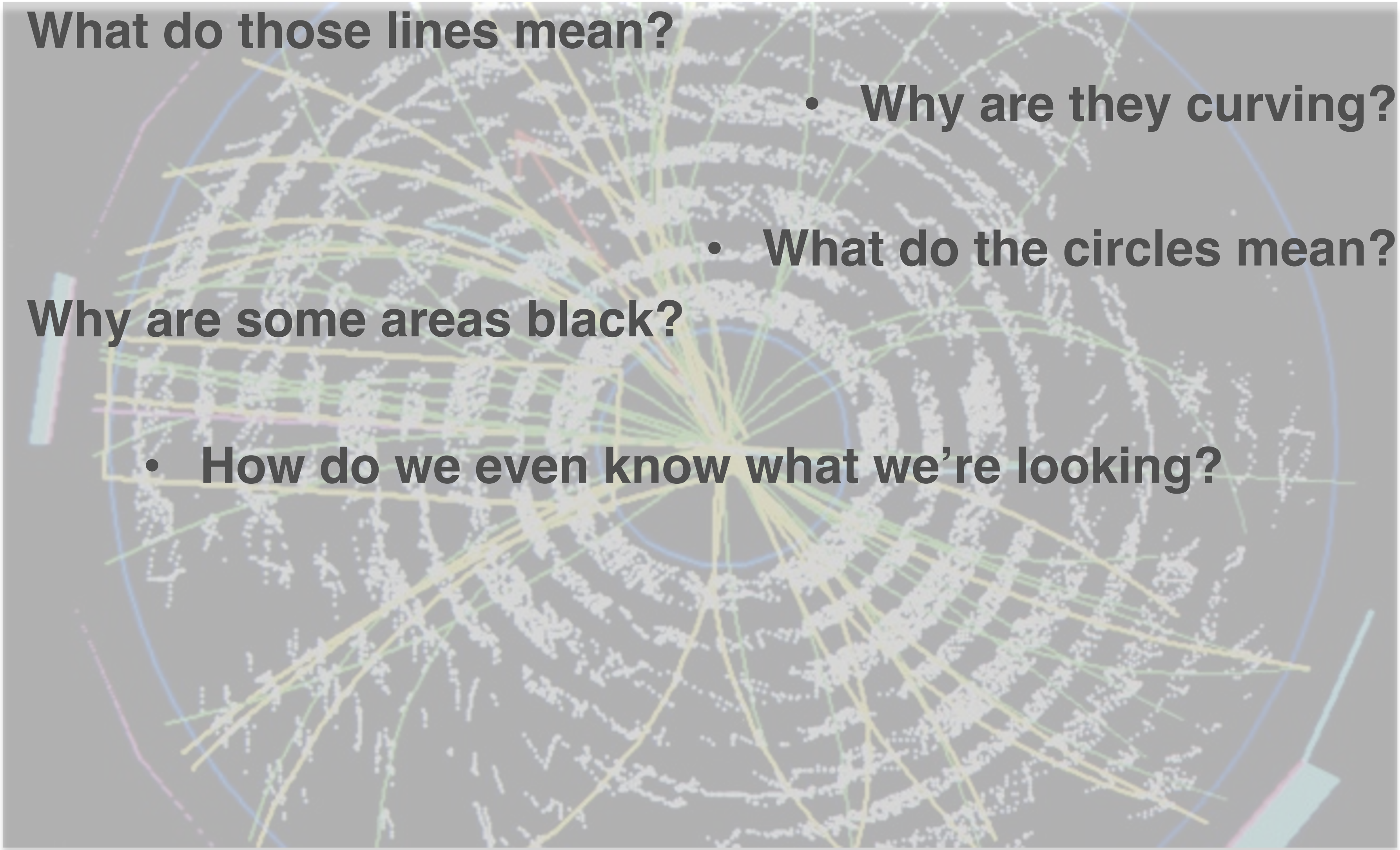
- We send a proton/antiproton towards each other



What we actually see



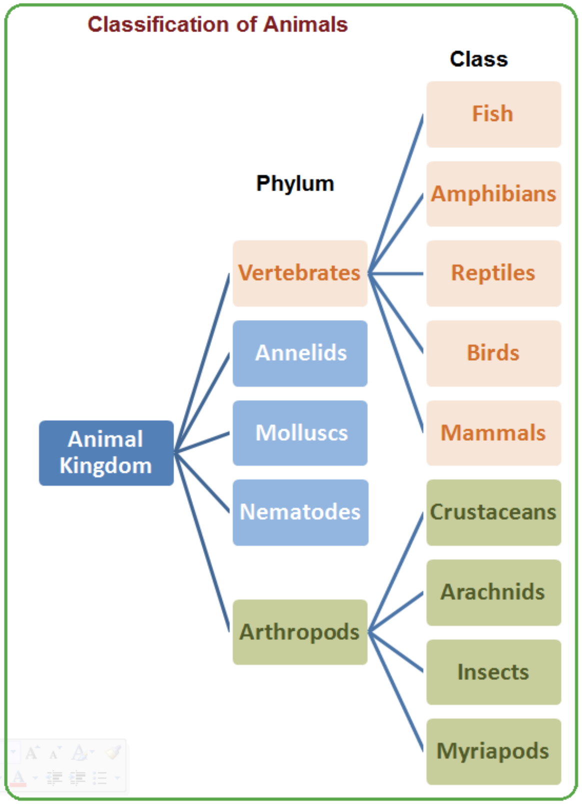
So Many Questions

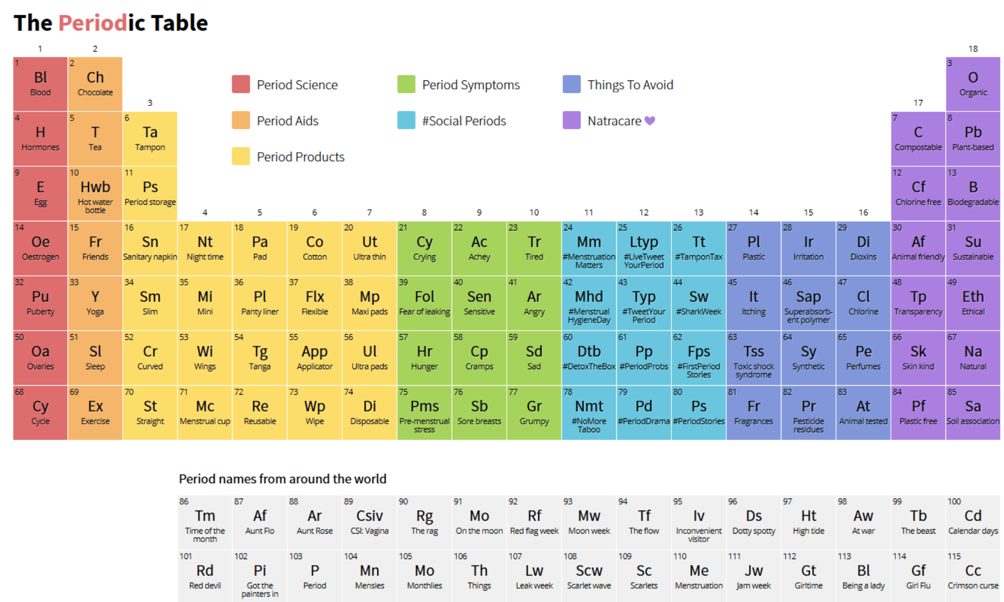


- What do those lines mean?
- Why are they curving?
- What do the circles mean?
- Why are some areas black?
- How do we even know what we’re looking?

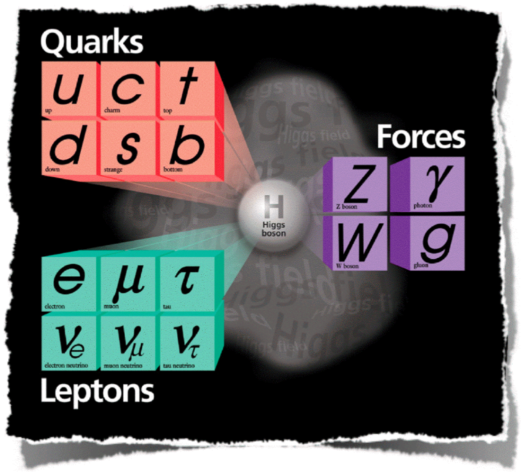
How do we identify particles?

- In biology and chemistry, we have classification schemes





How can we identify particles?



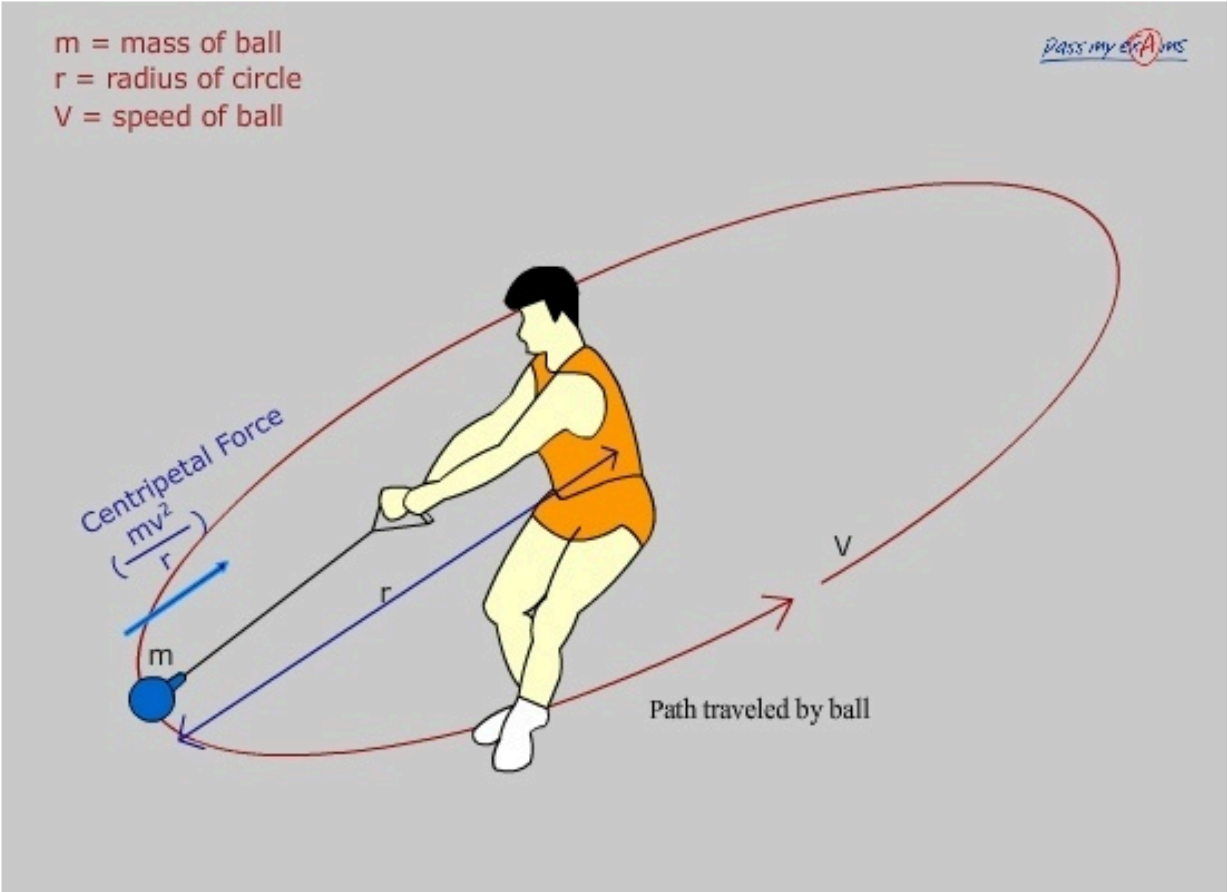
- We know that particles have a unique set of numbers that define them.
  - ***Mass, charge***, etc.
- Momentum conservation
  - ***Momentum*** before is the same as the momentum after a collision
- Energy conservation
  - Same ***energy*** before and after collision
- We can observe electromagnetic interactions and strong interactions
- We can tell types of particles based on their ***lifetime***
  - Muons, kaons, pions all decay at different times and into different things

