Physics of Particle Detectors

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Undergraduate Lecture Series

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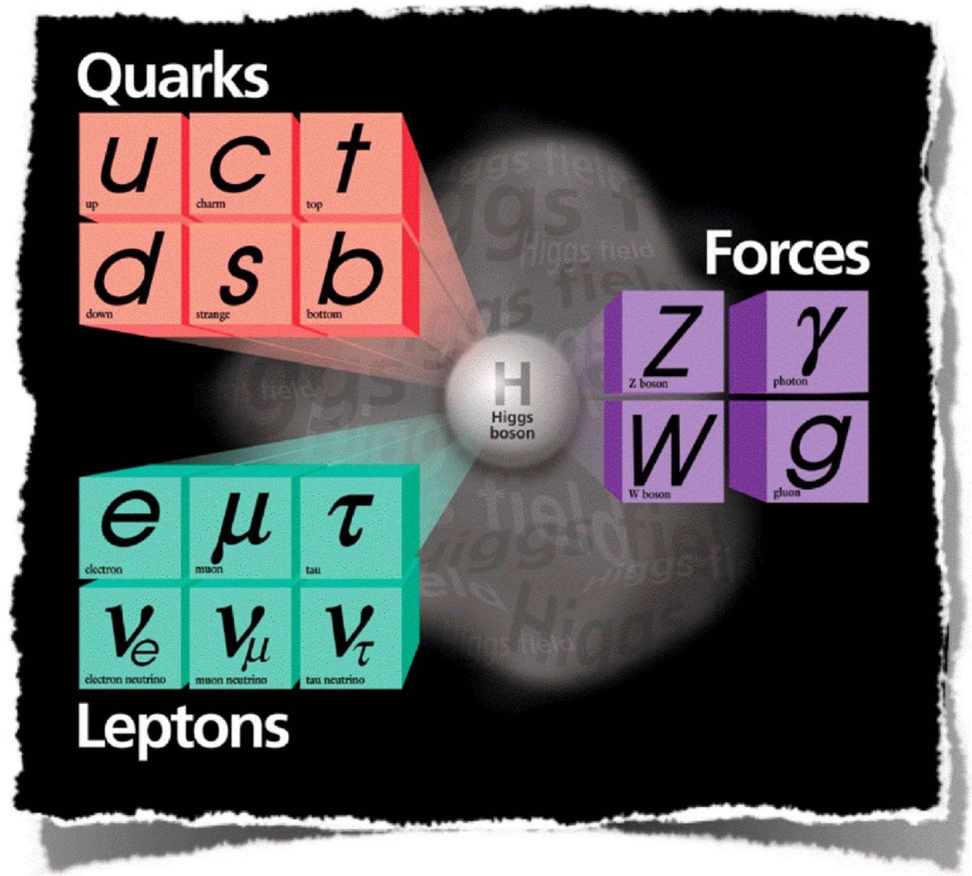
Outline

- What are we interested in seeing?
  - Individual particles
  - Interactions between particles
- How do we detect these?
  - Particles interact with various mediums, lose energy
  - Use basic physics principles
  - Detector technologies
- Full experiment
- Detectors at Fermilab
- Further reading

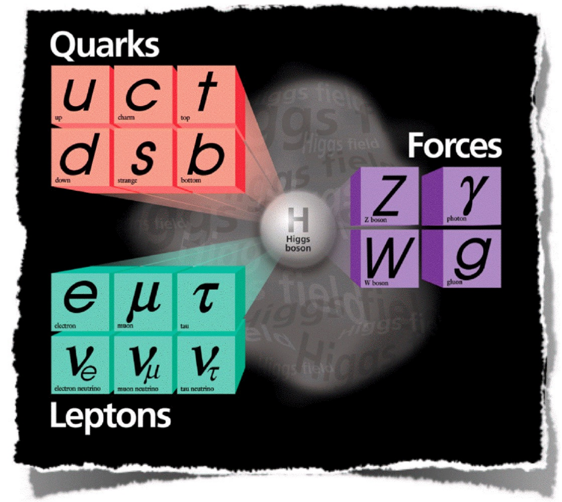
What do we know about?

- **Full Intro Lecture on 6/1**
- Standard Model
  - Matter is made of quarks and leptons
  - Interactions are mediated by gauge bosons
- For detectors we care about:
  - Strong Interactions
  - EM Interactions
- Most commonly detected: $e^{+/-}$, $mu^{+/-}$, $pi^{+/-}$, protons, neutrons, gamma, K0, $K^{+/-}$



Fermilab

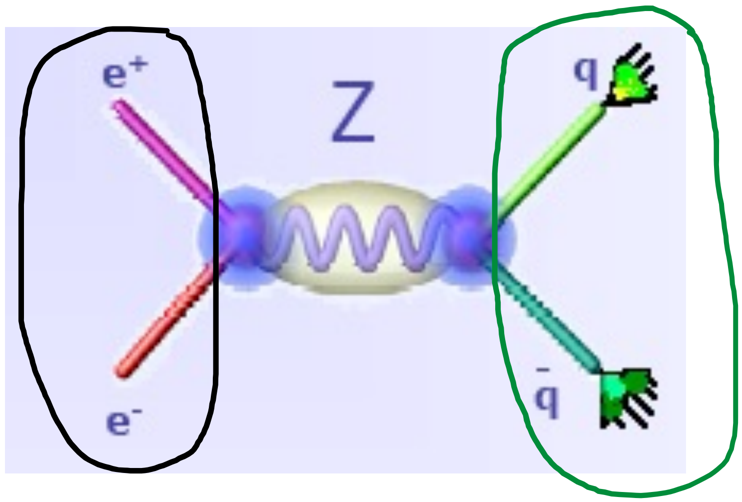
How can we identify particles?



- 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

In theory…

- Theory tells us that an electron and a positron interact via a Z boson and produce a quark-antiquark pair



$$e^{+} + e^{-} \rightarrow Z^{0} \rightarrow q\bar{q}$$
$$(+\text{hadronization})$$

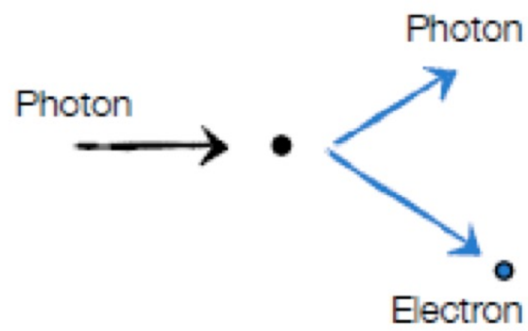
- We produce a beam of electrons and positrons at *a certain energy* and we detect the end products via energy/momentum loss

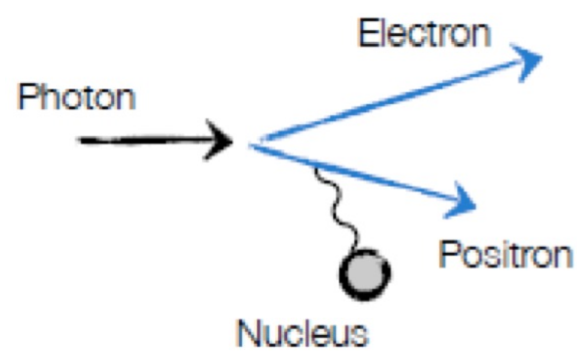
Physics Principles

- Energy loss
- Motion in a magnetic field
- Ionization
- Scintillation

Energy Loss

- Energy loss happens in a variety of ways
- EM Interactions:
  - Bremsstrahlung
  - Pair productions
  - Photo electric effect
  - Cherenkov radiation
  - Scattering (inelastic, elastic)
  - Ionization/Scintillation
- Strong Interactions
  - Hadronic showers
- Weak Interactions
  - Neutrinos





Bethe-Bloch Equation – Energy loss for "heavy particles"

- Relativistic Formula: Bethe (1932), others added more corrections later
- Gives "stopping power" (energy loss = dE/dx) for charged particles passing through material:

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

where

A, Z: atomic mass and atomic number of absorber

z: charge of incident particle

β,γ : relativistic velocity, relativistic factor of incident particle

$\delta(\beta\gamma)$: density correction due to relativistic compression of absorber

I: ionization potential

T_{max}: maximum energy loss in a single collision;

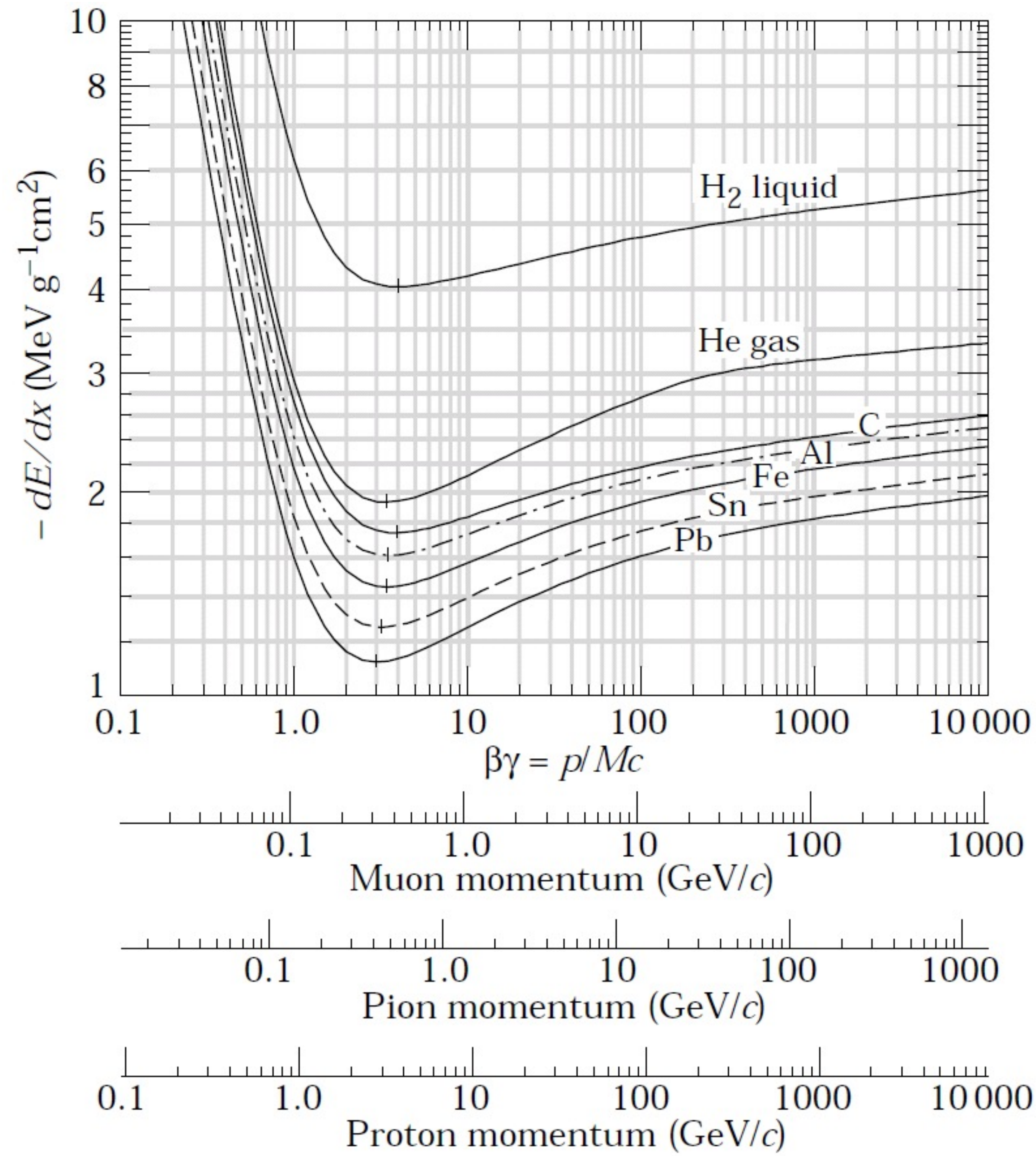
dE/dx has units of MeV cm^2/g

x is ρs, where ρ is the material density, s is the path length

****Note that this is NOT for electrons, that requires more math****

Minimum Ionizing Particles

- Bethe-Bloch has same shape regardless of material
- The minimum is about the same regardless of material: occurs around $p/Mc = 3\text{-}3.5$
- dE/dx can be used to identify particle type along with an energy or momentum measurement



