



# Physics of Particle Detectors

Mandy Rominsky

Undergraduate Lecture Series

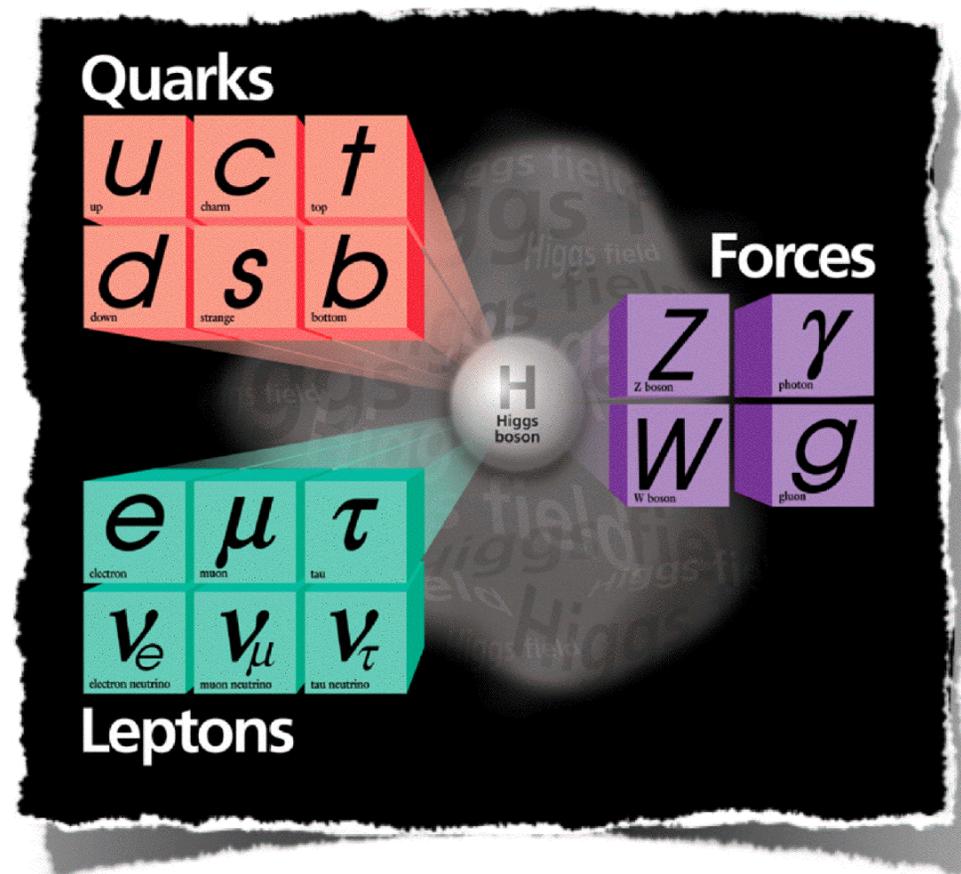
27 June 2019

# 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

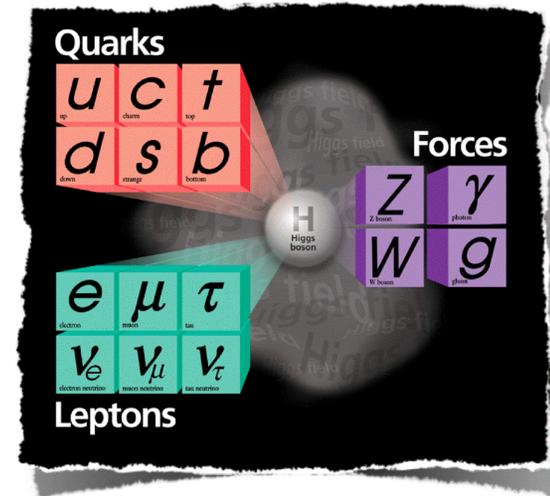
# What do we know about?