Add tools to our toolbox

- Motion in a magnetic field
- Ionization
- Scintillation
- Calorimetry

Motion in a uniform magnetic field

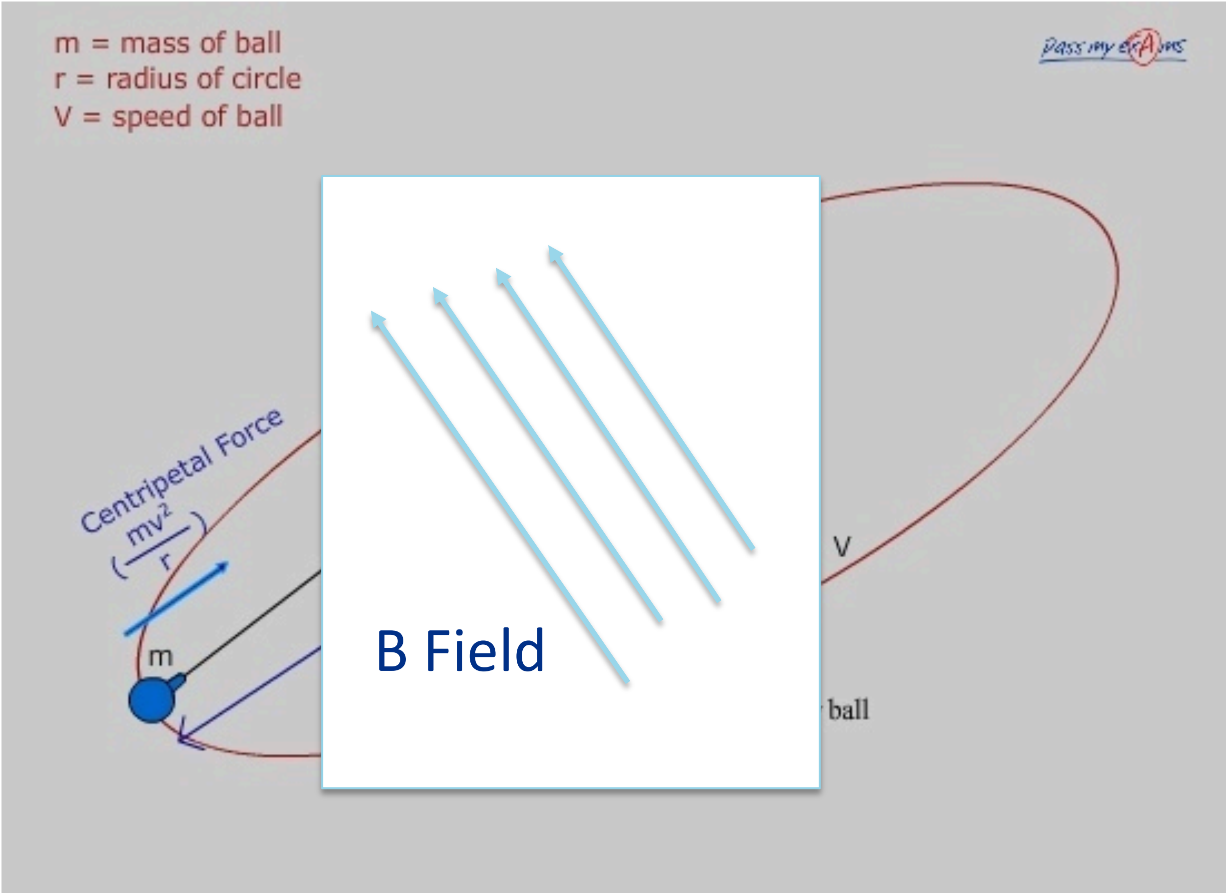
- Try this at home!! The tension in the string is keeping the ball moving in a circle



Fermilab

Motion in a uniform magnetic field

- Remove the person, add in a magnetic field.



Fermilab

Uniform circular motion in a magnetic field

- $F = \frac{mv^2}{r}$: Force in a circular motion
- $F = qvB$: Force on a particle in a uniform magnetic field

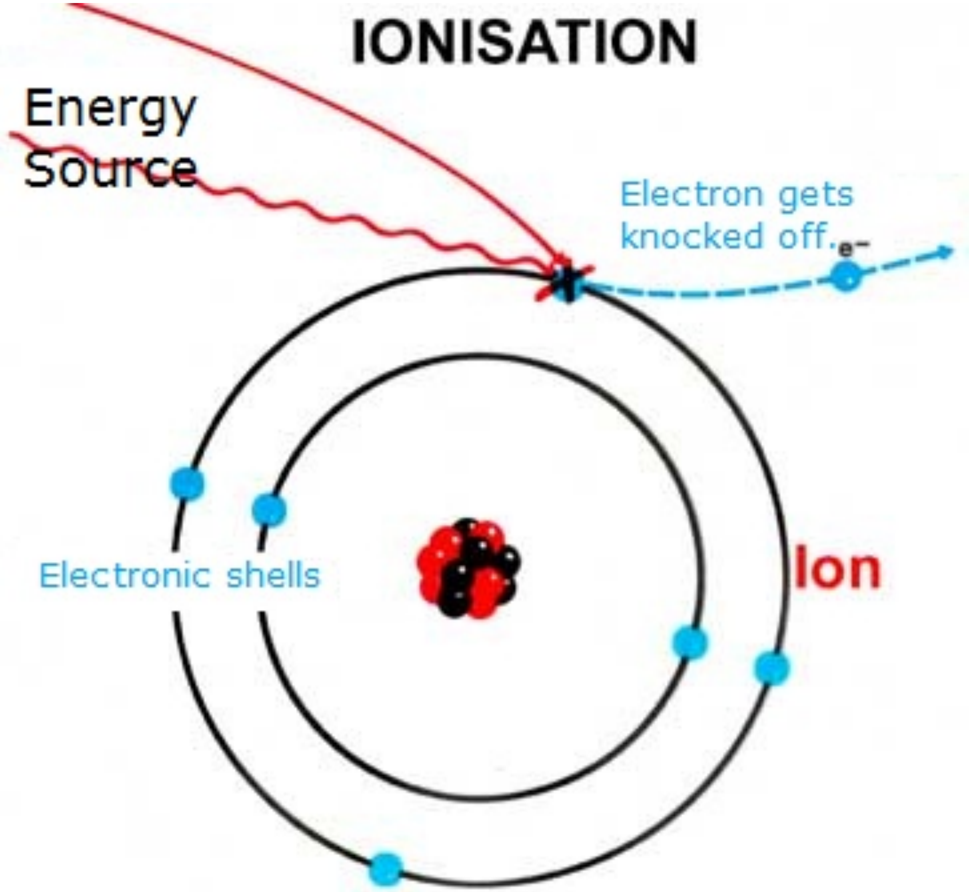
$$F = \frac{mv^2}{r} = qvB$$
$$r = \frac{mv}{qB}$$

- We can measure the radius of curve particles make to learn about their momentum

Fermilab

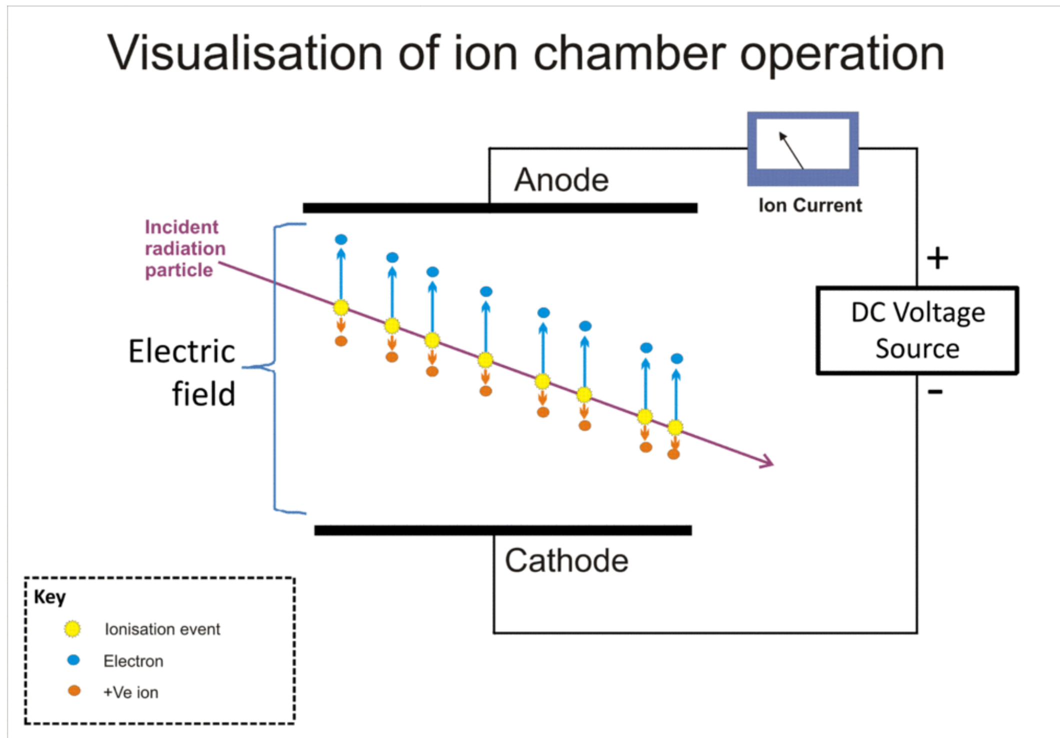
Ionization

- Definition: Ionization is the removal or addition of an electron to an atom to make it positive or negative.



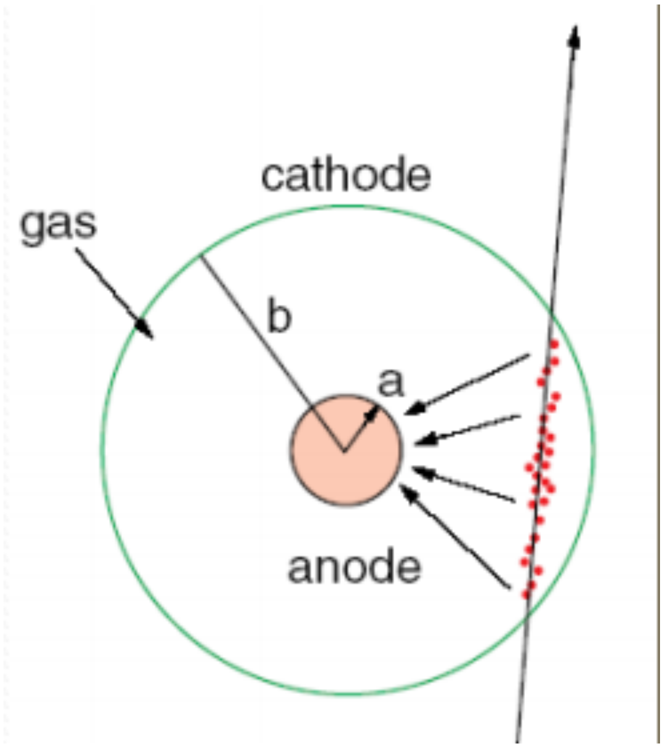
How does this help us?

- After ionization, you are left with a free electron (negative) and a positively charged atom
- Add an electric field