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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

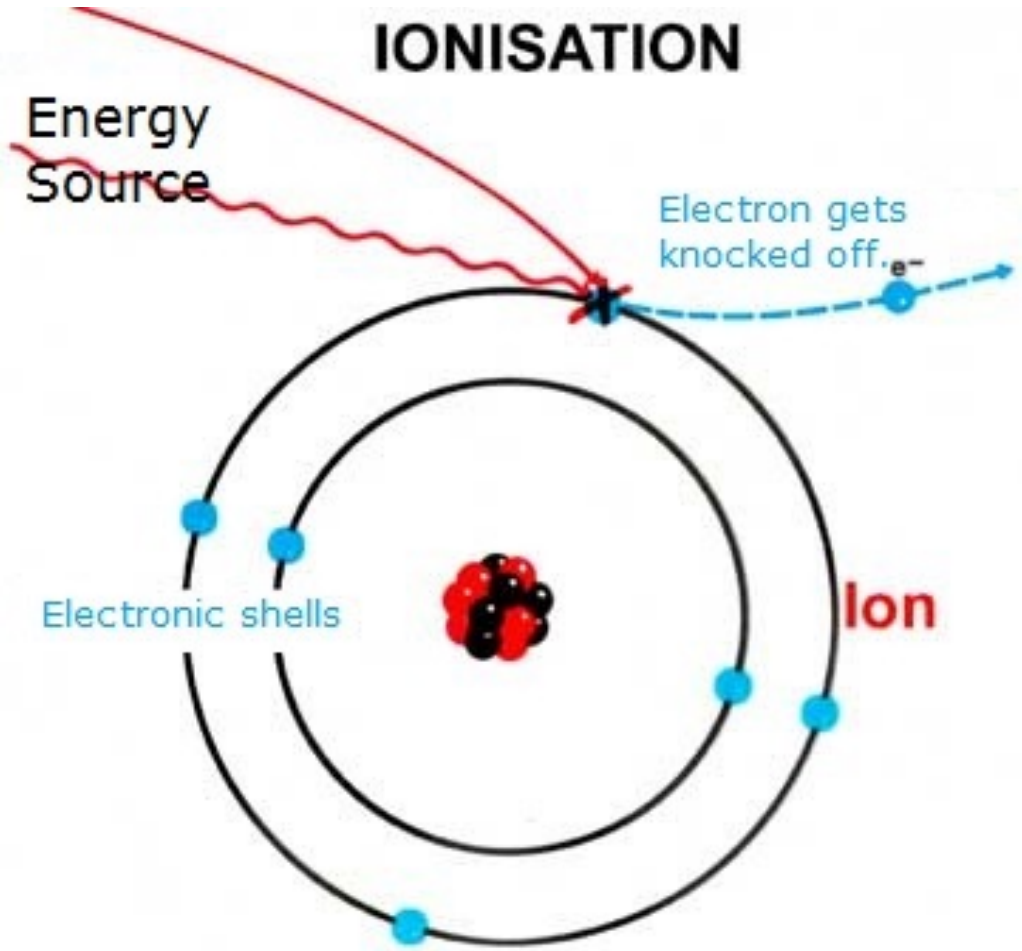
$$F = \frac{mv^2}{r} = qvB$$

$$r = \frac{mv}{qB}$$

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

Ionization

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



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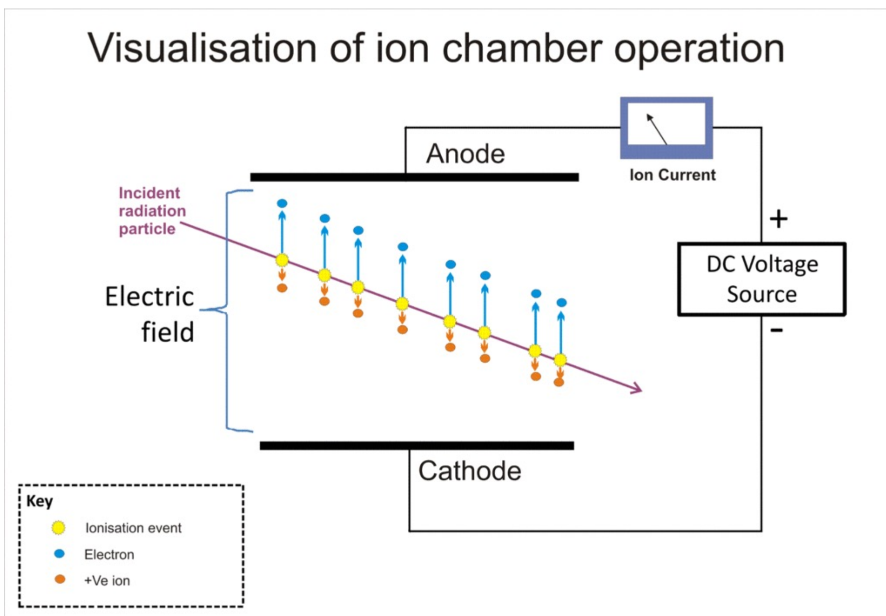
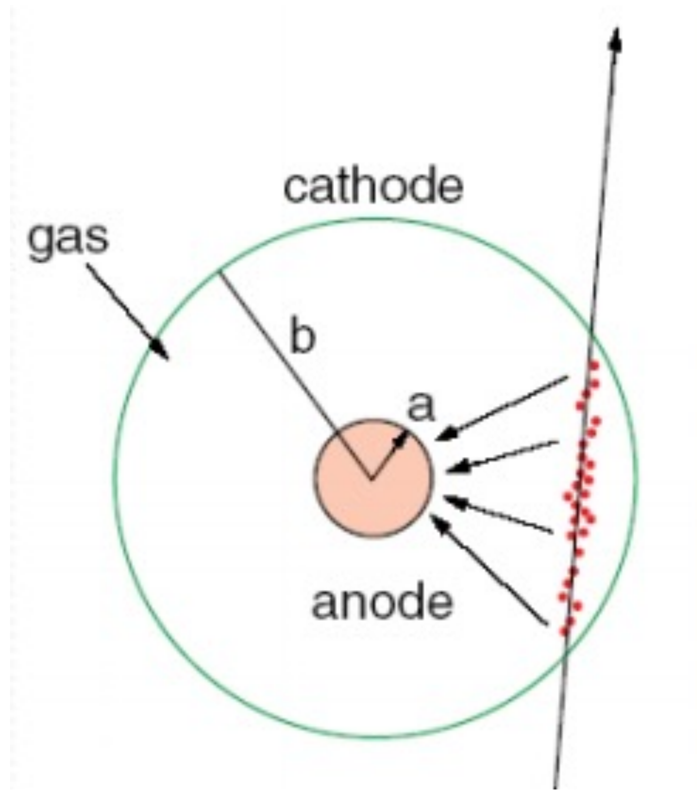
How does this help us?

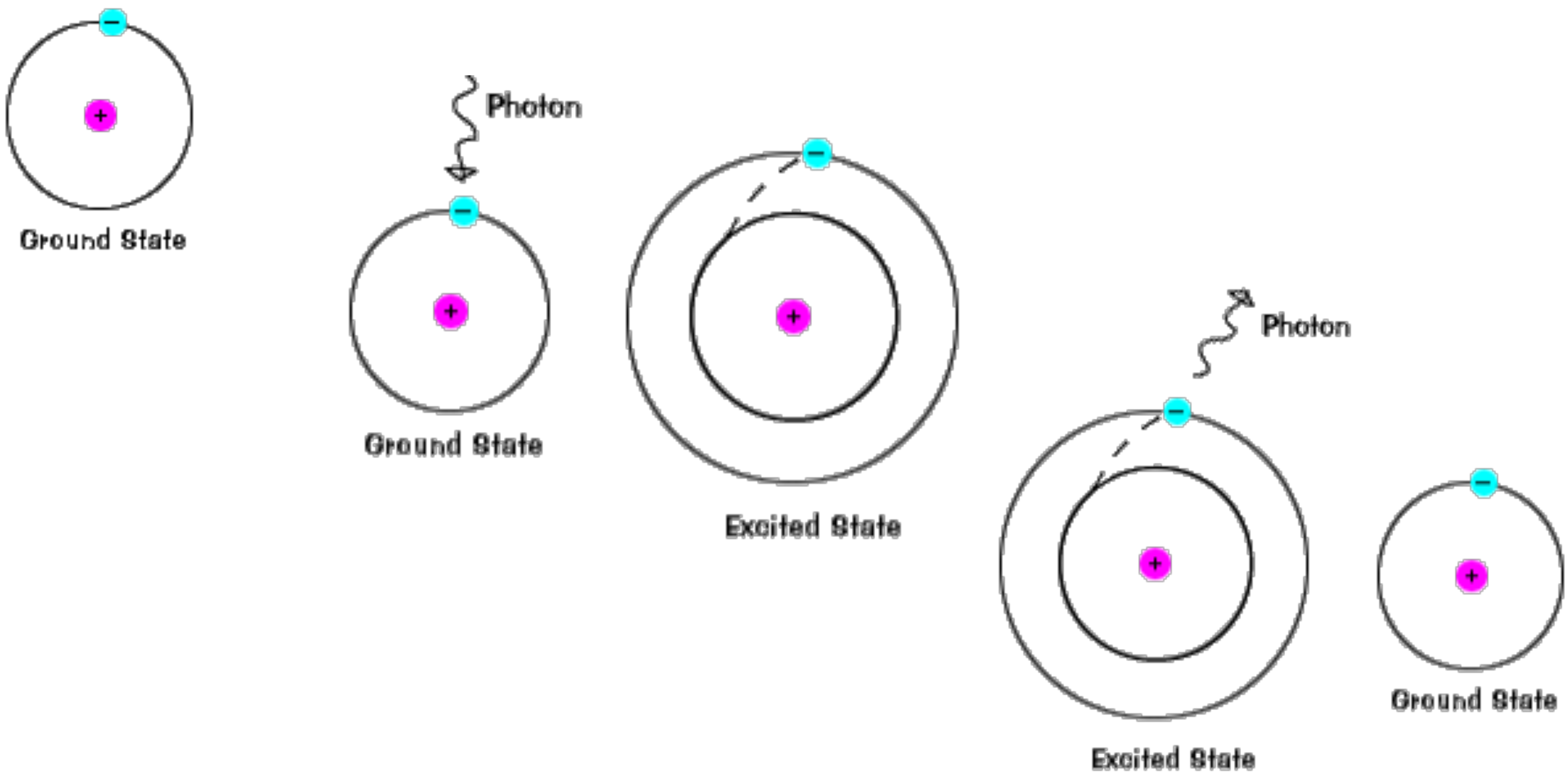
- After ionization, you are left with a free electron (negative) and a positively charged atom
- Adding an electric field – we can separate the different types of charges.
- Electrons will leave a charge on a sensor that we can read out.