- **\*\*Full Intro Lecture on 6/25\*\***
- 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,  $K^0$ ,  $K^{+/-}$



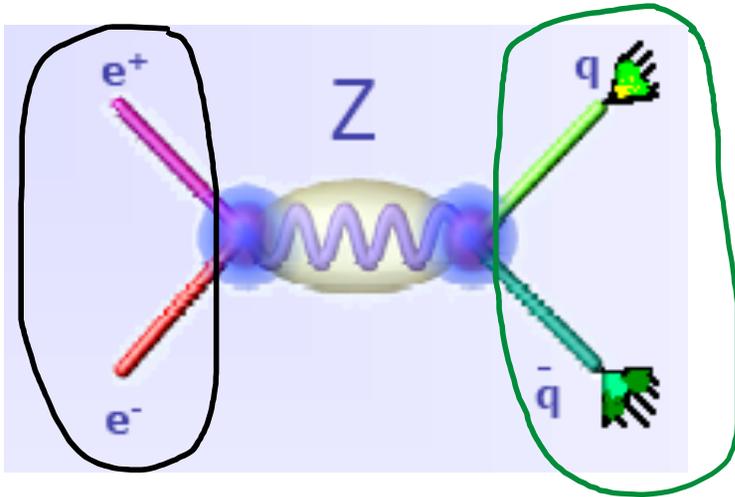
# How can we identify particles?

- 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



$$e^+ + e^- \rightarrow Z^0 \rightarrow q\bar{q}$$

(+ 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

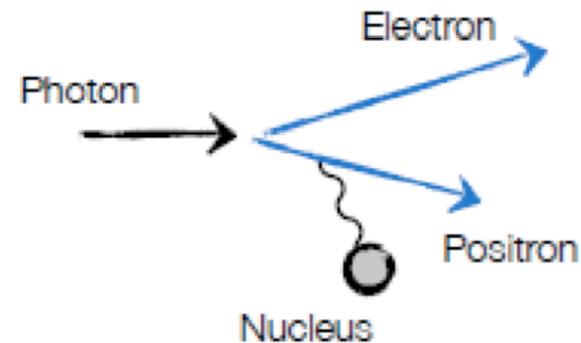
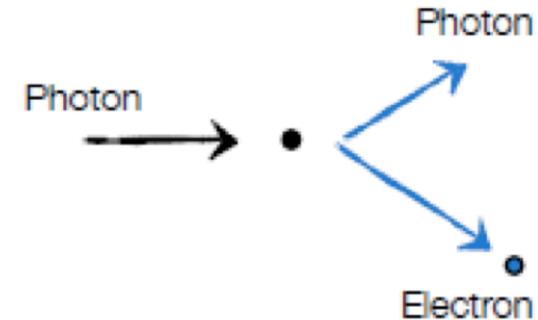
- Energy loss
- Motion in a magnetic field
- Ionization
- Scintillation



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# 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:

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

where

$A, Z$ : atomic mass and atomic number of absorber

$z$ : charge of incident particle

$\beta, \gamma$ : 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;