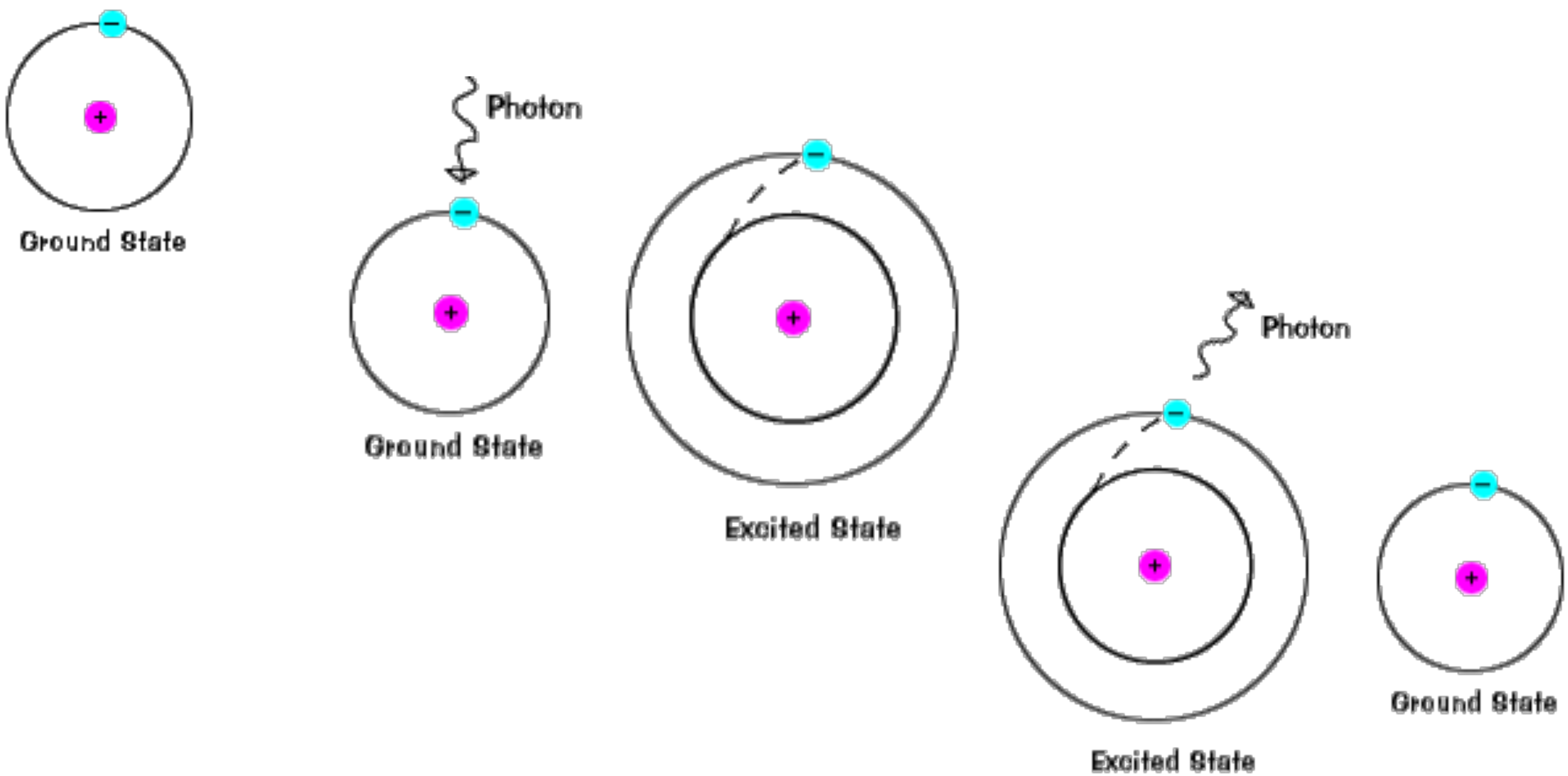
How does this help us?

- After ionization, you are left with a free electron (negative) and a positively charged atom
- Adding an electric field – we can separate the different types of charges.
- Electrons will leave a charge on a sensor that we can read out.



Scintillation Light

- Sometimes, in some materials, a particle moving through does not knock out an electron

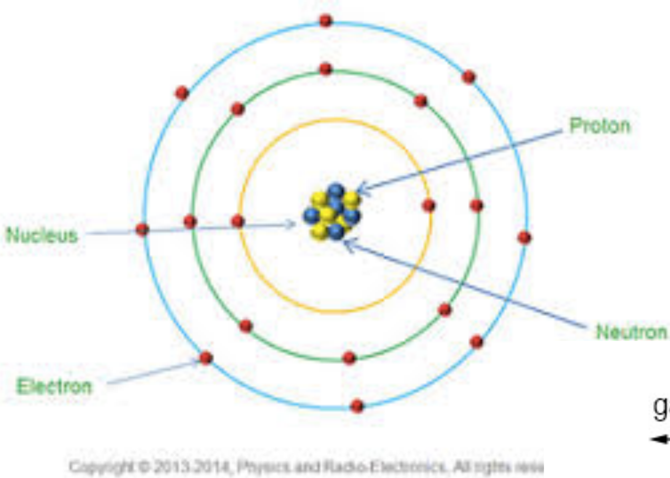


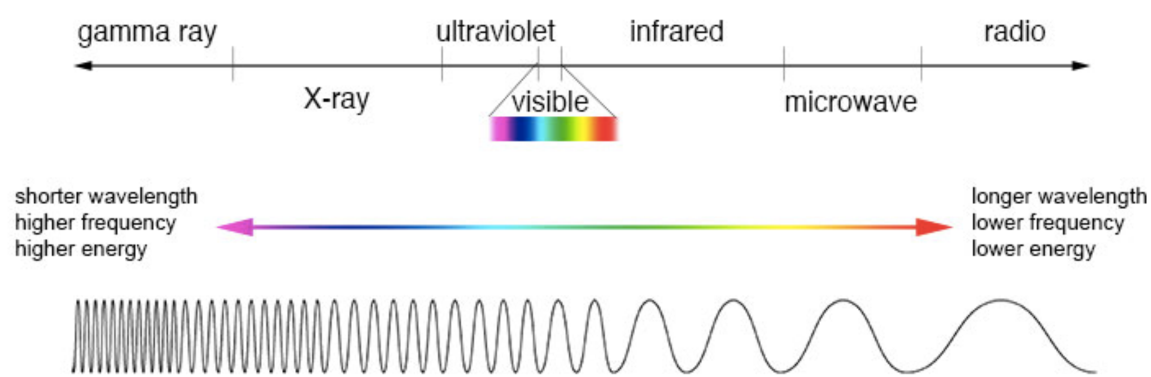
What can we do with scintillation light?

- The photon emitted will have a very specific energy
- We can count the number of photons that go to our readout tools

Fundamental Interactions

- We'll study 2 types – Electromagnetic interactions and nuclear interactions
  - Particles are either going to interact with detector material electrons or with it's nucleus





Types of particles we can see

- **Electrons (charged) and photons (no charge)**
  - Interacts with free electrons in atom
- **Muons (charged)**
  - Interacts with free electrons in atom
- **Pions and protons (charged), kaons (charged)**
  - Interacts with nucleus
- **Neutrons (no charge)**
  - Interacts with nucleus

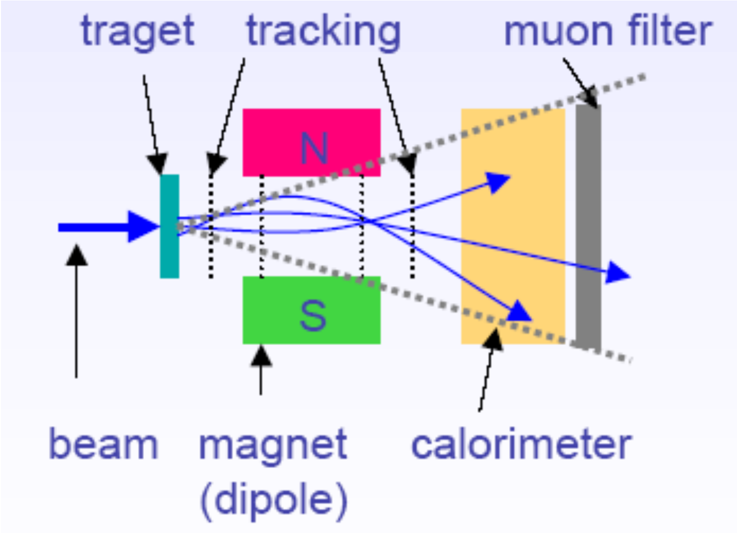
Let's build detectors!

- We have a well stocked toolbox
  - Theory tells us which particles we can see at the end of the collision
  - 3 basic processes (motion in a magnetic field, ionization, scintillation)
  - Conservation laws (final state will tell us something about the initial state)

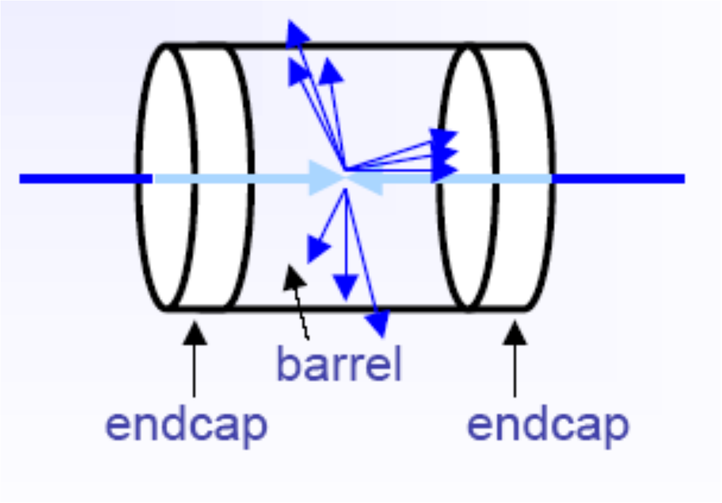
Go back to our car crashes

- In order to fully understand an interaction, we should use multiple detectors. There are 2 classic geometries: fixed target and collider.

Fixed Target Geometry



Collider Geometry

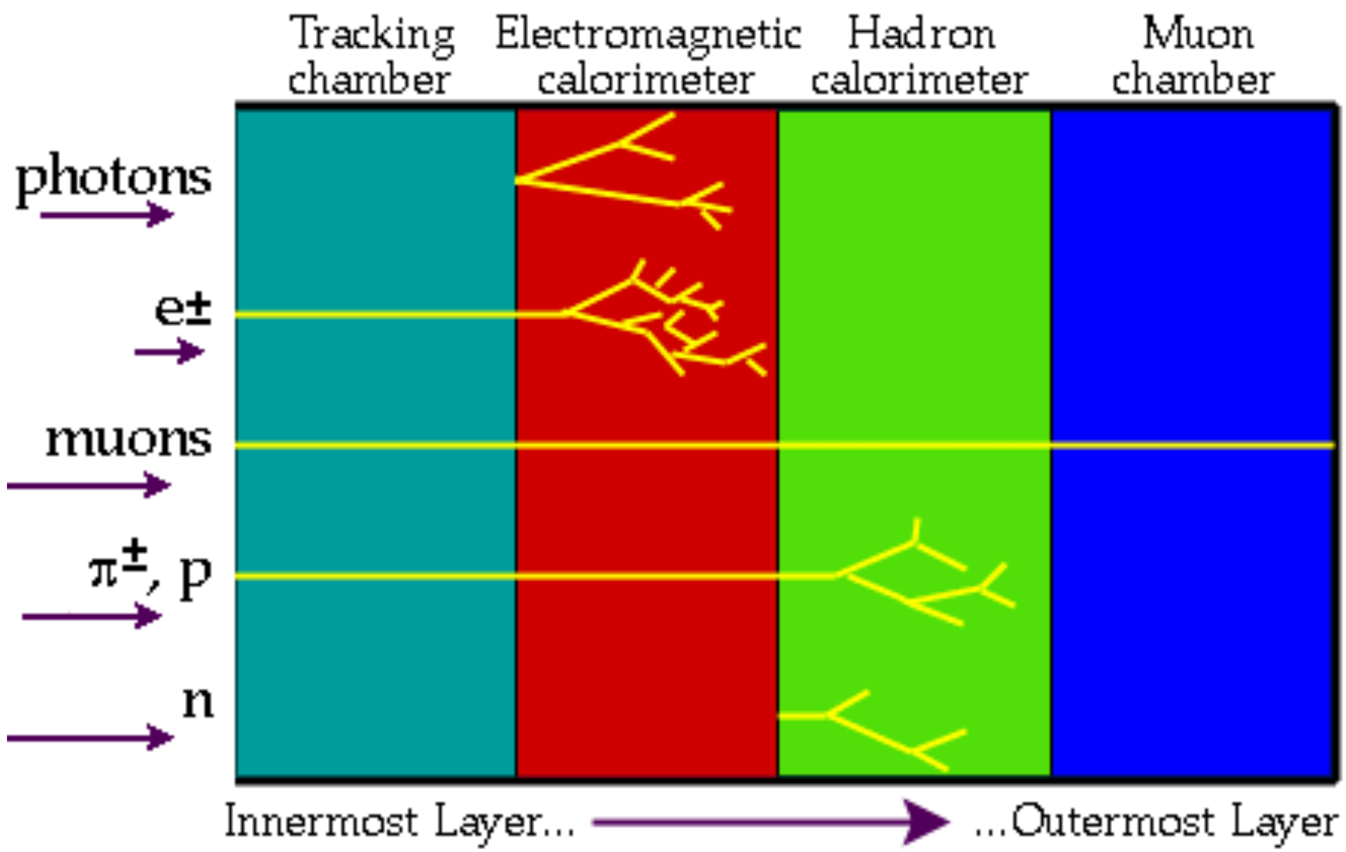


Particle Interactions

- Trackers (momentum, charge measurements)
  - Electromagnetic interactions
    - Scintillation (excitation)
    - Ionization
- Calorimeters (energy, mass measurements)
  - Electromagnetic interactions
    - Ionization
  - Strong interactions
    - Hadronic showers
- Cherenkov Detectors and Time Projection Chambers
- Let’s look at these one by one

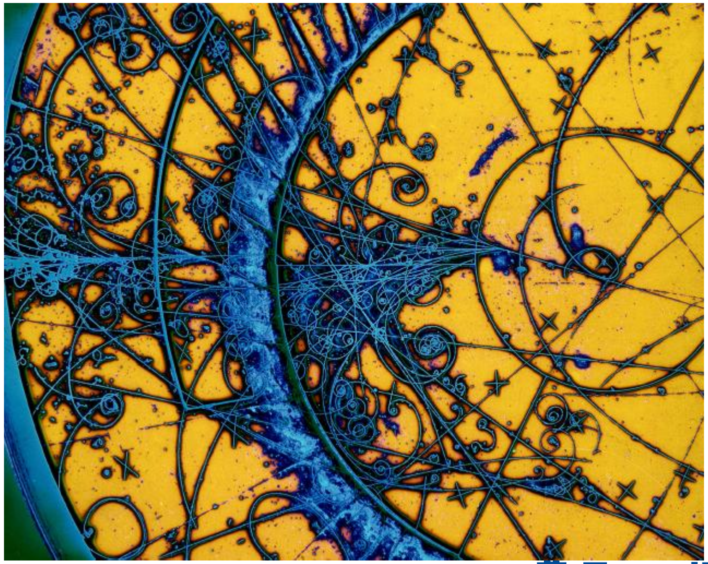
Break down into a slice

- Put least amount of material and fastest detectors near the interaction point, build out from there.