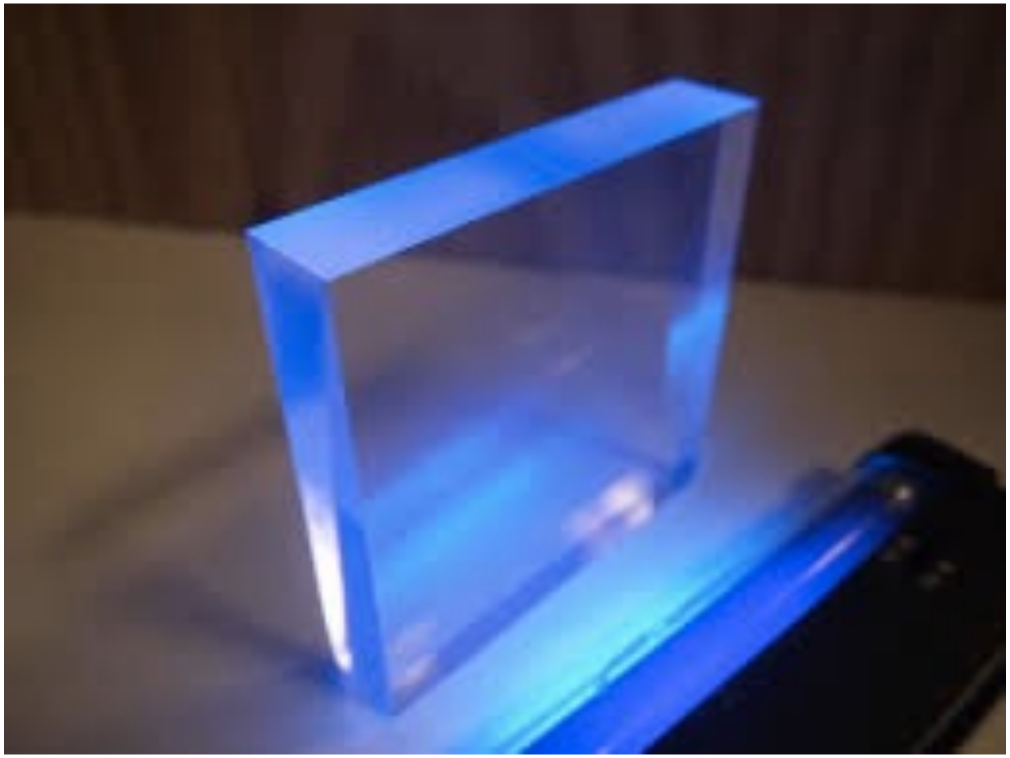
Scintillation Light

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



What can we do with scintillation light?

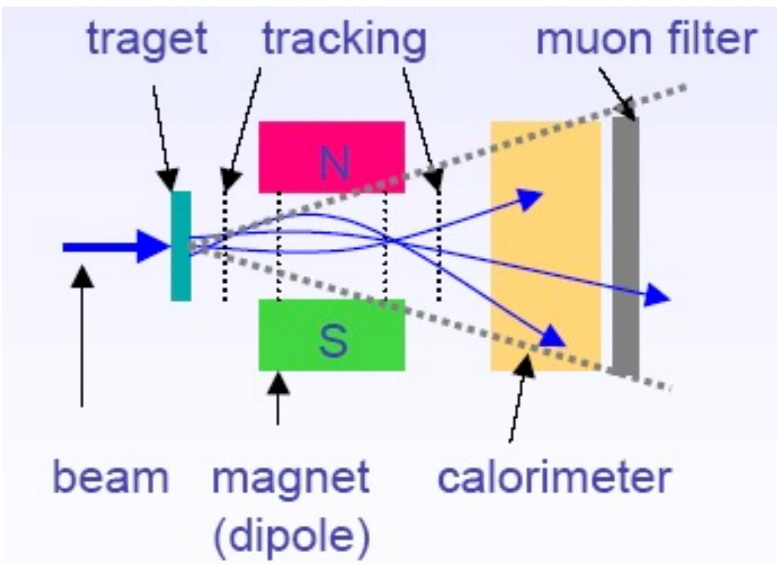
- The photon emitted will have a very specific energy
- We can count the number of photons that go to our readout tools



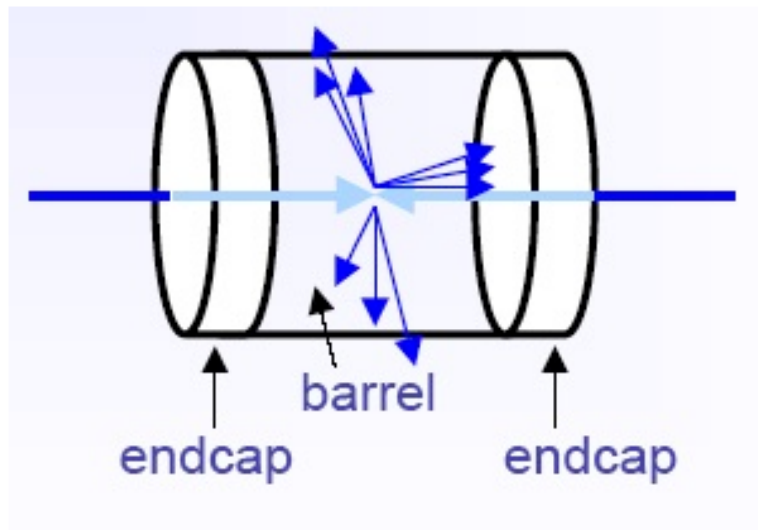
How to build a detector

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

Fixed Target Geometry

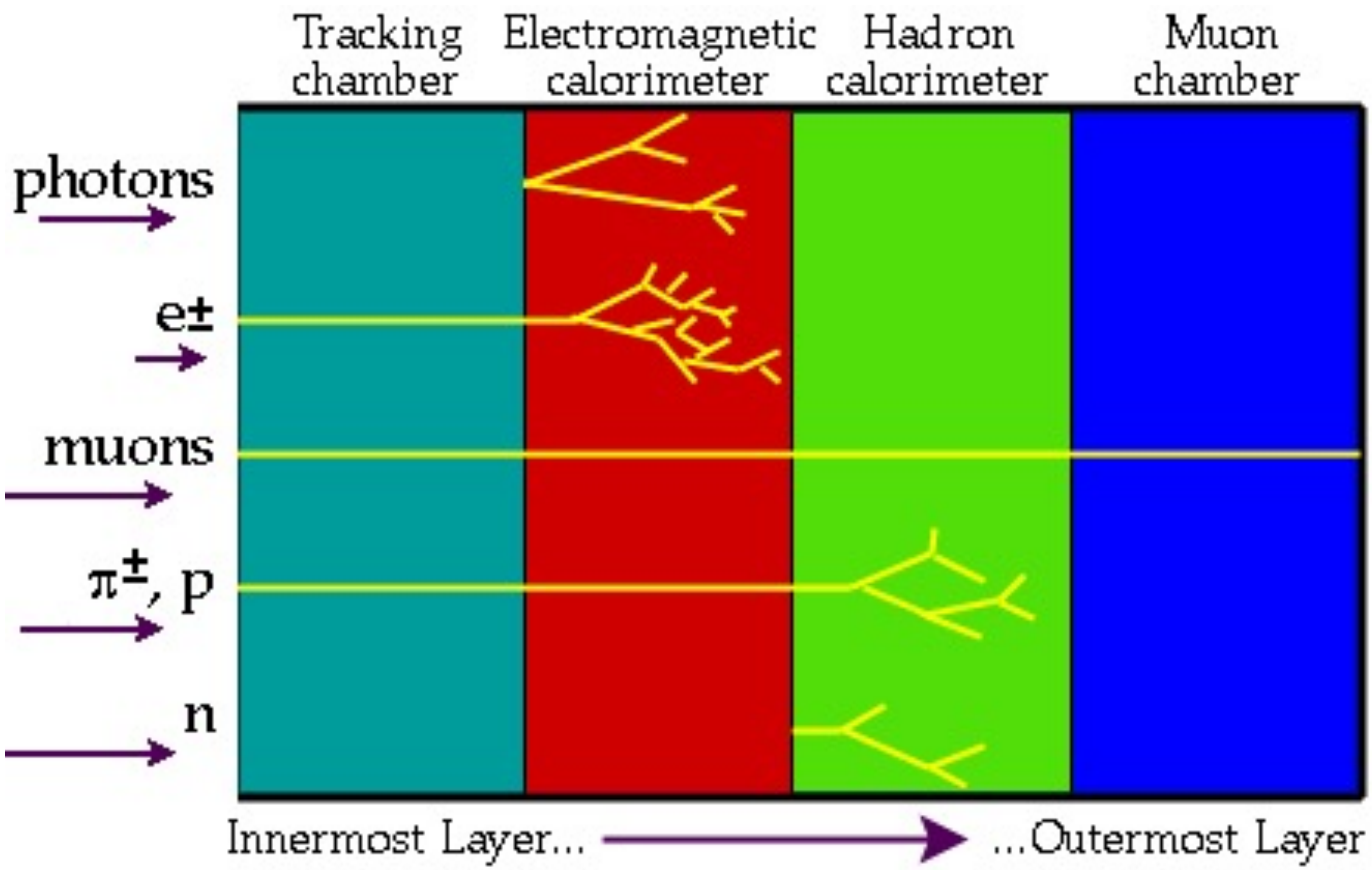


Collider Geometry



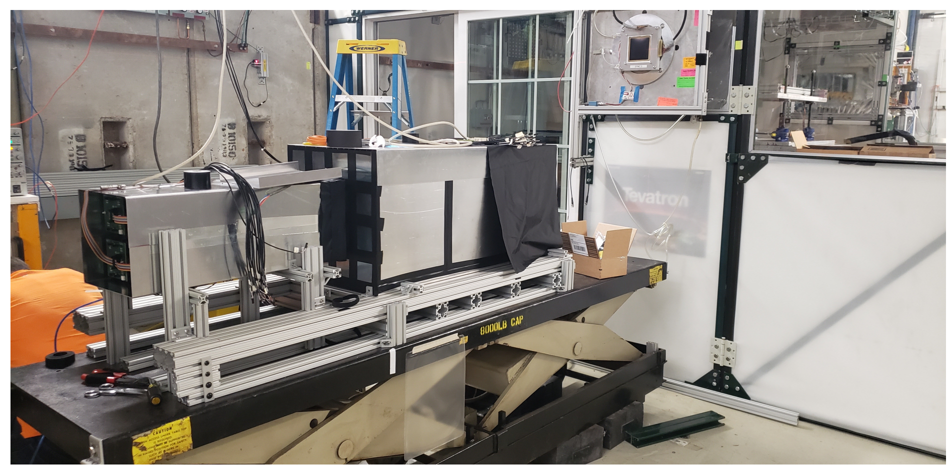
What do events look like?