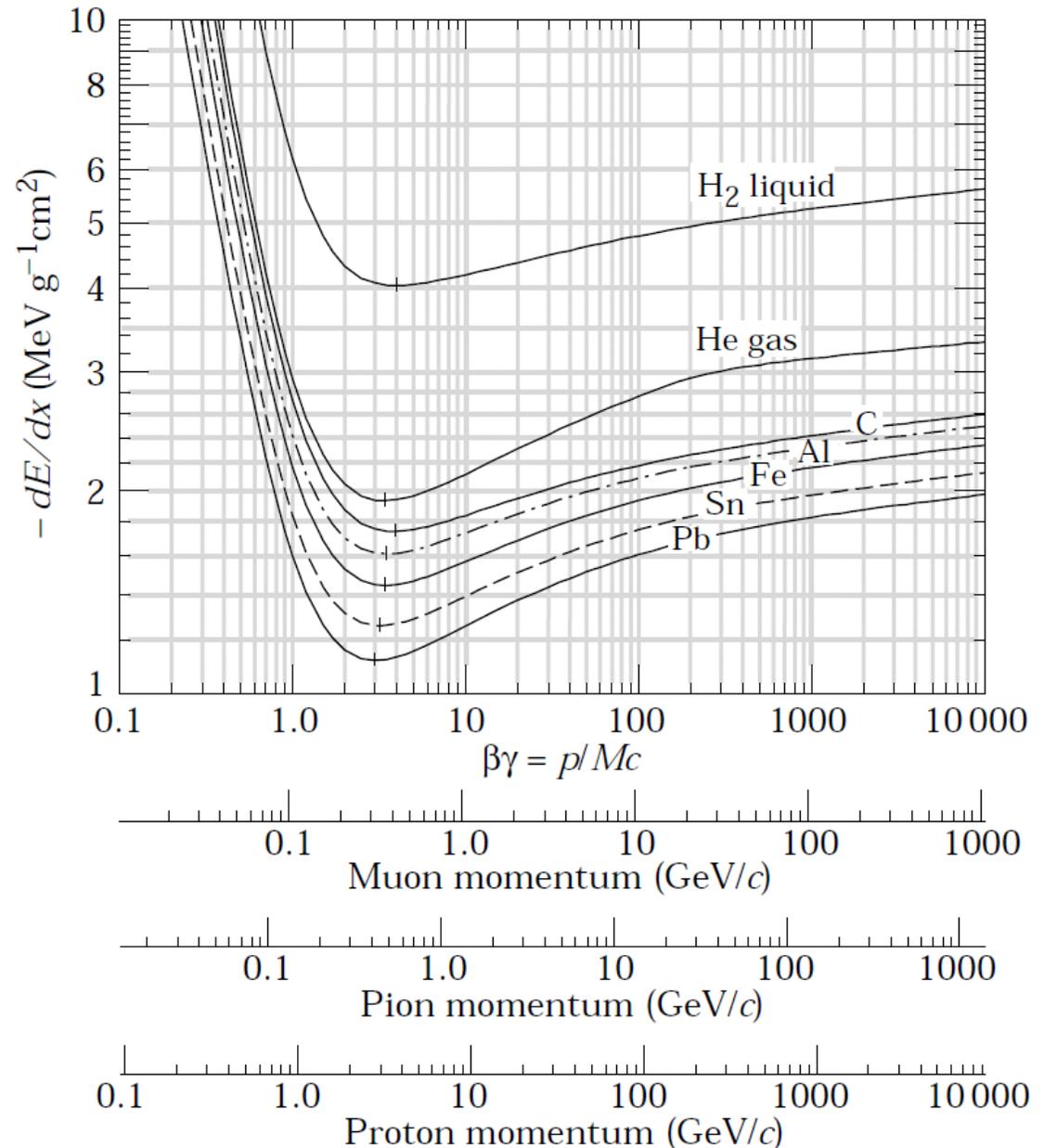
$dE/dx$  has units of MeV cm<sup>2</sup>/g

$x$  is  $\rho S$ , where  $\rho$  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  $p/Mc = 3-3.5$
- $dE/dx$  can be used to identify particle type along with an energy or momentum measurement