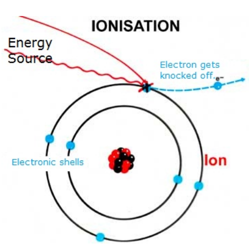
Tracking Detectors

- **Used for:**
  - momentum measurements (**p**)
  - charge determination
  - *particle production position (primary and secondary)*
- **Main Concepts**
  - Motion in Magnetic field
  - Ionization
- **What are trackers made out of?**
  - Gaseous detectors
  - Silicon detectors
  - Scintillating fiber trackers



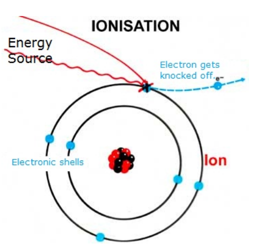
Tracking detectors

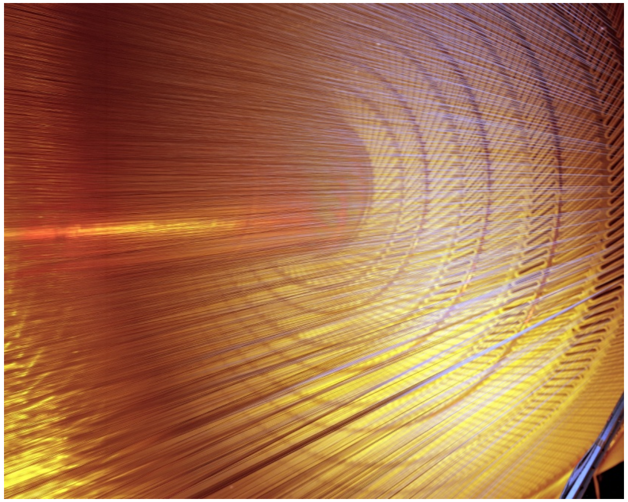
- Measures the momentum, direction of the particle, and charge
  - It **only** sees *charged particles*
- Usually the first detector to see the collision
  - Inside a magnetic field
- Will show the direction of a particle without hindering it
- Will also show if other particles are created after the collision
  - Called a ”secondary vertex”



Gas based trackers

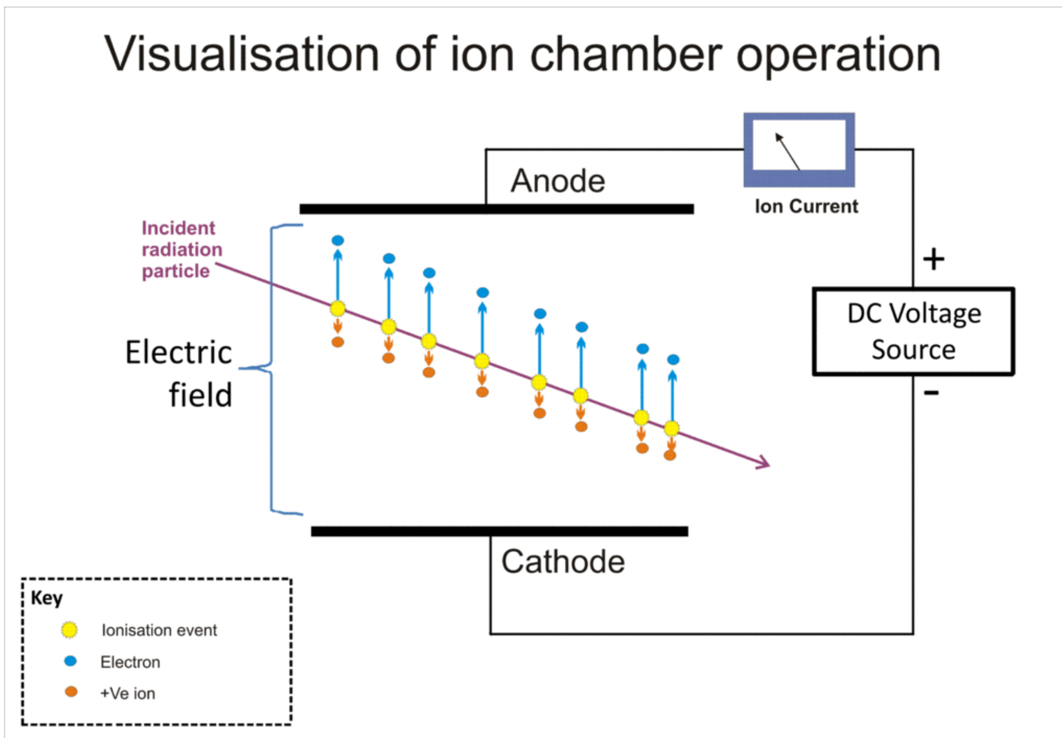
- Basic construction: Gas filled region (tube, big containter) with signal wires or plans.
- Low mass (gas!)
- Works with ionization and electric fields



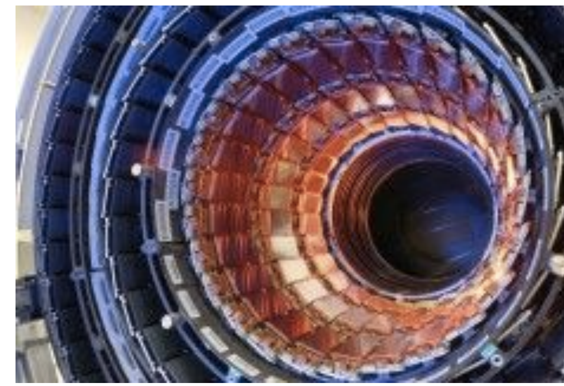


Silicon trackers

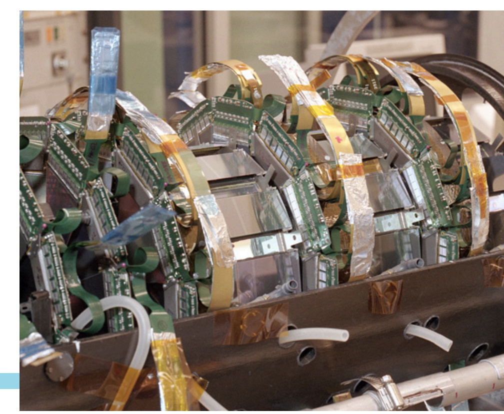
- Very important – radiation hard!
- Can tell trajectory of particles very precisely
- More material than gas trackers
- Works via ionization



CMS Silicon Tracker

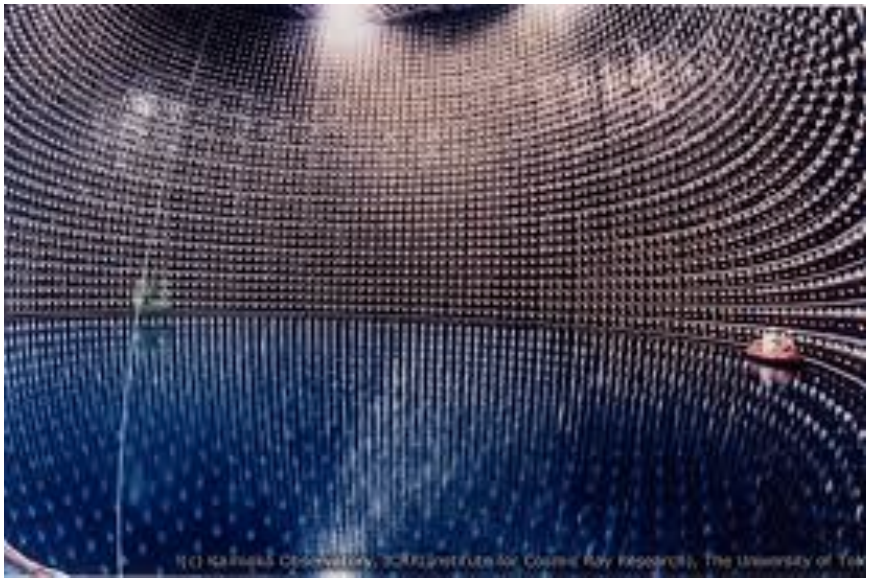


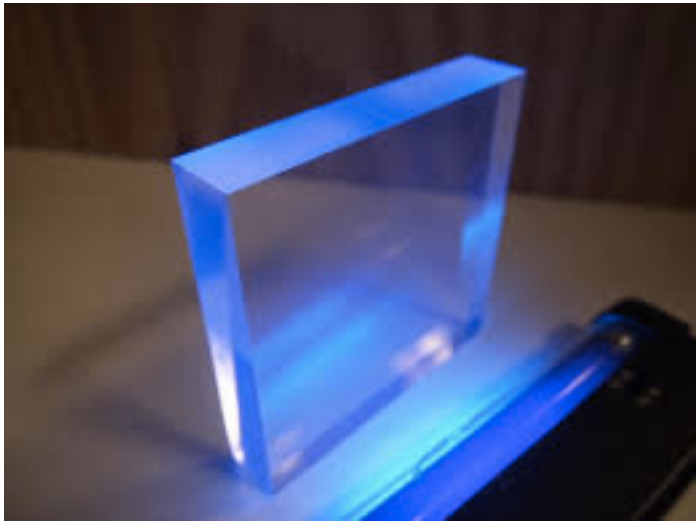
n Tracker

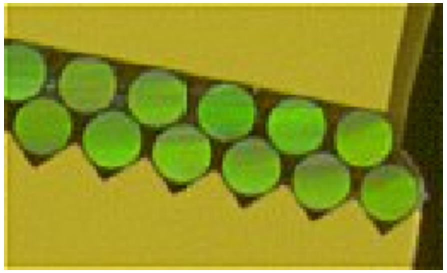


Scintillating Detectors

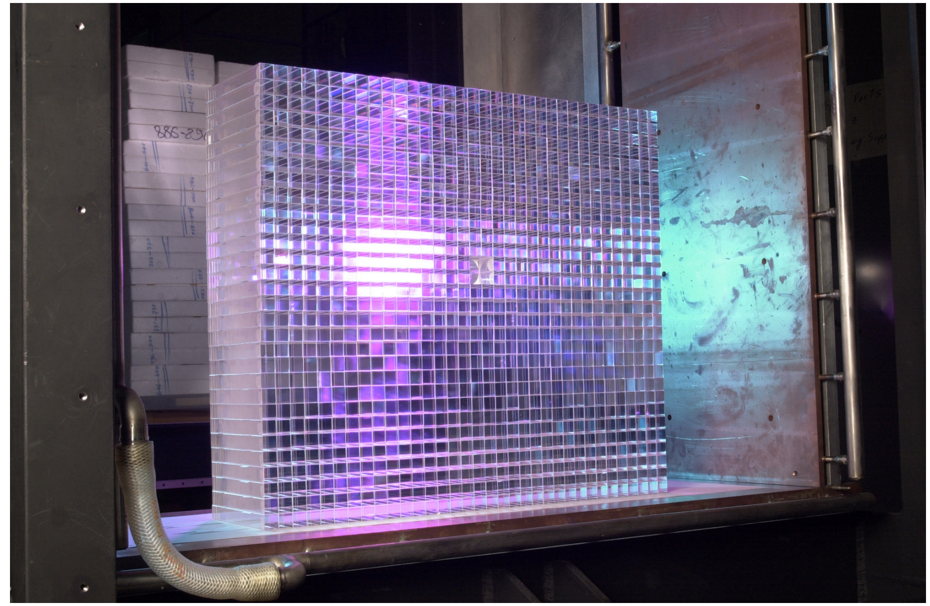
- Can be used in a variety of situations.