- We can use the different detectors to figure out the signals



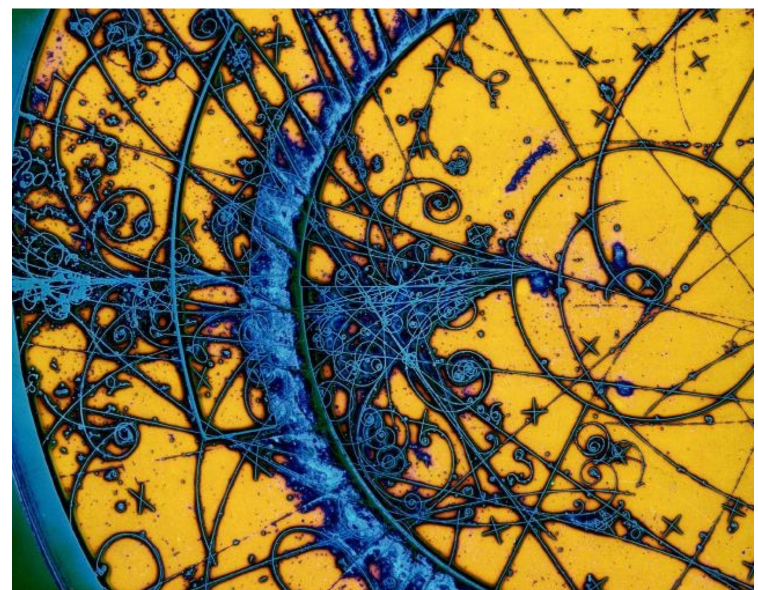
Particle Detectors

- Tracking Detectors
  - Scintillation
  - Ionization
  - Pair production
- Calorimeters
  - Hadronic showers
  - Pair production
  - Bremsstrahlung
- Transition Radiation Detectors
  - Transition radiation
  - Cherenkov radiation



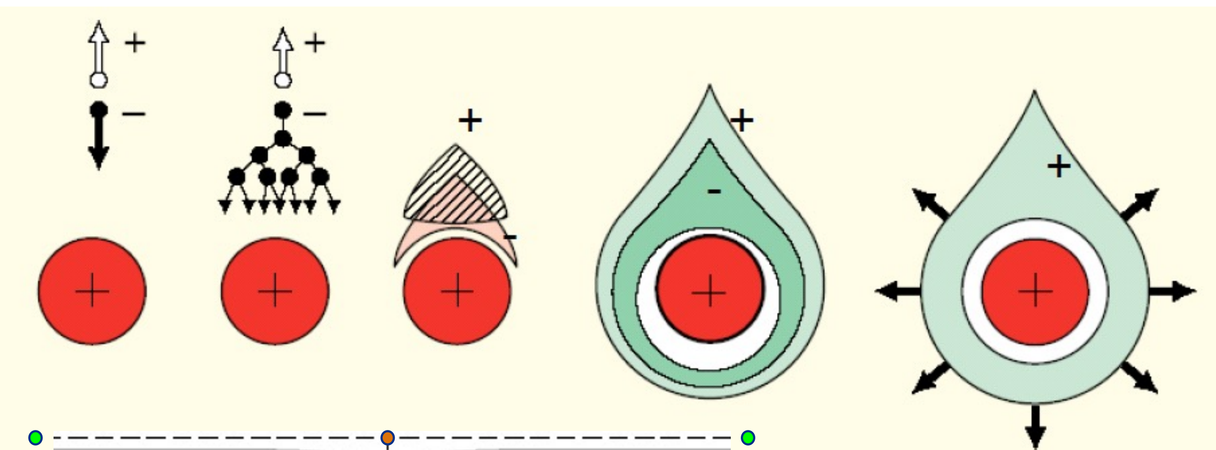
Tracking Detectors

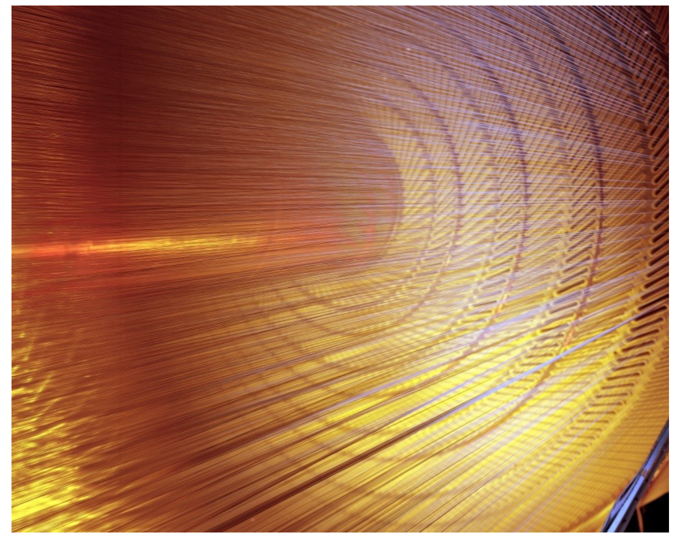
- **Used for:**
  - momentum measurements (**p**)
  - charge determination
  - *particle production position (primary and secondary)*
- **Main Concepts**
  - Motion in Magnetic field
  - Ionization / scintillation
  - Resolution
- **What are trackers made of?**
  - Gaseous detectors
  - Silicon detectors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

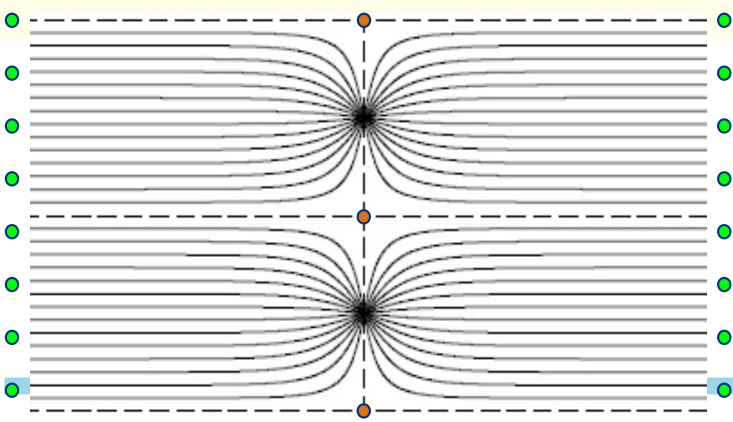


Gaseous Trackers

- Straws, Proportional Chambers, Drift chambers, GEMS, TPCs, and many others
- Operate with high voltage, cathode/anode geometry, charge multiplication

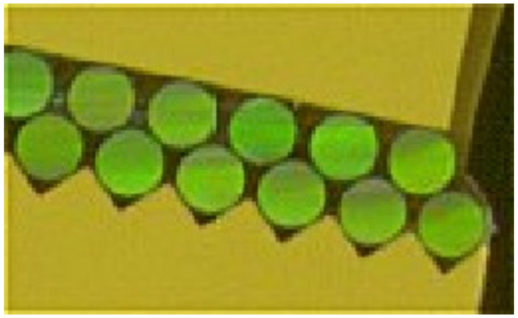




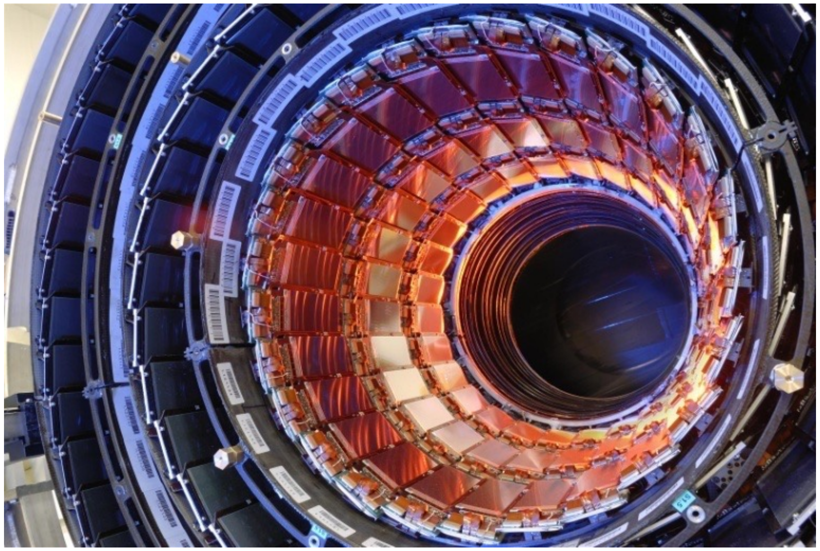


Solid State Detectors and Fibers

- Vertex detectors, microstrips, pixel detectors, fibers
  - Radiation hard (very important!)
- Silicon detectors have many nice features
  - Commercially produced
  - Can make fine granularity



CMS
9.6M ch



Tracking Summary

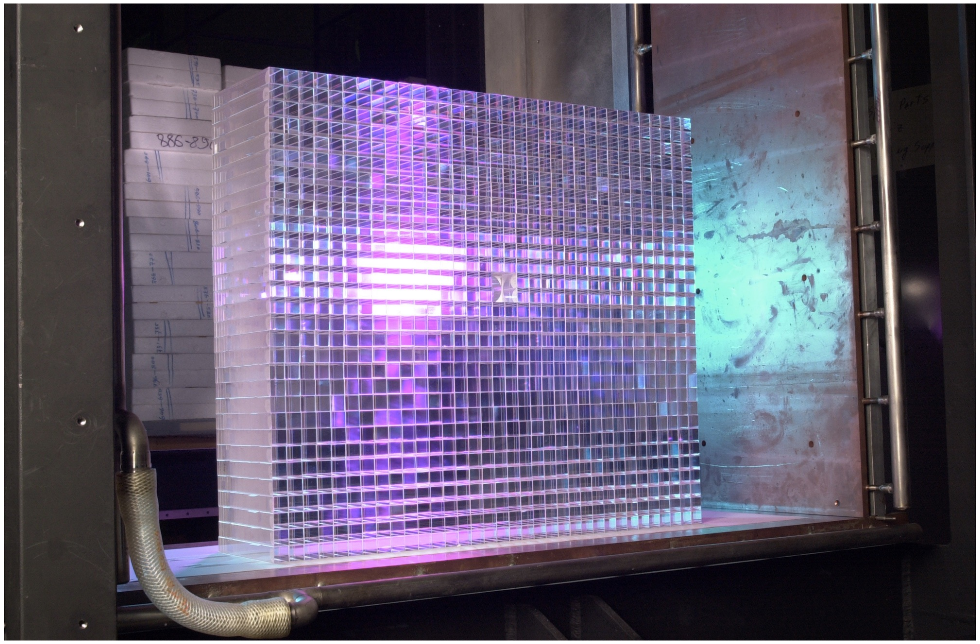
- Three types of tracking detectors: gaseous, solid state, scintillating
- Gaseous detectors rely on charge multiplication
  - Gas choice is a bit of "magic"
  - Covers large areas "cheaply" with sensitive materials
- Solid state/scintillating
  - Fine granularity, commercially produced
  - Can have problems with too much material in the beamline

Calorimeters

- **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



Lead Tungstate crystals

EM Calorimetry

- EM calorimeters measure response from coulomb interactions (EM force)
  - Used to determine photons and electrons
  - Hadronic showers also have an EM component

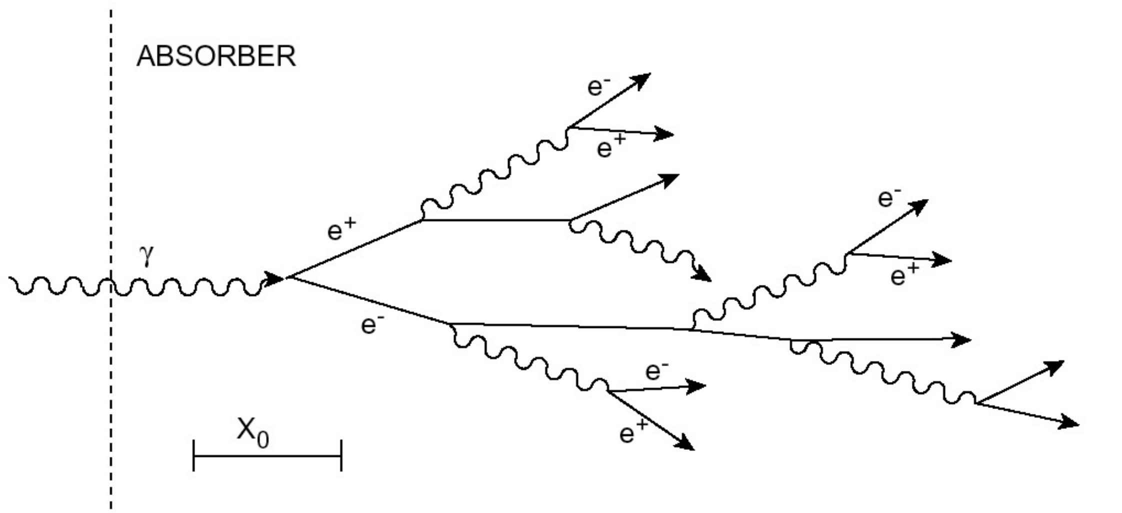


Figure 5: Schematic development of an electromagnetic shower.

How does a calorimeter work?