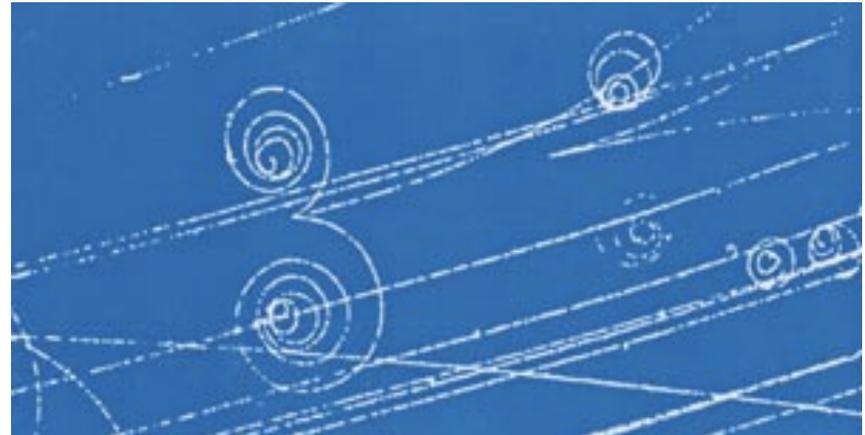


# Uniform circular motion in a magnetic field

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

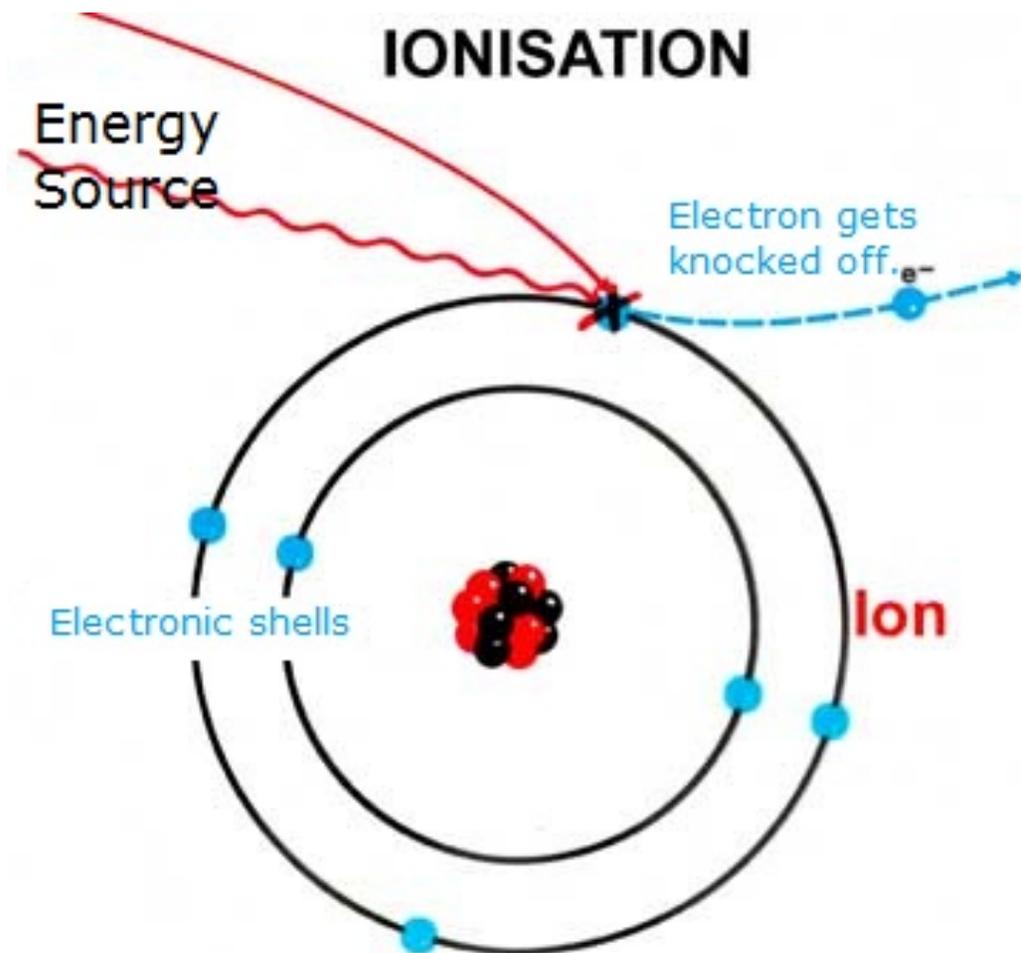
$$F = \frac{mv^2}{r} = qvB$$
$$r = \frac{mv}{qB}$$