Calorimeters



Lead Tungstate crystals

- **Used for:**
  - Energy measurements
  - Mass measurements
- **Main concepts**
  - Ionization
  - Nuclear interactions = “showering”
- **What type of calorimeters are there?**
  - Electromagnetic calorimeters
  - Hadronic calorimeters
  - Sampling vs homogeneous

How does a calorimeter work?

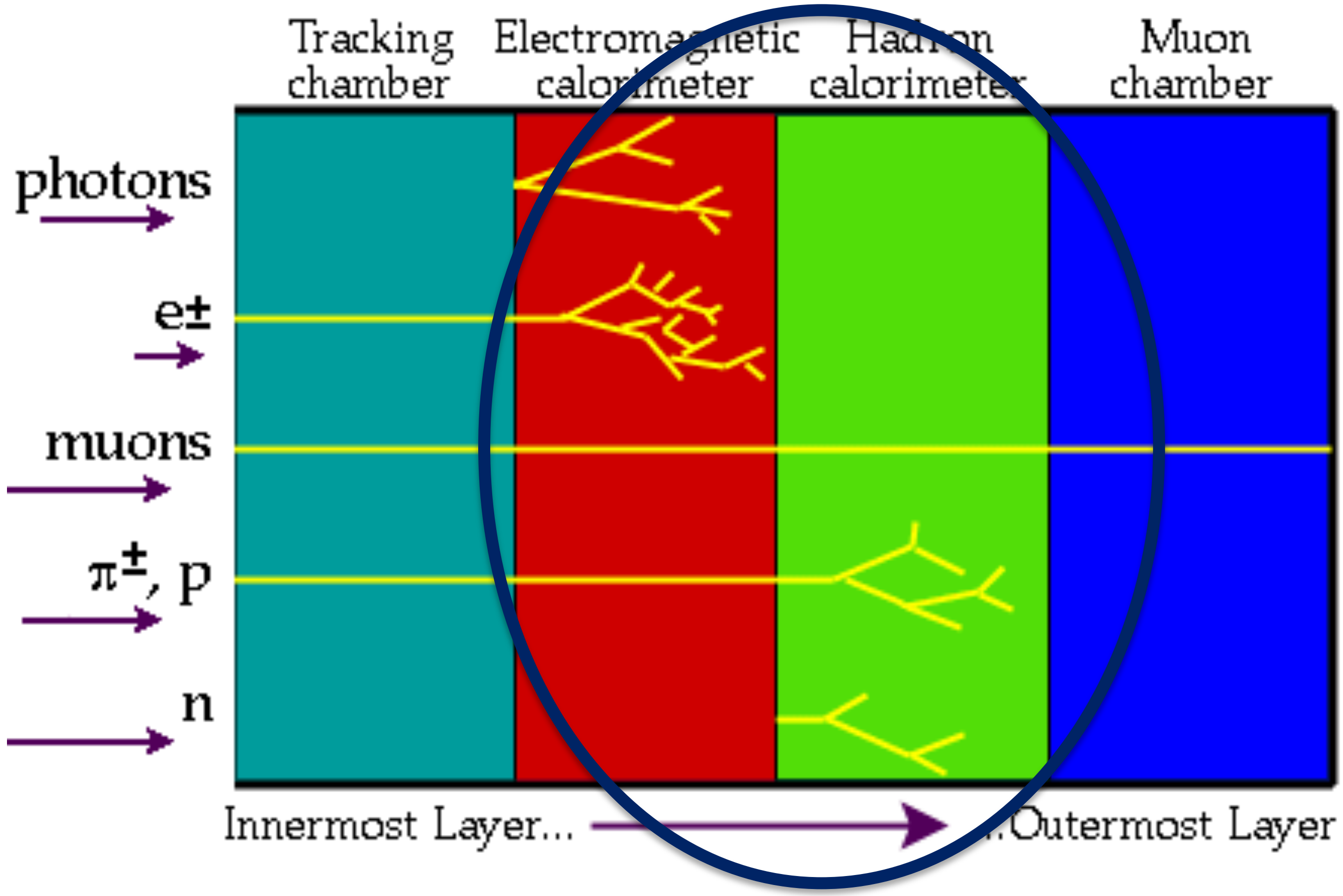
- Particles have gone through the trackers with only minimal energy loss (they haven't really slowed down).

- If they never stop- they can leave our detectors and we can't tell the difference between them or how much energy they have.

- So we stop them.
  - Deposit all their energy
  - We can tell a lot from ***how*** they stop

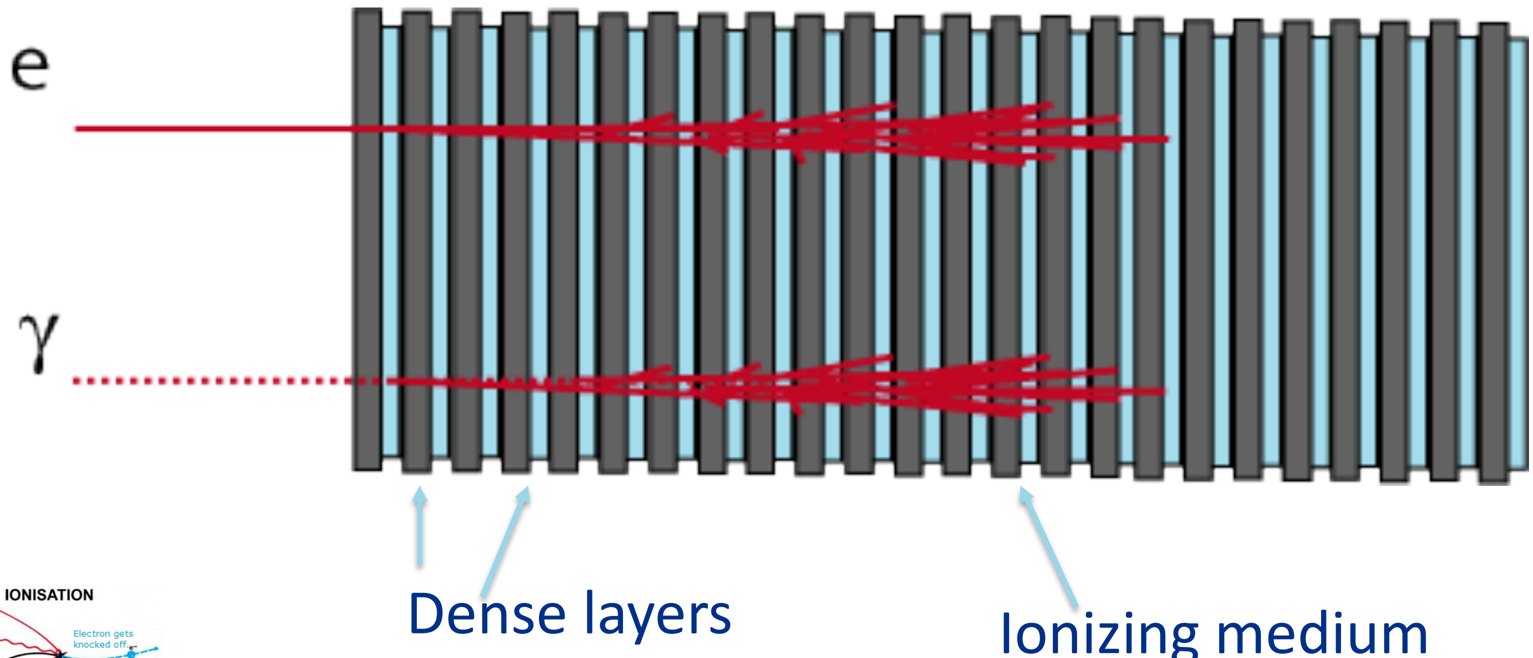
Detector slice

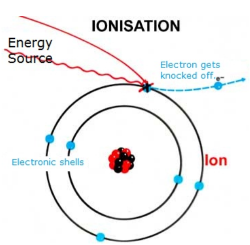
- Calorimeters can cause particle to shower. Where this occurs tells us something about the particle there.



How do calorimeters stop particles?

- Particles will interact with different materials in understandable ways
  - We put specific materials in their path





Electromagnetic Calorimetry

- Electromagnetic calorimeters measure the electrons (positrons) and photons that interact with the electrons in the atoms
  - Used to determine photons and electrons

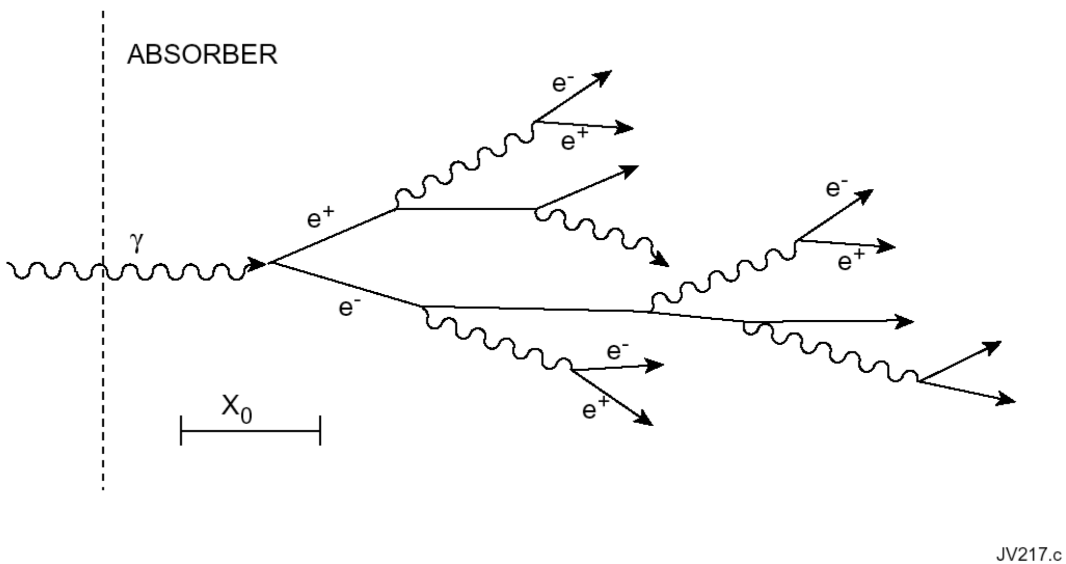


Figure 5: Schematic development of an electromagnetic shower.

Hadronic Calorimetry

- Hadronic calorimeters
  - Contain both an EM component driven by EM interactions and a hadronic component driven by Strong interactions
  - Can detector neutral particles and ”see” missing energy