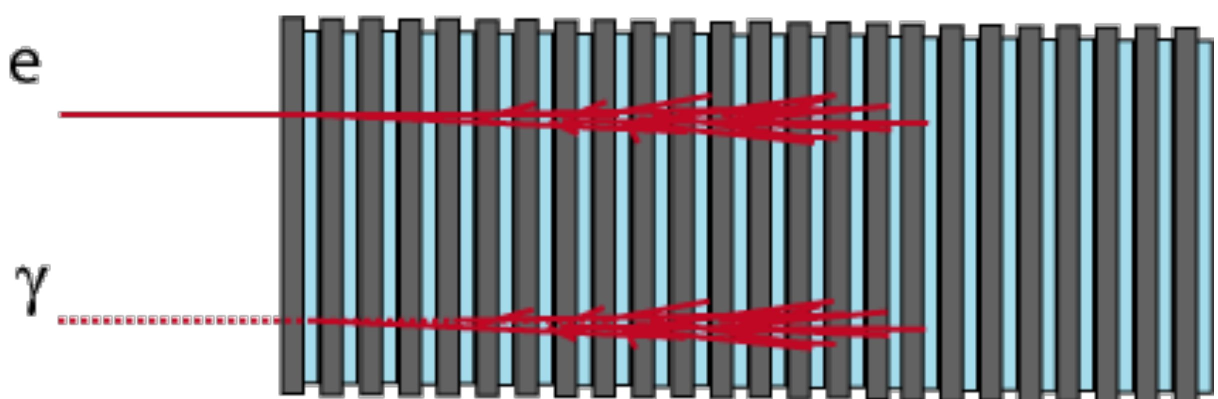
- Particles have gone through the trackers with only minimal energy loss (they haven't really slowed down).

- 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

EMCal: Definitions of Important parameters

- Radiation length: When a particle's energy is reduced to 1/e. This is how we describe the thickness of an EMCal:
  - $X_0 = 180\ (A/Z^2)\ (g/cm^2)$
- Critical energy: When the loss of energy from Bremsstrahlung equals the ionization loss of Energy: $E_c = 800/(Z + 1.2)$ (MeV)
- Moliere radius: Contains 90% of the shower and characterizes the width of the shower
  - $r = 21.2$ (MeV) X_0/E_c
- Max shower: $S_{max} = \ln(E_{incoming}/E_c)$



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Hadronic Calorimetry

- Hadronic calorimeters
  - Contain both an EM component driven by EM interactions and a hadronic component driven by Strong interactions

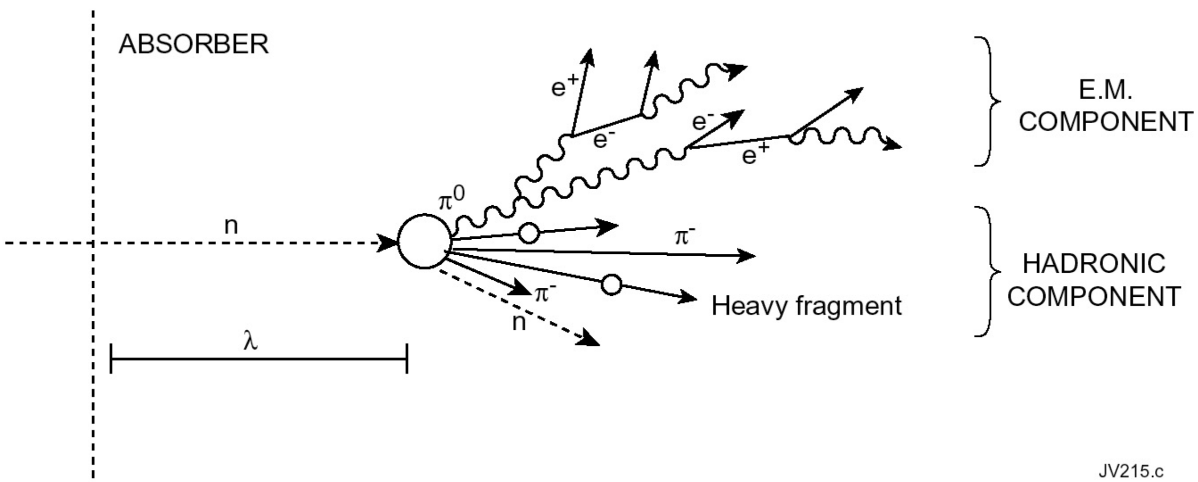
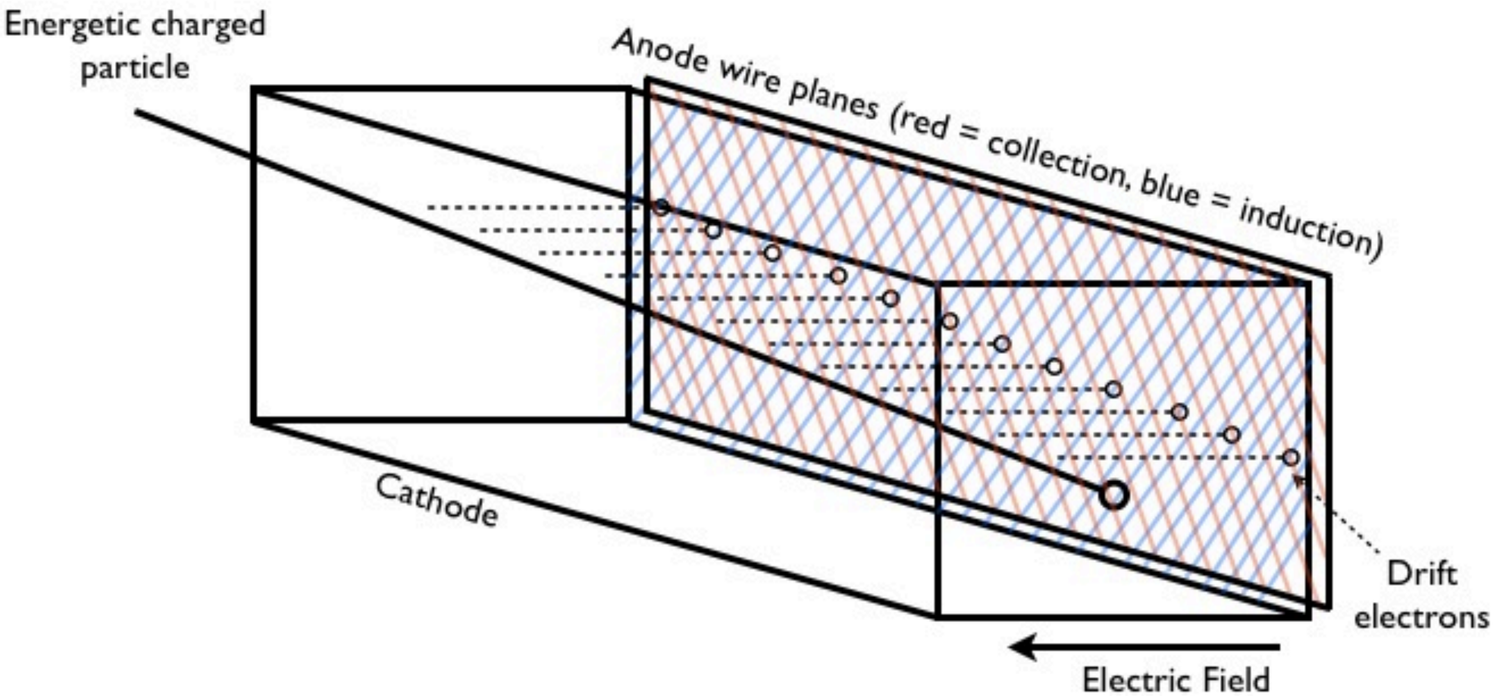


Figure 12: Schematic of development of hadronic showers.

HCal: Definitions of Parameters

- Defined by nuclear interaction lengths instead of radiation lengths
  - Lambda = A / (cross section)*Number of atoms
- Much more complicated, no easy formulas to use to define various concepts (shower max, etc)
- Several orders of magnitude bigger than EM interactions
  - Might need 25 cm to contain an EM shower, but need 2.5 meters to contain Hadronic shower

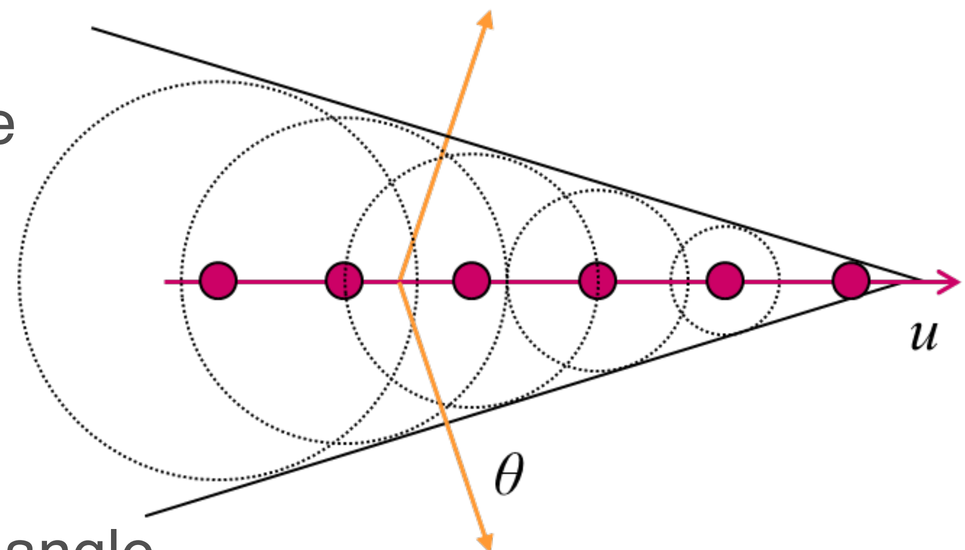
Time Projection Chambers



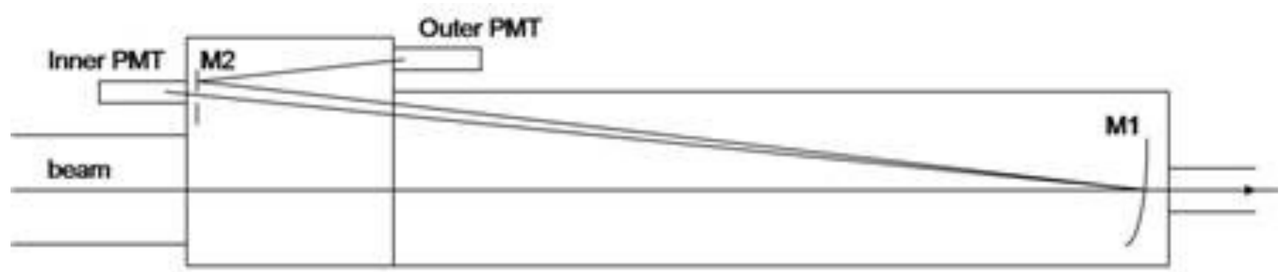
- Uses ionization
- Can be used for both position and energy measurements
- Filled with either gas or liquid

Cherenkov Detectors

- In some materials, particles will travel faster than the speed of light
  - "Sonic boom" or a boat in the water