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



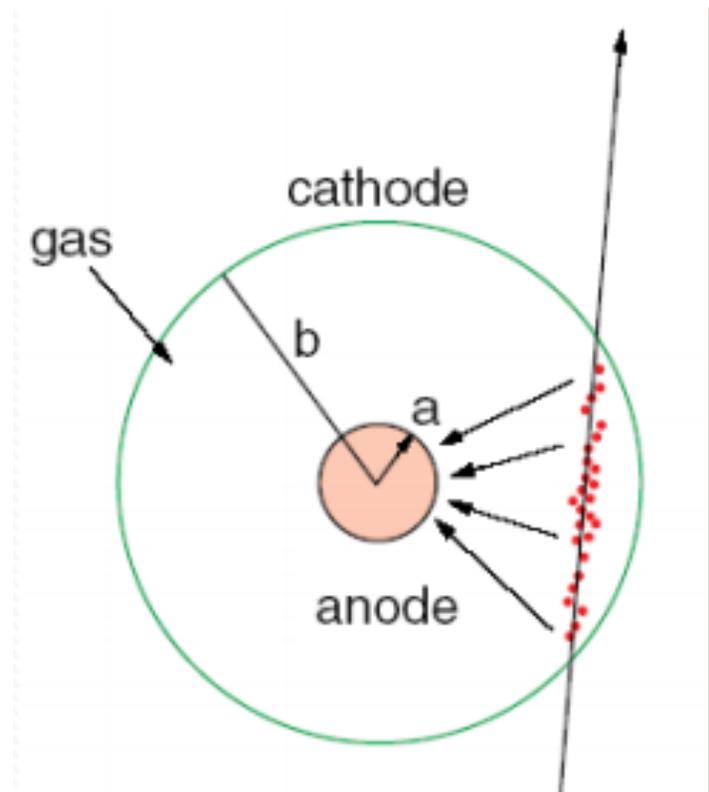
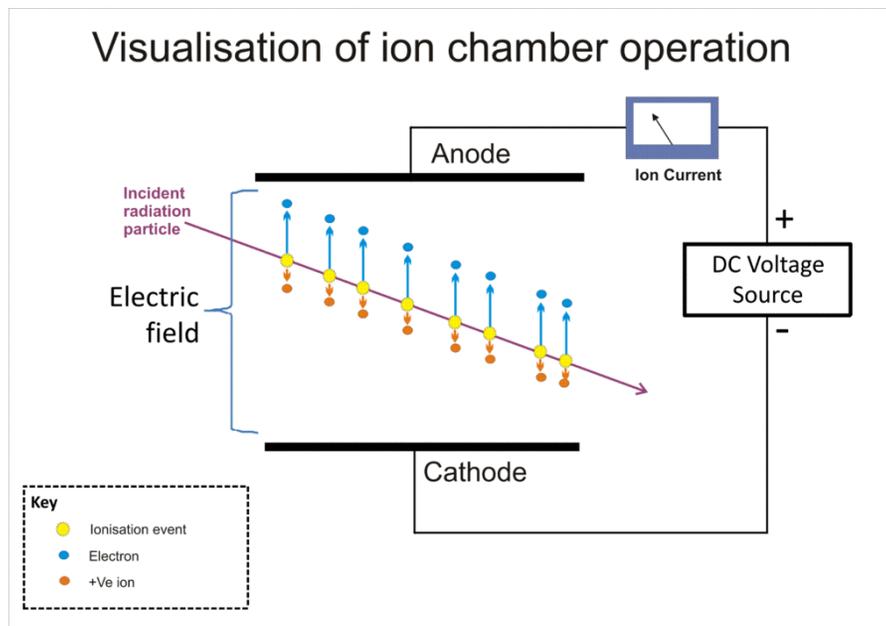
# Ionization