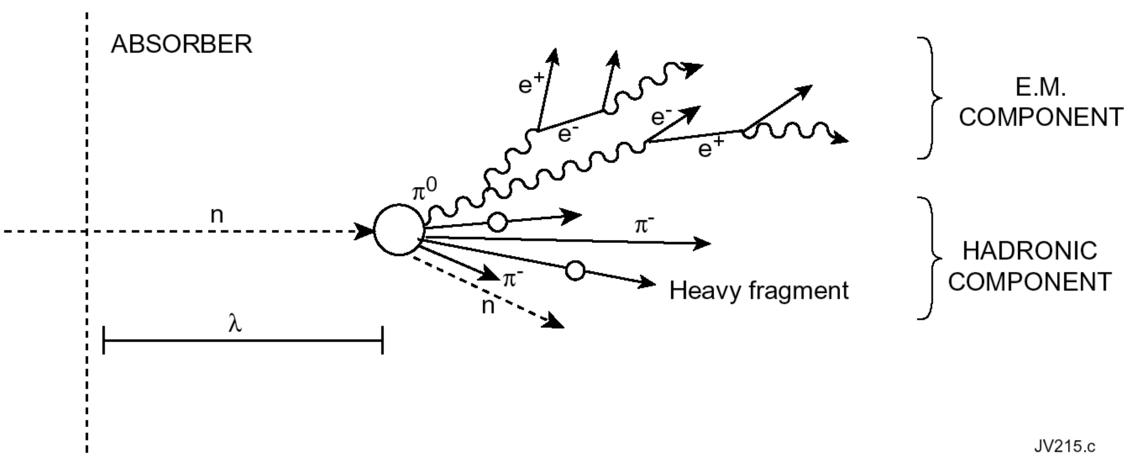
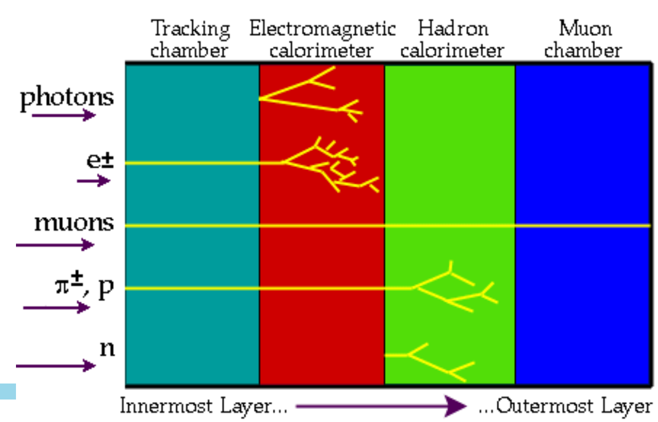
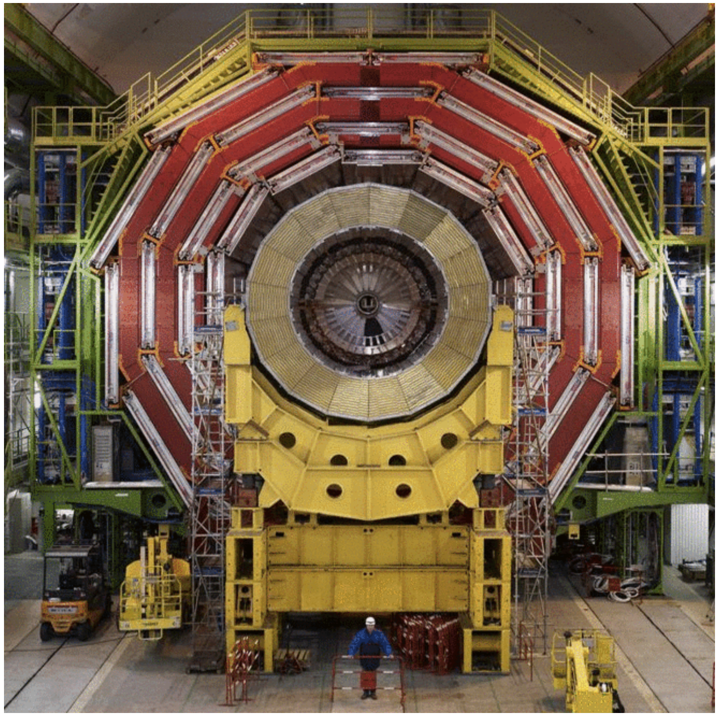


Figure 12: Schematic of development of hadronic showers.



Containing the shower

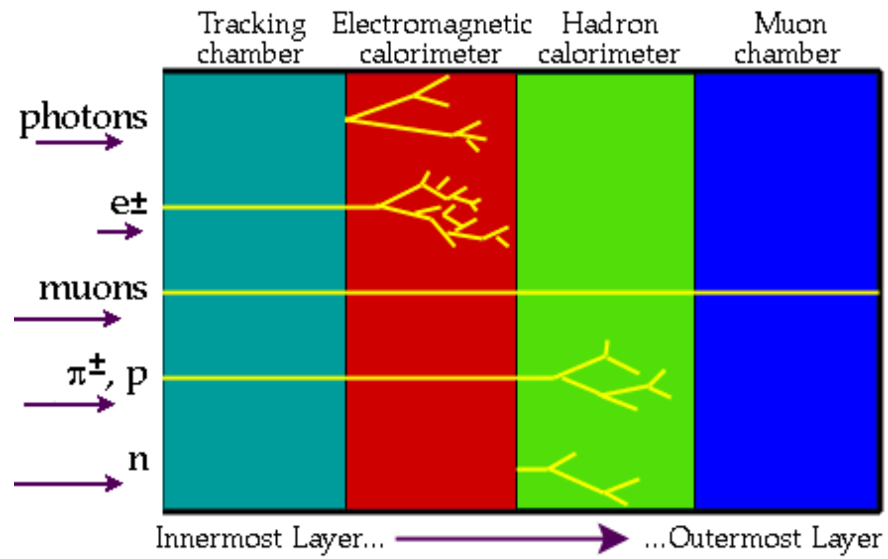
- In both Electromagnetic and Hadronic calorimeters, we want all the information from a particle to stay in the detector
  - This drives the size of the calorimeter
  - More energy = harder to stop



CMS Hadronic Calorimeter

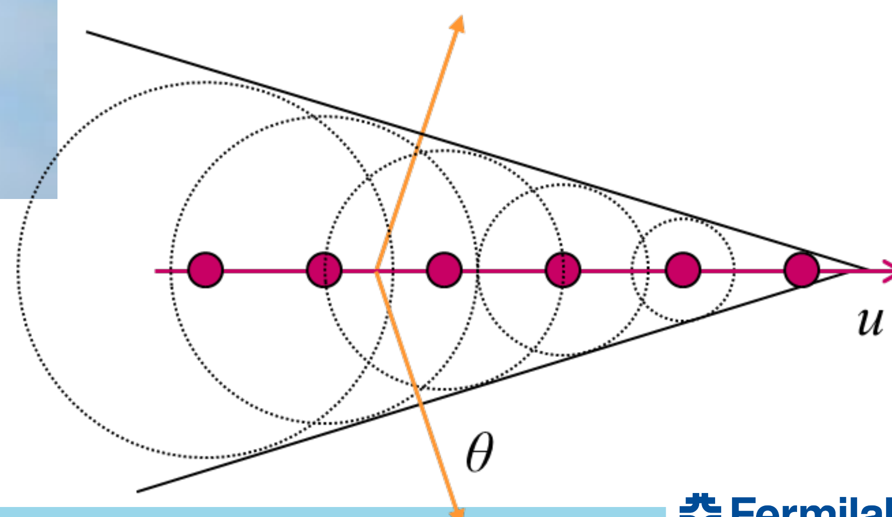
Calorimeter summary

- Calorimeters are part of the reason detectors are so huge.
  - Takes a lot of material to stop and contain the traversing particles
- Two main types
  - Electromagnetic
  - Hadronic
- Homogeneous calorimeter
  - Typically crystal
  - The whole thing is active
- Sampling calorimeter
  - Absorbing material + active readout layer



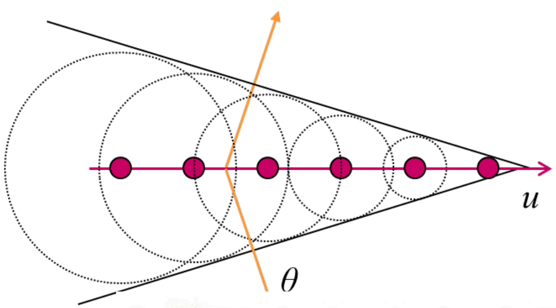
Cherenkov radiation

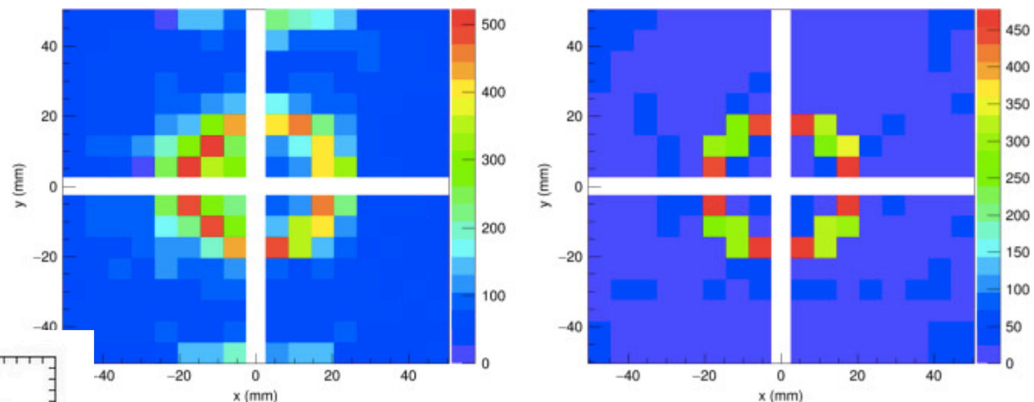
- The fastest speed anything can go in vacuum is the speed of light
- But in some materials, particles can go faster

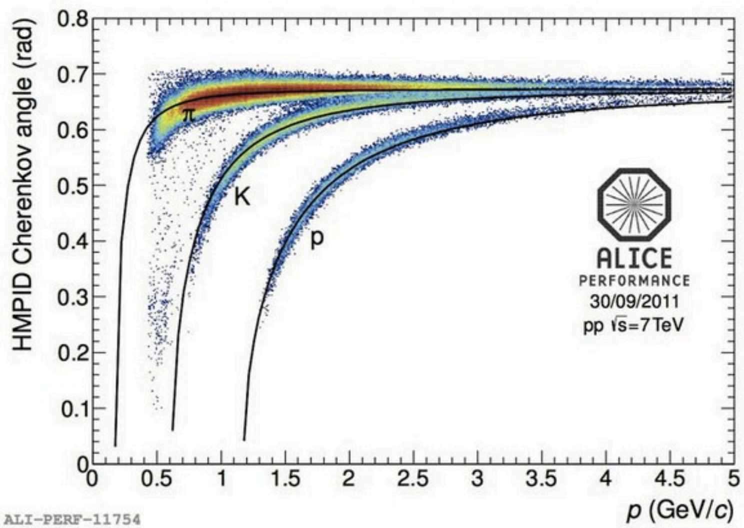


Cherenkov Radiation

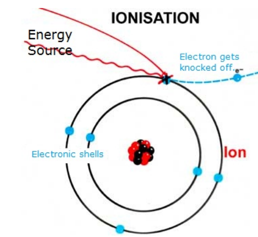
- The velocity (u in this picture) will depend on mass of the particle
- Angle will also change depending on velocity, mass, and material used for detector