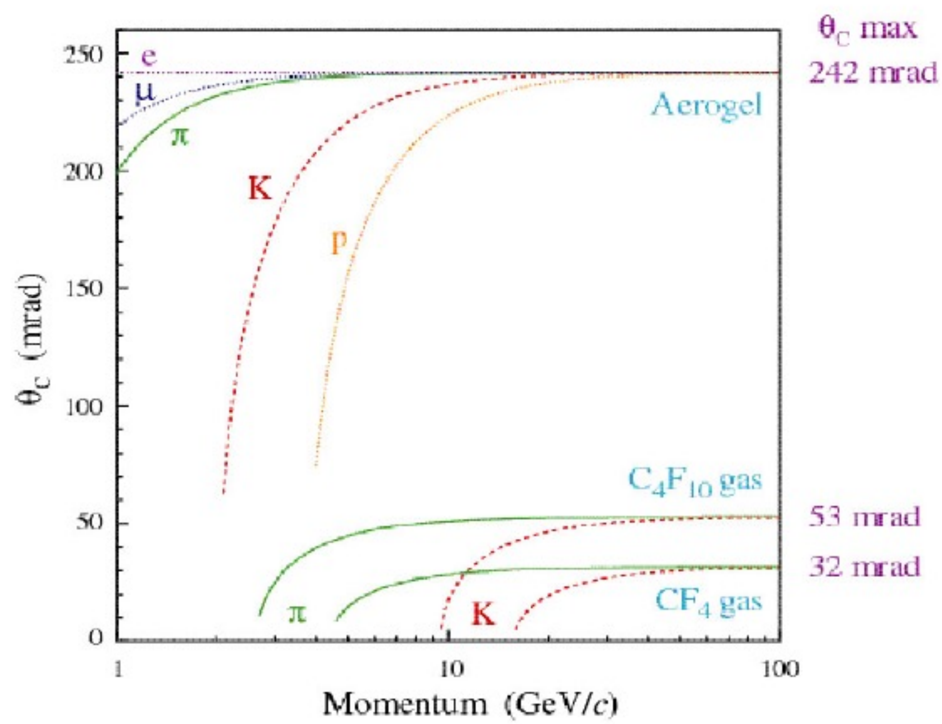


  - Main parameter: Cherenkov angle
    - Cos(theta) = 1/(n*beta)
    - Dependent of velocity of particle and the index of refraction for the material



Cherenkov and Transition Radiation detectors

- Both used for Time of Flight and particle identification
  - Depending on mass and speed of particle, it will arrive in different places
- Important piece of the whole detector



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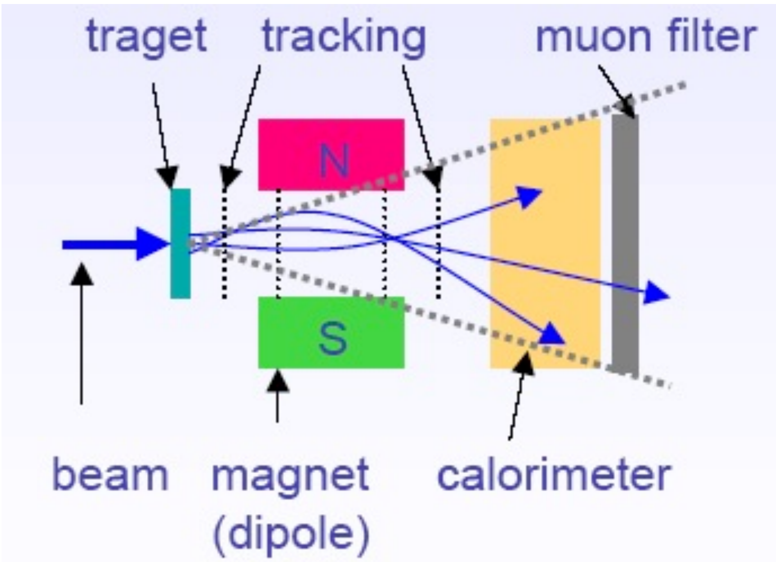
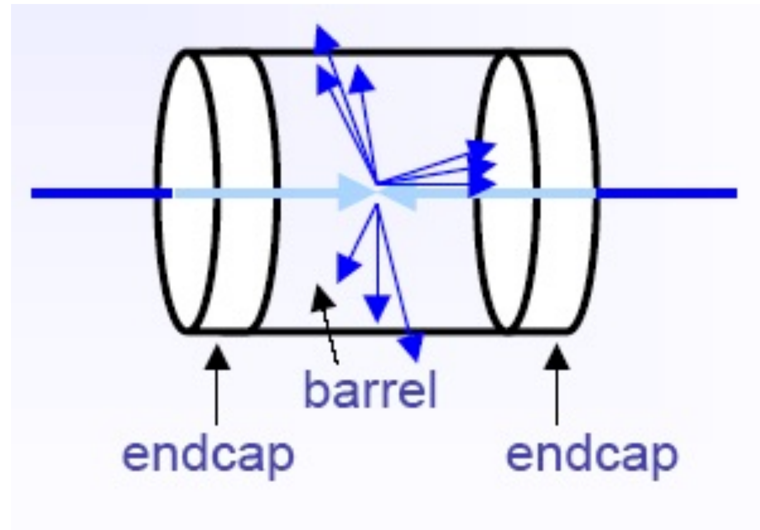
Putting it all together

Fixed Target Geometry



Collider Geometry

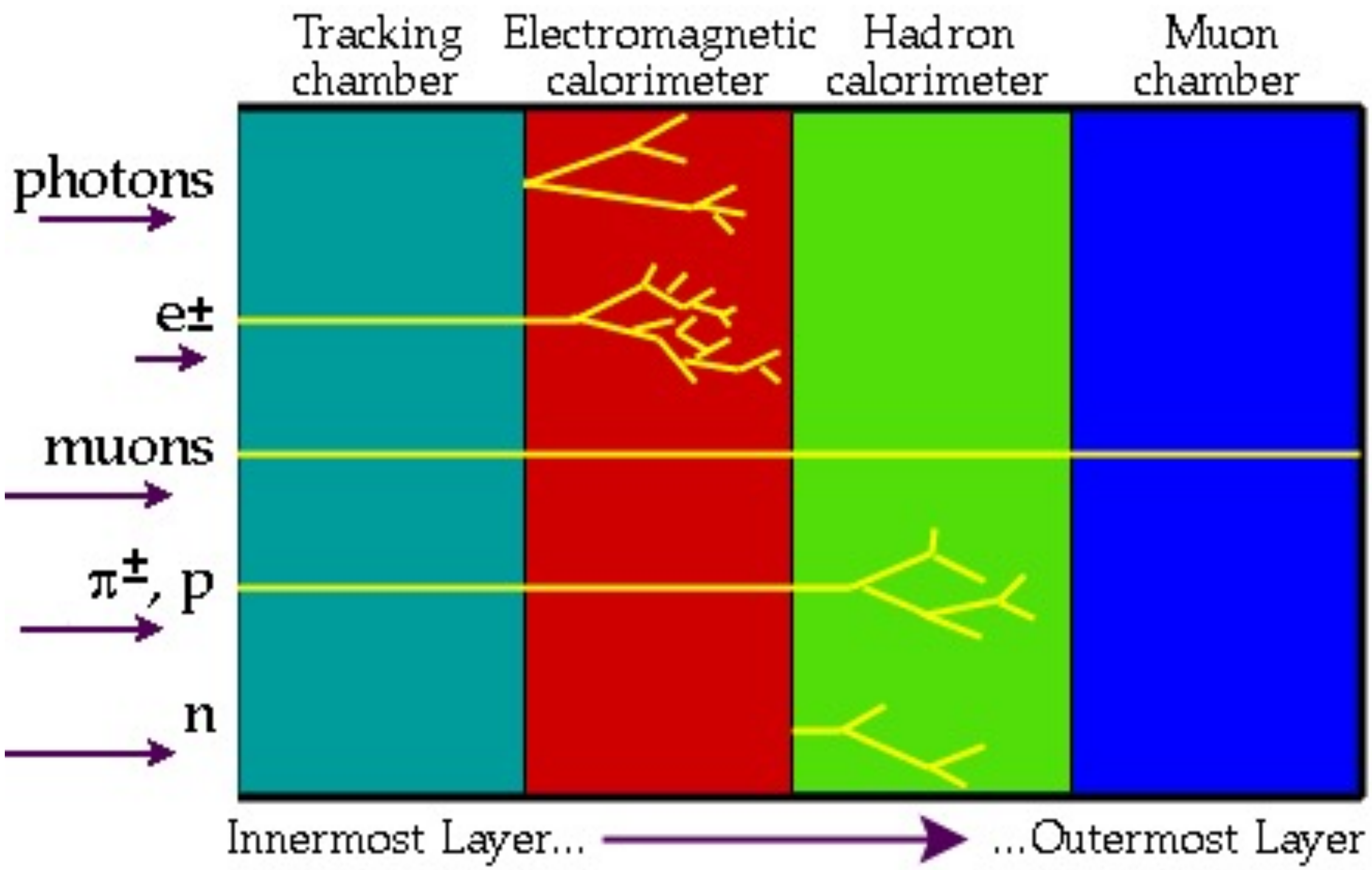


- **LHCb**
- **NOvA**

- **CMS**
- **ATLAS**
- **sPHENIX**

What do events look like?

- We can use the different detectors to figure out the signals



More information on what they look like

Signature	Detector Type	Particle
Jet of hadrons	Calorimeter	u, c, t$\rightarrow$Wb, d, s, b, g
'Missing' energy	Calorimeter	ν_e, ν_μ, ν_τ
Electromagnetic shower, X_o	EM Calorimeter	e, γ, W$\rightarrow$eν
Purely ionization interactions, dE/dx	Muon Absorber	μ, $\tau\rightarrow\mu\nu\nu$
Decays, $c\tau \geq 100\mu m$	Si tracking	c, b, τ

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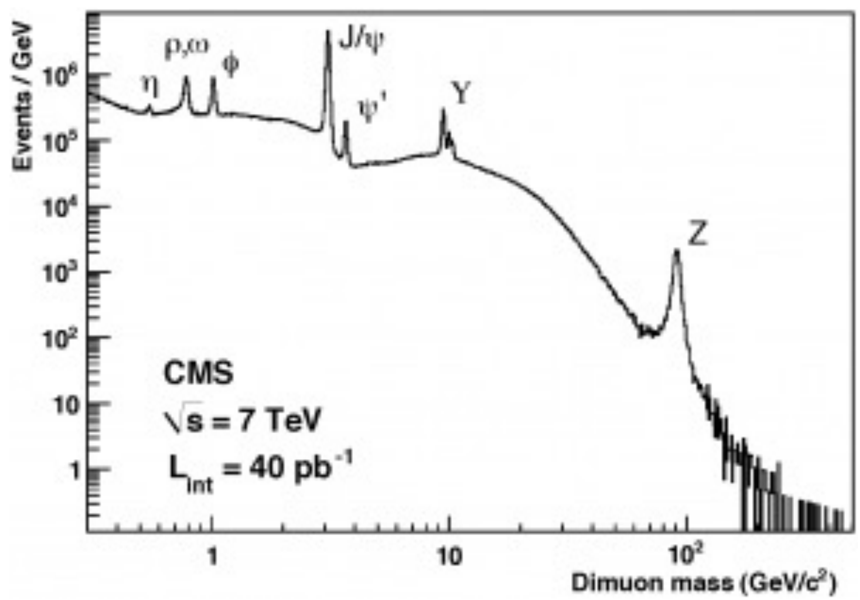
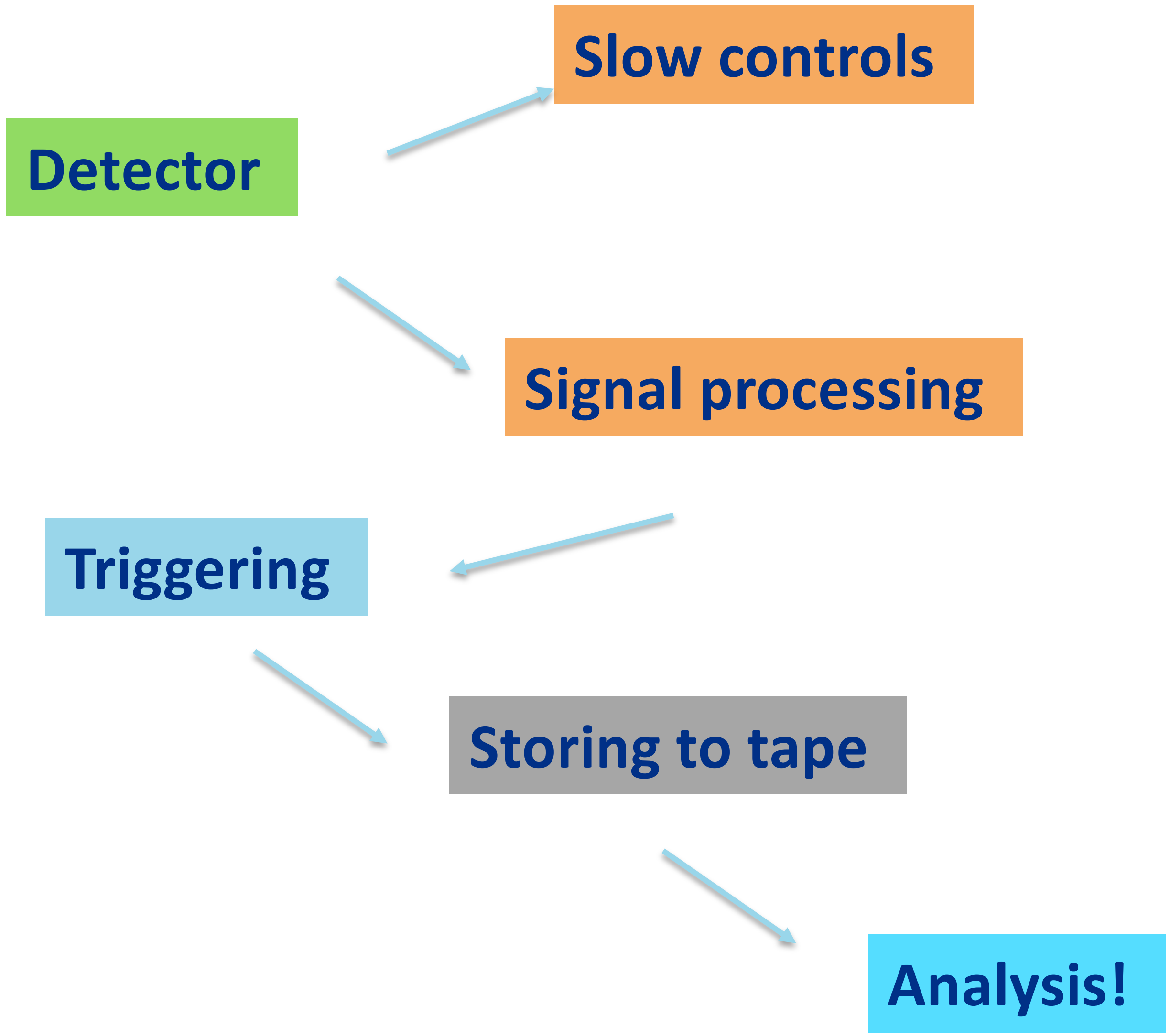
DAQ and electronics