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



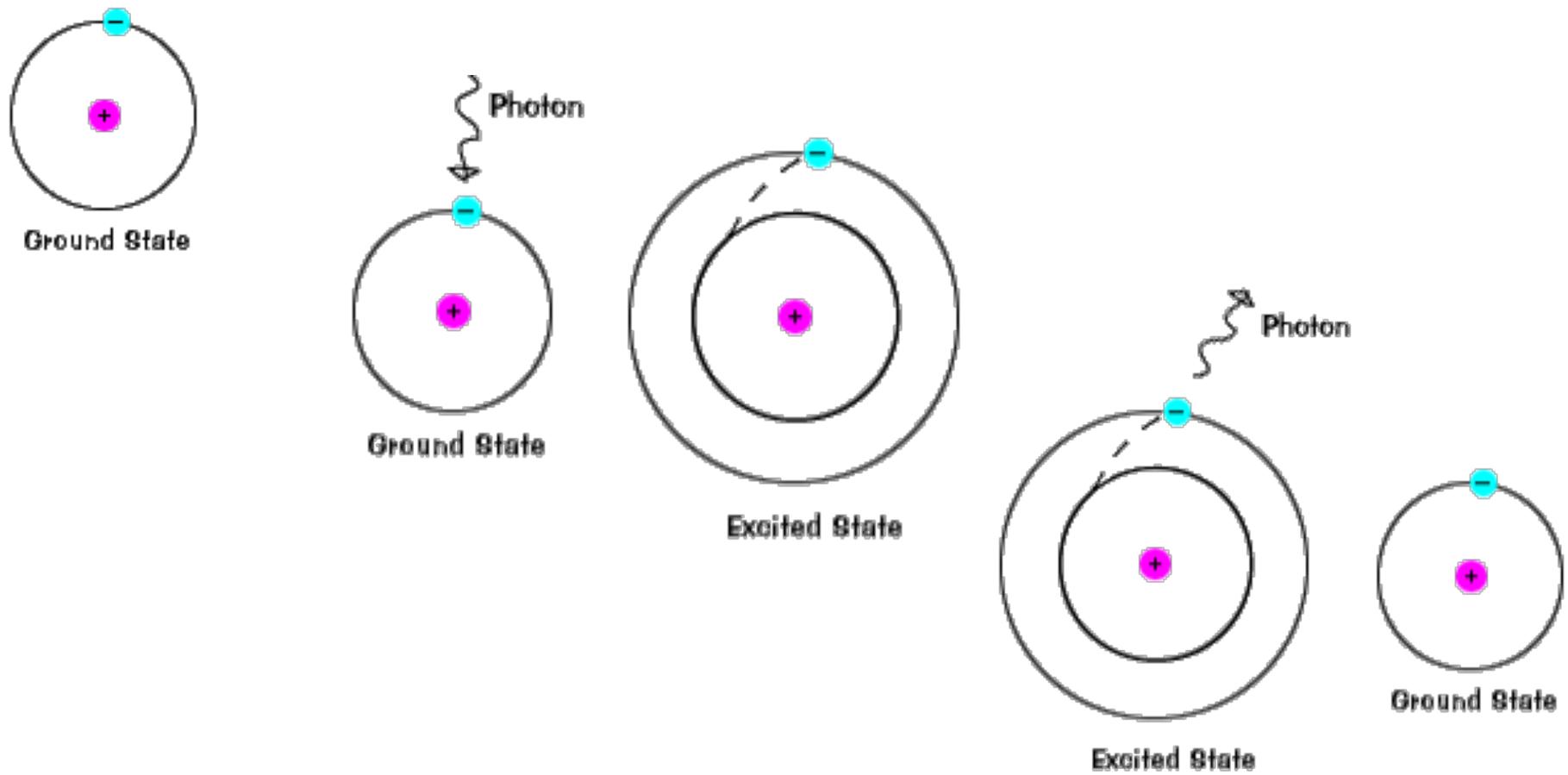
# How does this help us?

- 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.