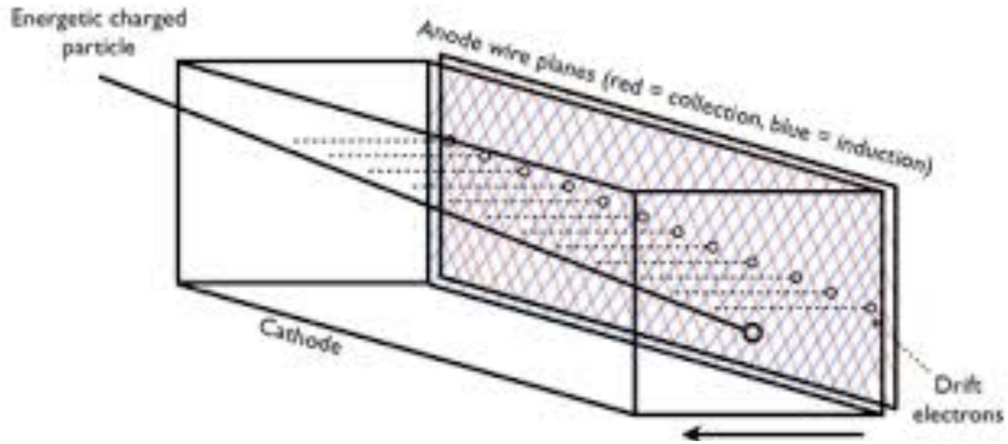


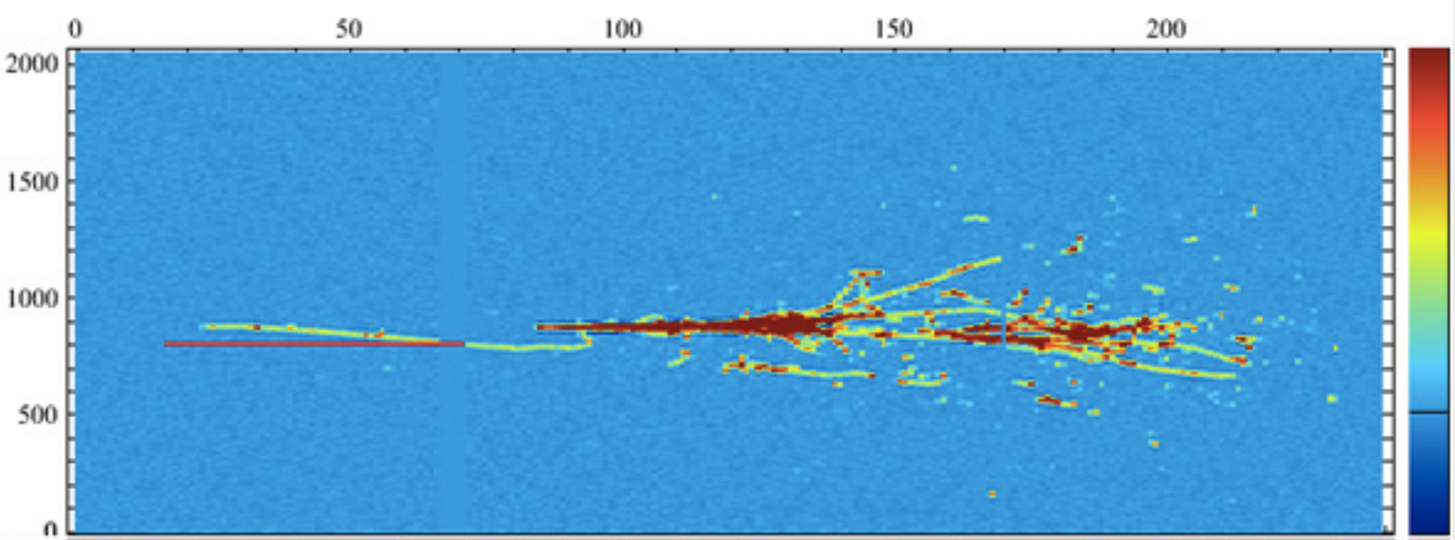


Liquid Argon Time Projection Chambers



- DUNE! Next big neutrino detector

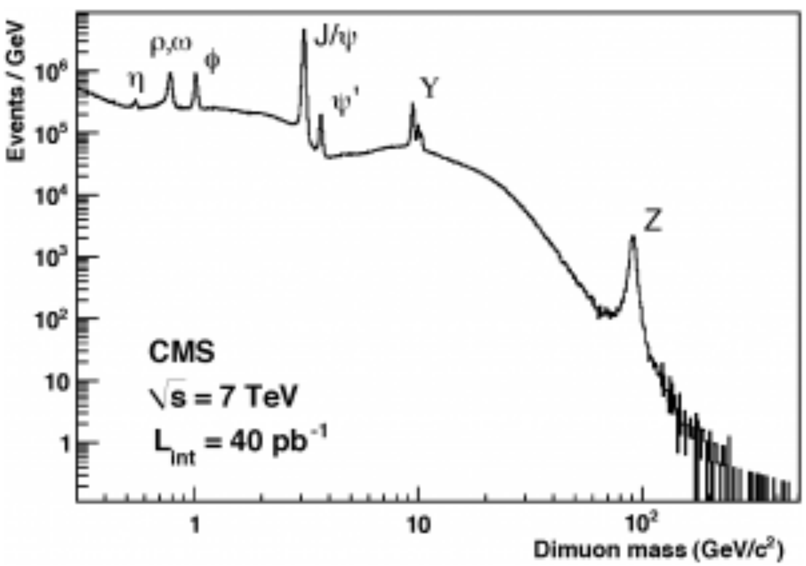




Event display from LArIAT

DAQ and electronics

- Okay, the particles have interacted with our detectors – now what?
- Final product is
  - A number: mass of the Higgs = 125 GeV
  - A plot:



- How do we get from trackers and calorimeters to this?

Data Acquisition Process

Detector

Slow controls

Signal processing

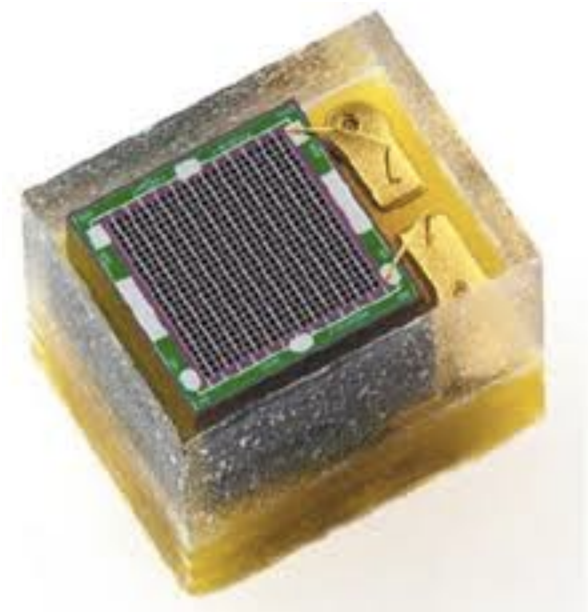
Triggering

Storing to tape

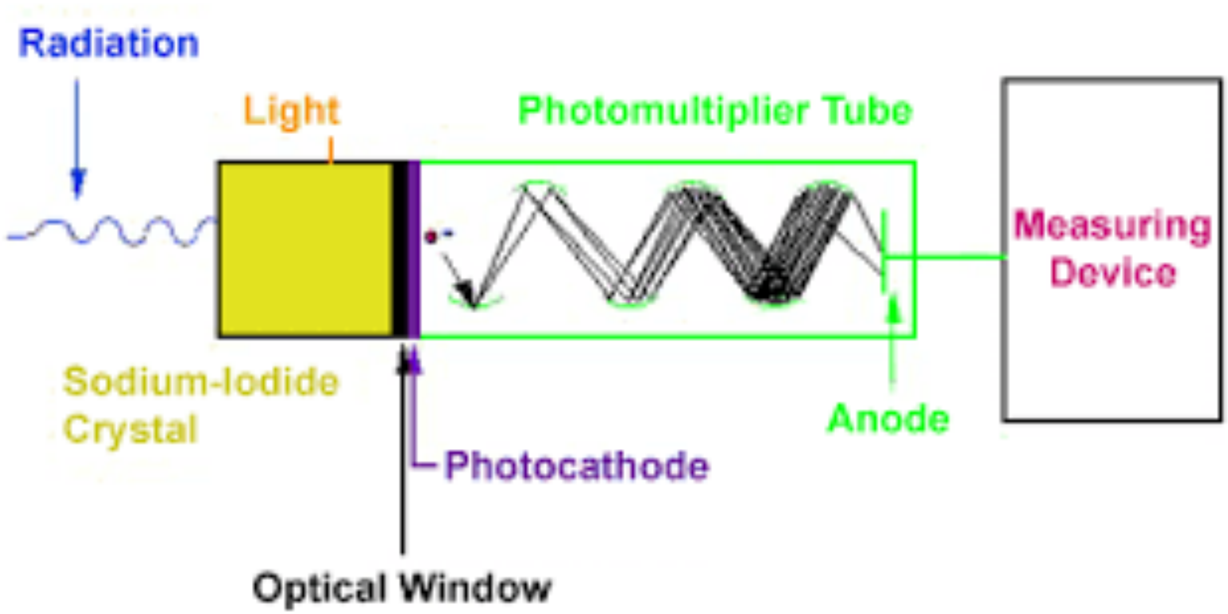
Analysis!

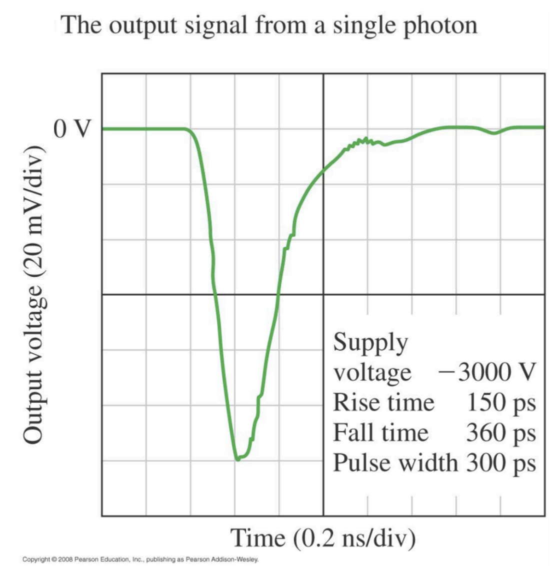
Detector signals

- Trackers, calorimeters, TPCs all have “eyes”
  - Photomultiplier tubes
  - Silicon Photomultiplier tubes
  - Sense wires that collect charge



Example – Photomultiplier Tube



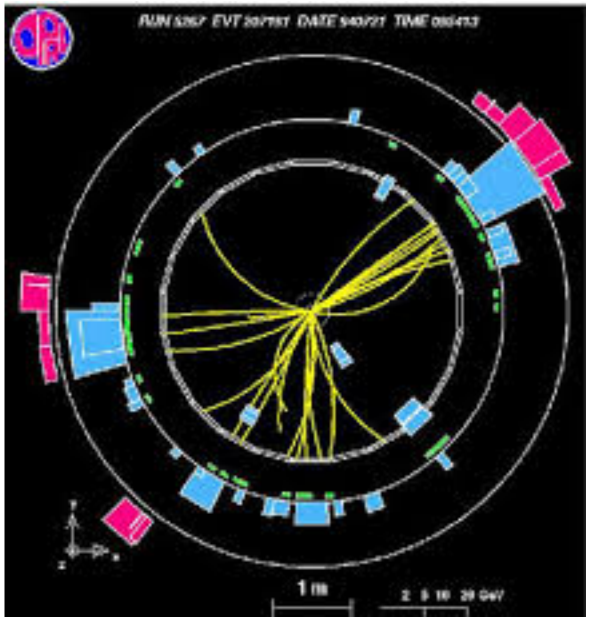


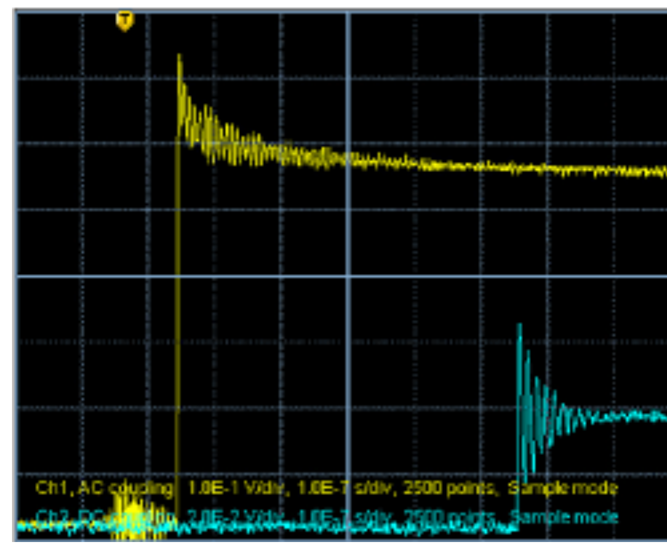
Signal processing

- Shape
  - Look at the shape of the signal – will tell you important information
- Amplify
  - Make a small signal large enough to see
- Discriminate
  - Only look at signals above a certain threshold.