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



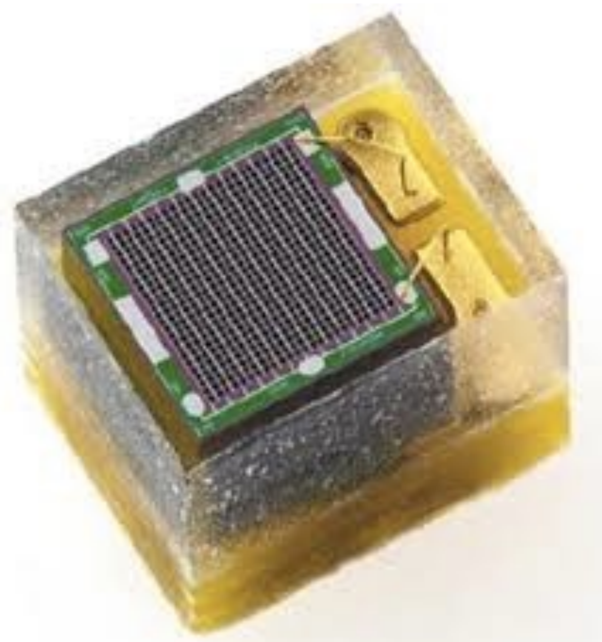
- How do we get from trackers and calorimeters to this?

Data Acquisition Process



Detector signals

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



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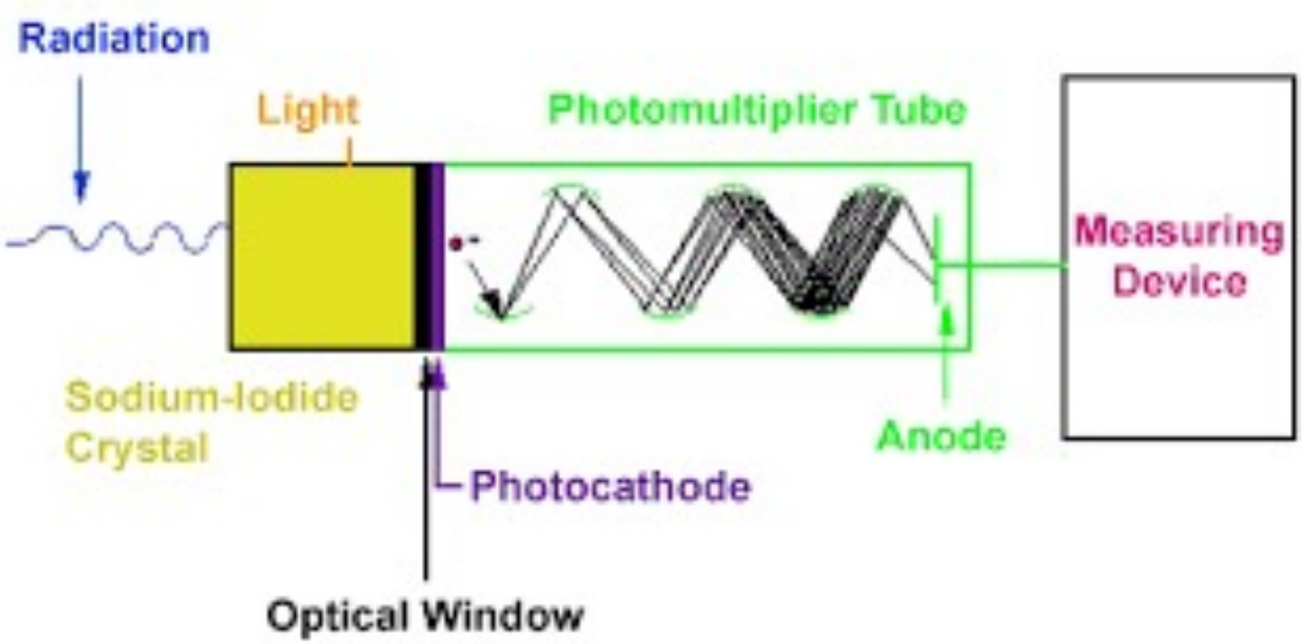
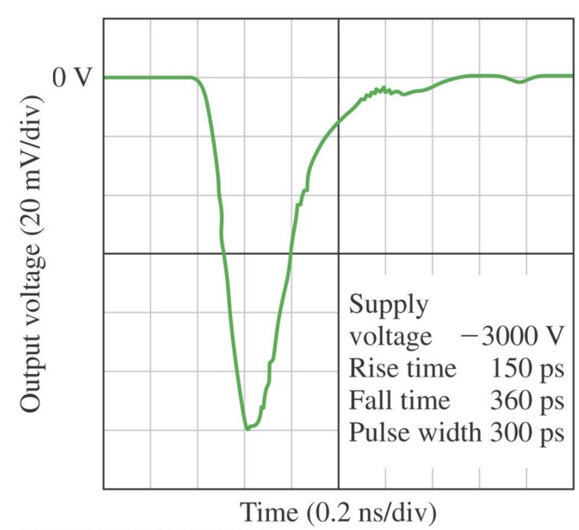
Example – Photomultiplier Tube

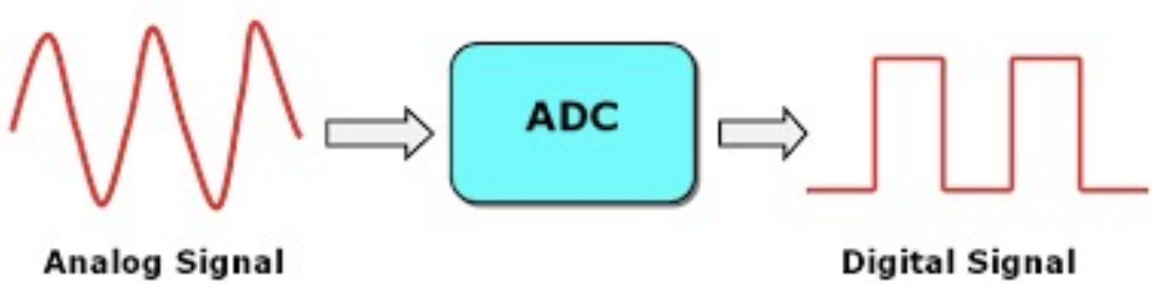


The output signal from a single photon



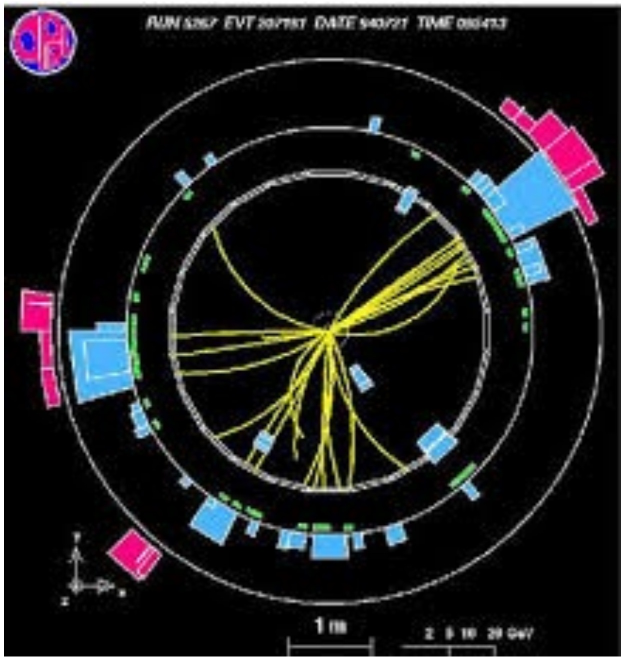
Signal processing

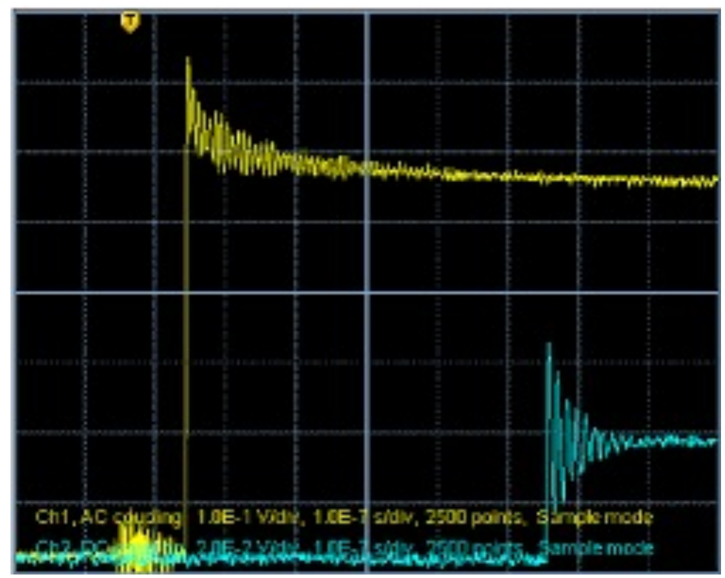
- Shape
  - Look at the shape of the signal – will tell you important information
- Amplify
  - Make a small signal large enough to see
- Discriminate
  - Only look at signals above a certain threshold.