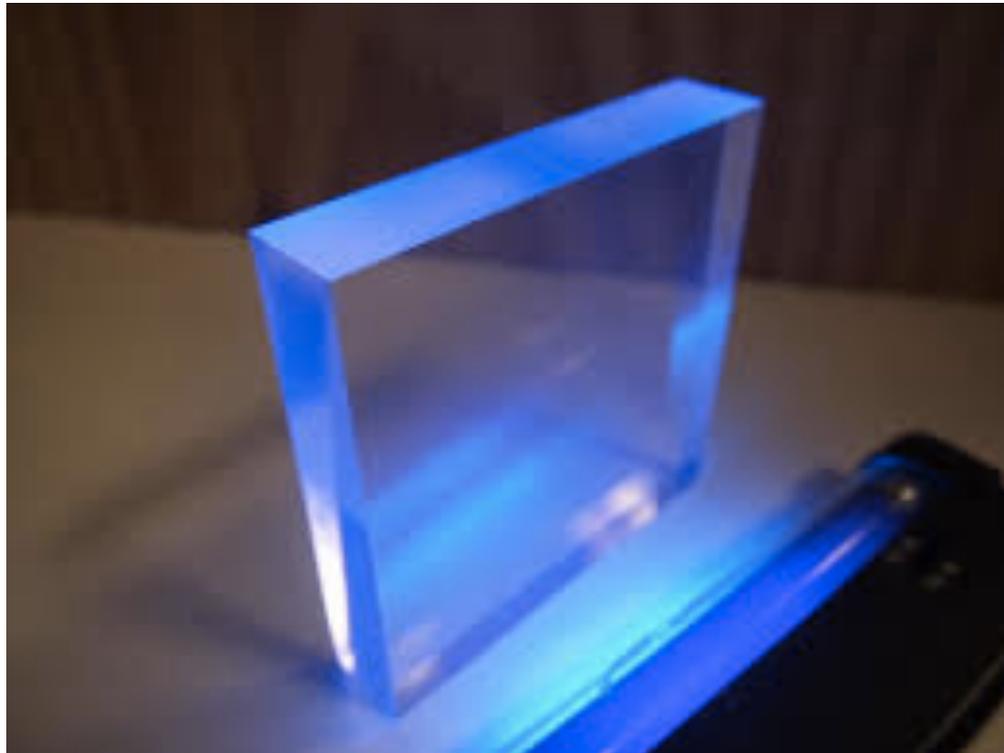
# Scintillation Light

- 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



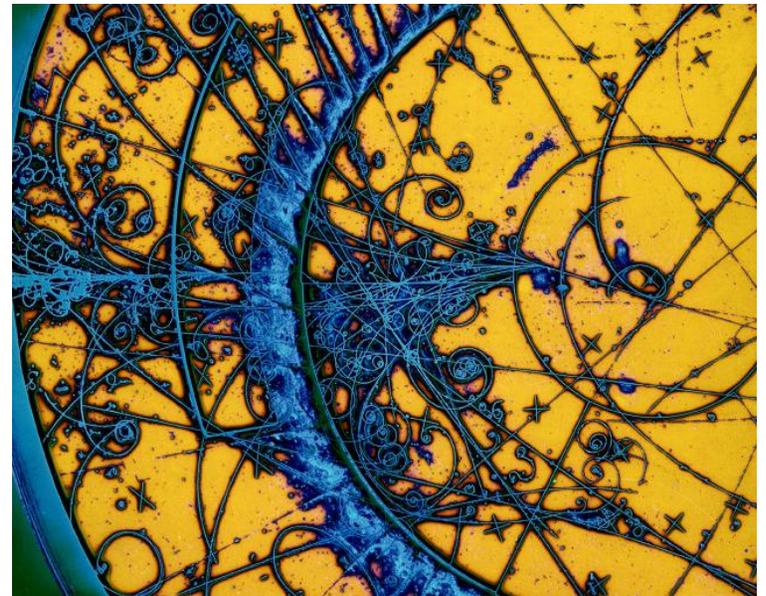
# Particle Detectors

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



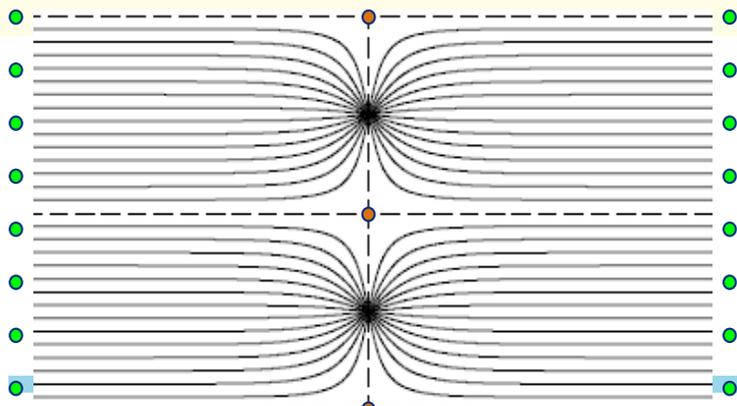
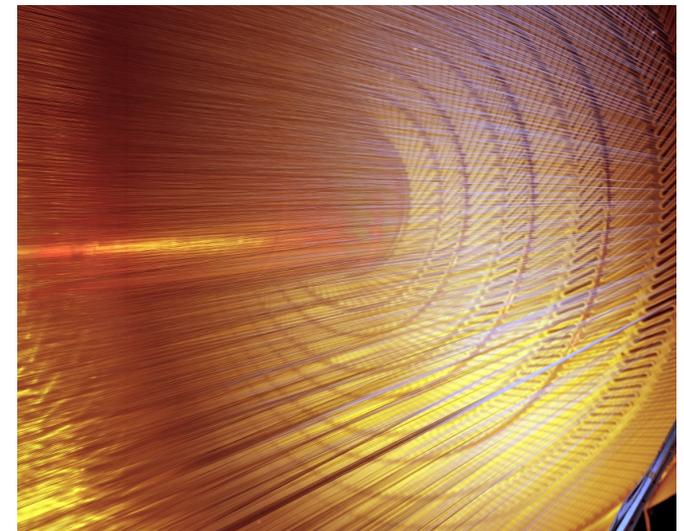