Processing signals

- We’ve turned those particle interactions into electronic signals

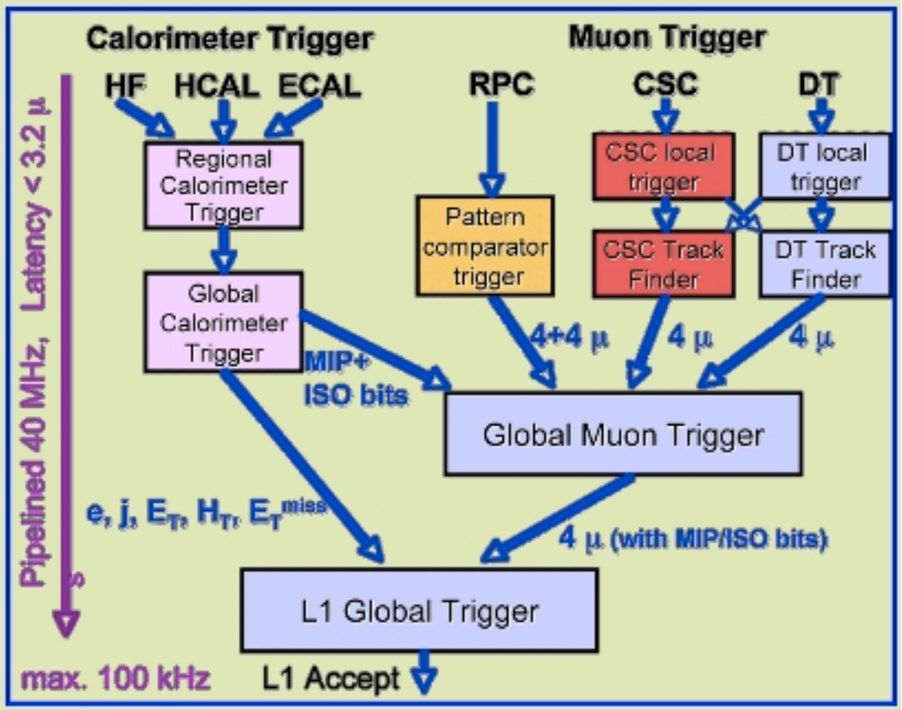




Trigger systems

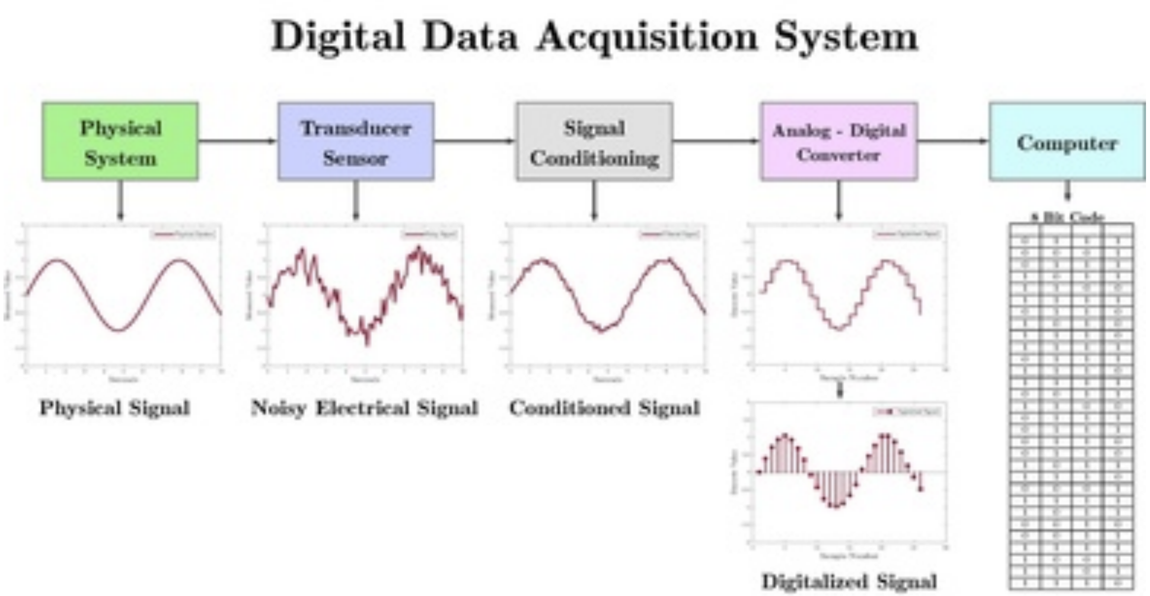
- Take the input from all the sub systems and detectors
  - Make a decision: keep or not?
- Usually multi-level
  - Make decisions based on which detector sub systems have events.

CMS Level 1 Trigger



Detector Readout – Put it all together

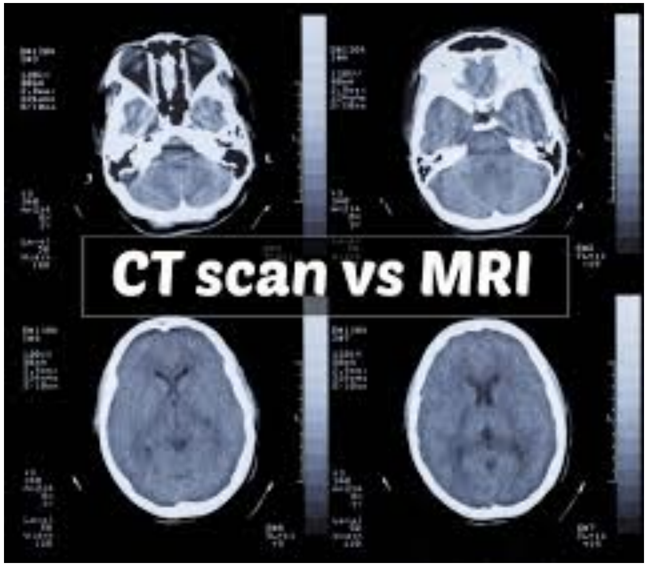
- Detectors have “eyes”
- Turn the signals into something readable by electronics
- We trigger on only what we want to keep
- Finally – Data is stored into a system and later retrieved for analysis
  - Also used in data quality monitoring.



Fermilab

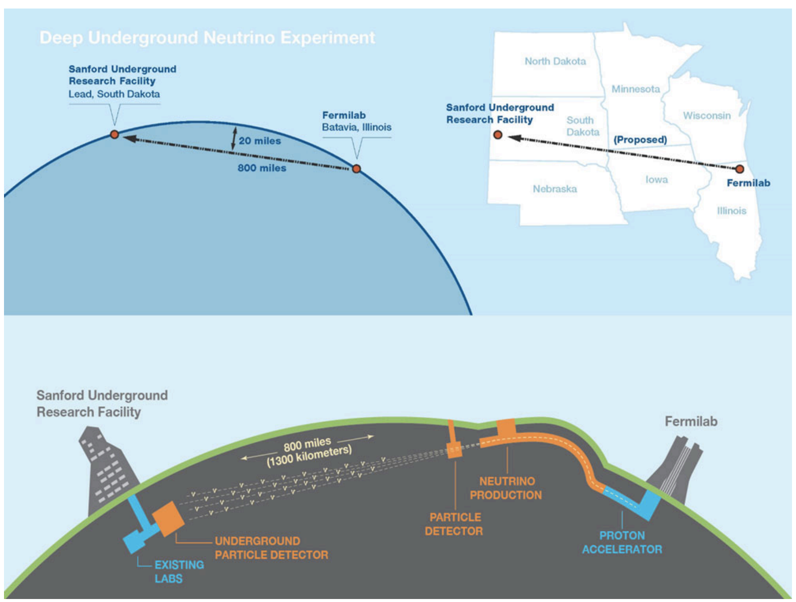
So Many Detectors

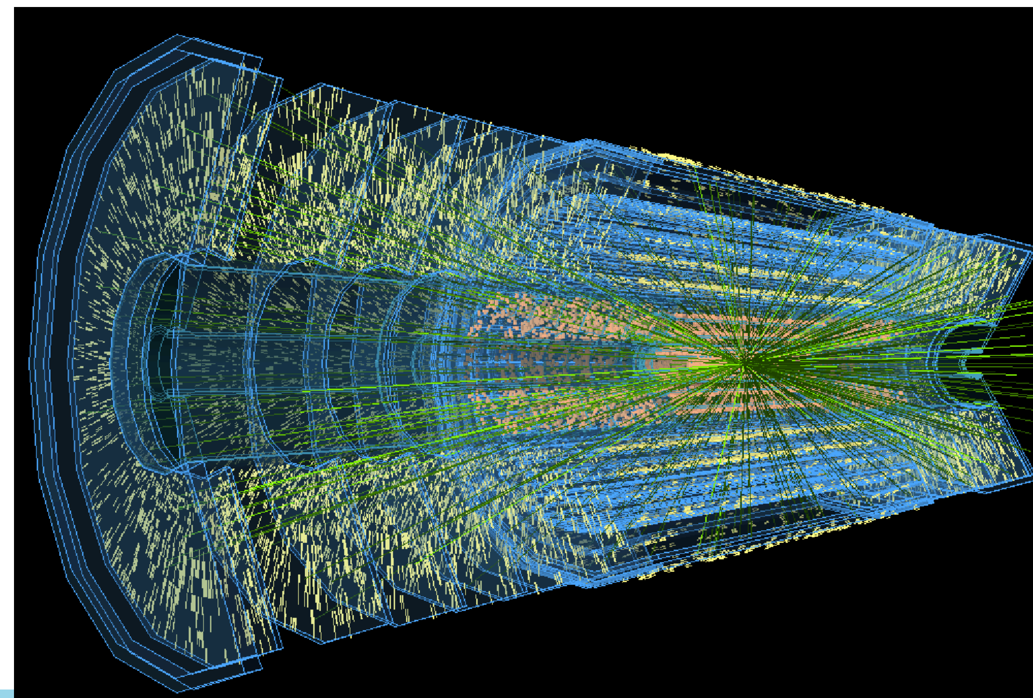
- Particle detectors are used in many fields, not just particle physics
  - Medical physics, security, studying the pyramids



Outlook – What is up and coming

- As we move ahead, things get more complicated!
- High Luminosity Large Hadron Collider
  - lots of radiation
- DUNE
  - Large amount of liquid argon



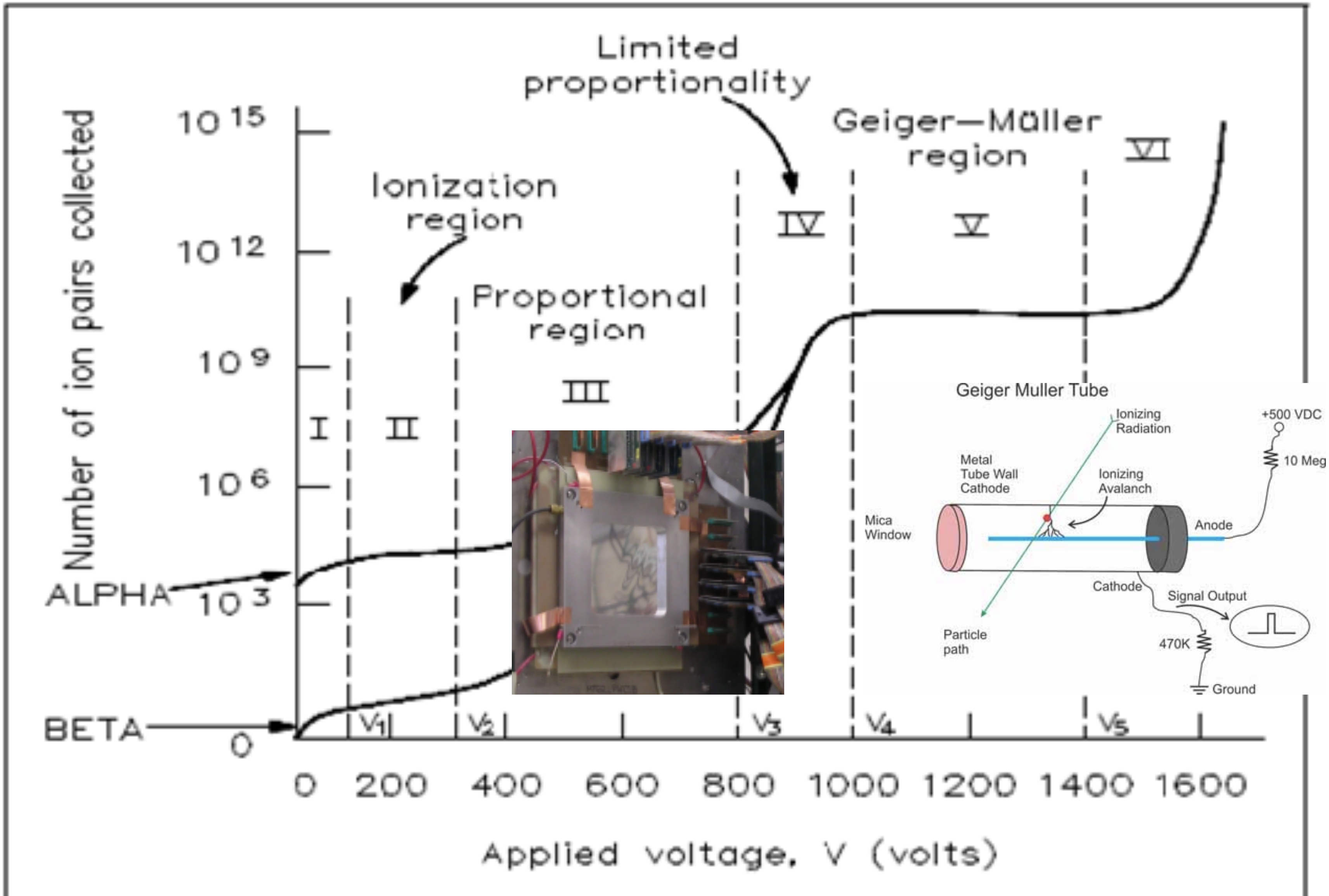


Summary

- The physics of particle detectors comes down to matter interacting with matter
  - Could spend a lifetime studying these different effects

- What I want you to remember:
  - Charged particle interactions are our main source of information
    - Ionization
    - Scintillation
  - Use energy loss to determine what type of particles you are viewing
    - Interact with atom’s electrons
    - Interact with the atom’s nucleus

Gas Detector Types



Tracking Summary

- Okay, so we've learned how to tell the ***charge***, what ***direction it went***, and it's ***momentum***
- Three types of tracking detectors: gaseous, solid state, scintillating
- Gaseous detectors rely on charge multiplication
  - Gas choice is a bit of "magic"
  - Covers large areas "cheaply" with sensitive materials
- Solid state/scintillating
  - Fine granularity, commercially produced
  - Can have problems with too much material in the beamline