Processing signals

- We've turned those particle interactions into electronic signals

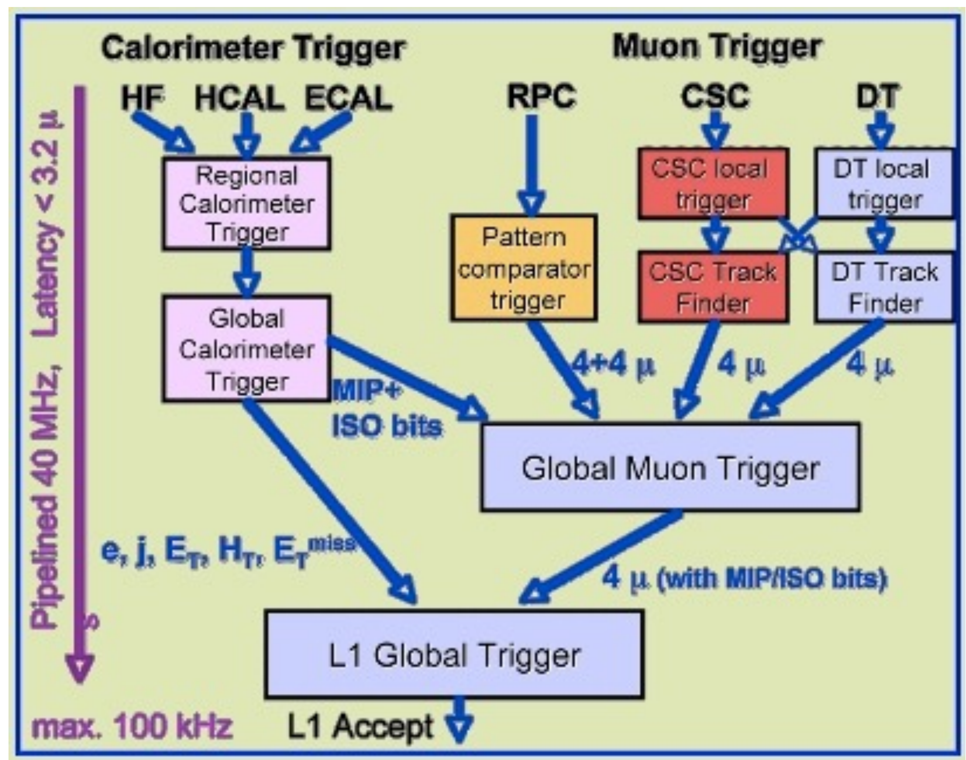




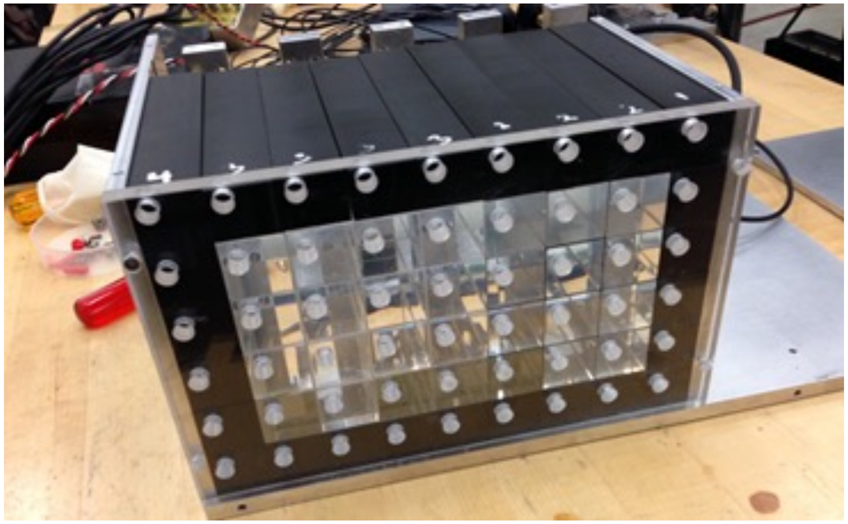
Trigger systems

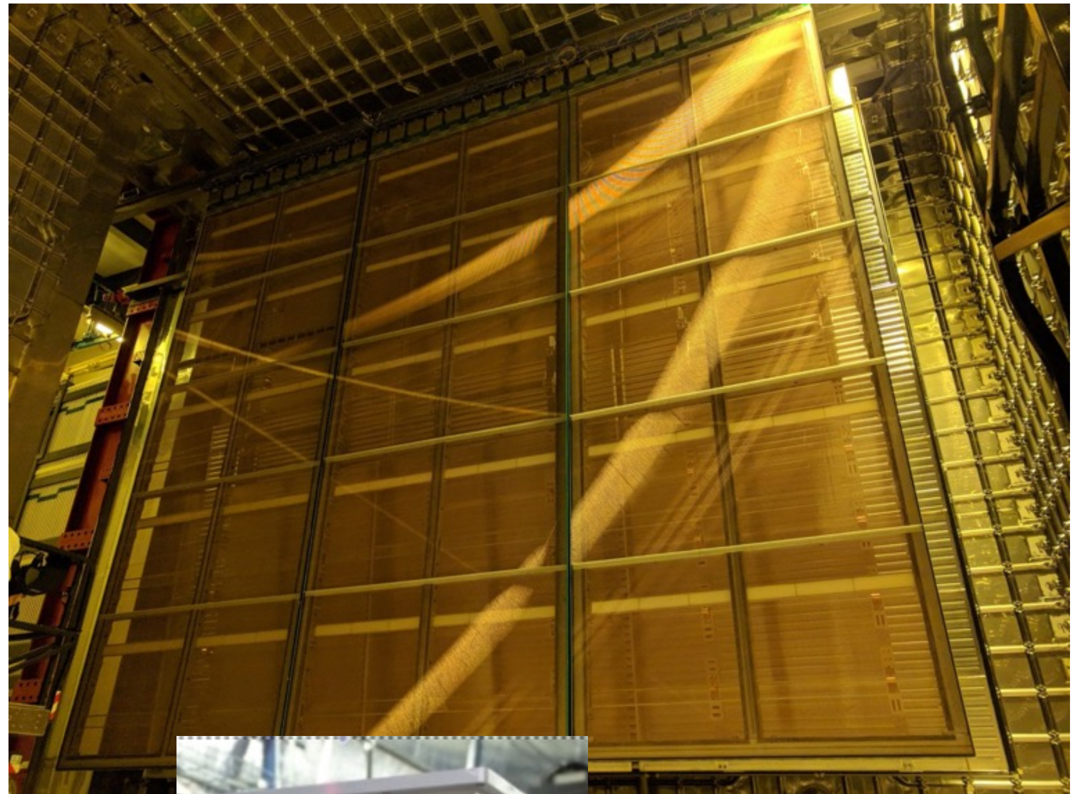
- Take the input from all the sub systems and detectors
  – Make a decision: keep or not?
- Usually multi-level
  – Make decisions based on which detector sub systems have events.

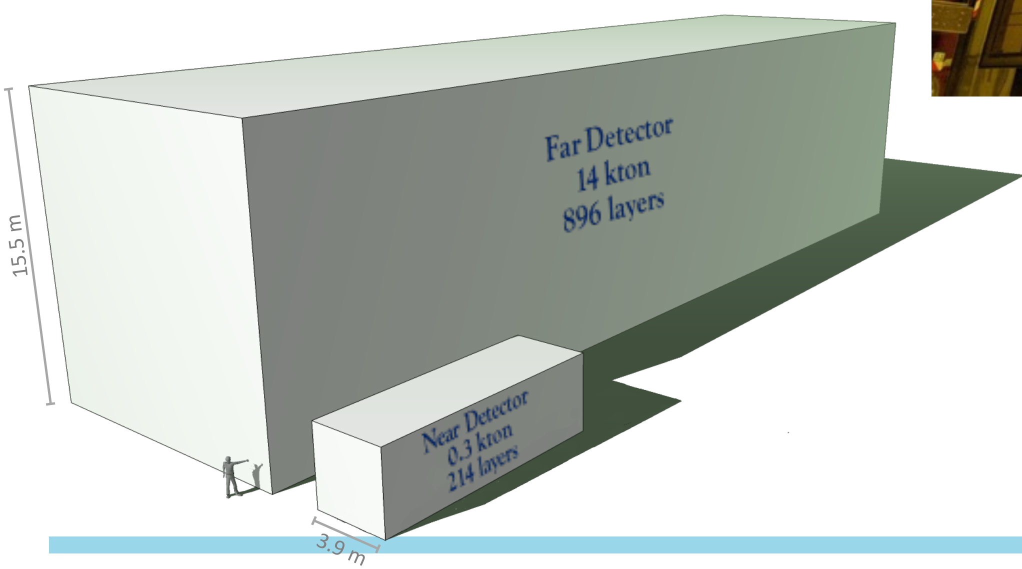
CMS Level 1 Trigger

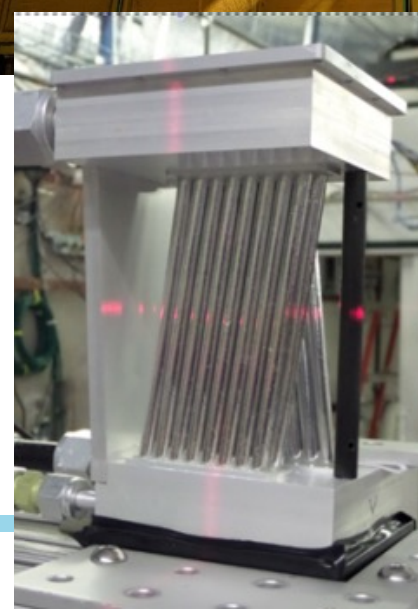


Detectors at Fermilab (A Sample)









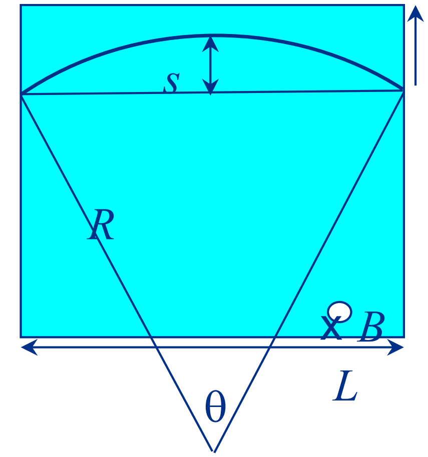
Summary

- 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
  – Use energy loss to determine what type of particles you are dealing with
- Things not touched on at all
  – Readout electronics: extremely important!!!
  – Services: HV and gases, etc: also extremely important!!!
- This is an active field
  – New experiments will have different configurations

References

- Interesting Lecture notes:
  - physics.ucdavis.edu/Classes/Physics252b/Lectures/252b_lecture3.ppt
  - http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/Lectures_SS2012.htm
  - https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_InteractionsWithMatter_1.pdf
  - https://indico.cern.ch/event/145296/contributions/1381063/attachments/136866/194145/Particle-Interaction-Matter-upload.pdf
- Books
  - Dan Green's "Physics of Particle Detectors"
  - Any of the CERN Yellow books on detectors (particularly anything by Sauli) http://cds.cern.ch/collection/CERN%20Yellow%20Reports?ln=en

Resolution – How good is your tracker?



- Note that most trackers are in a magnetic field
  - p_T (Gev/c) = 0.3 B R
  - How well can we measure R?

$$s = R\left(1-\cos\frac{\theta}{2}\right) \approx R\left(1-(1-\frac{\theta^2}{8})\right) = R\frac{\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}$$

- Depends on a variety of things, including the magnetic field
  - For three hits in a tracker: $$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma_s}{s} = \frac{\sigma_x}{s}\sqrt{3/2} = \frac{\sigma_x \cdot p_T}{0.3 \cdot BL^2}\sqrt{96}$$
  - Note this equation improves with length squared and improves with magnetic field. It degrades with position resolution and the momentum
  - A rough estimate of how well we can measure resolution: $\frac{\sigma(p_T)}{p_T^2}$