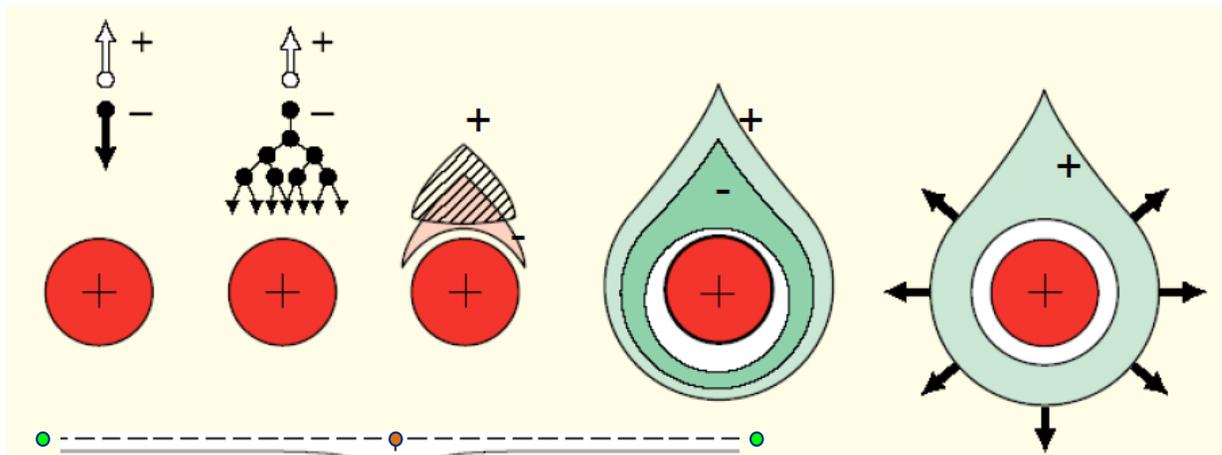
# Tracking Detectors

- **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 out of?**
  - Gaseous detectors
  - Silicon detectors
  - Scintillating fiber trackers



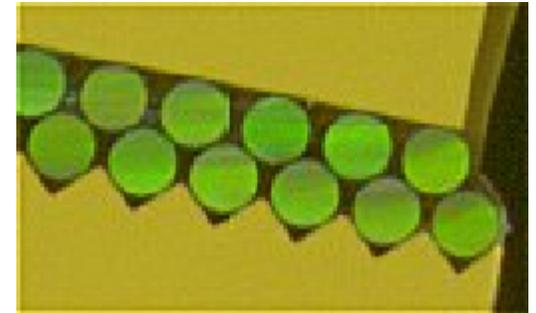
# Gaseous Trackers

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

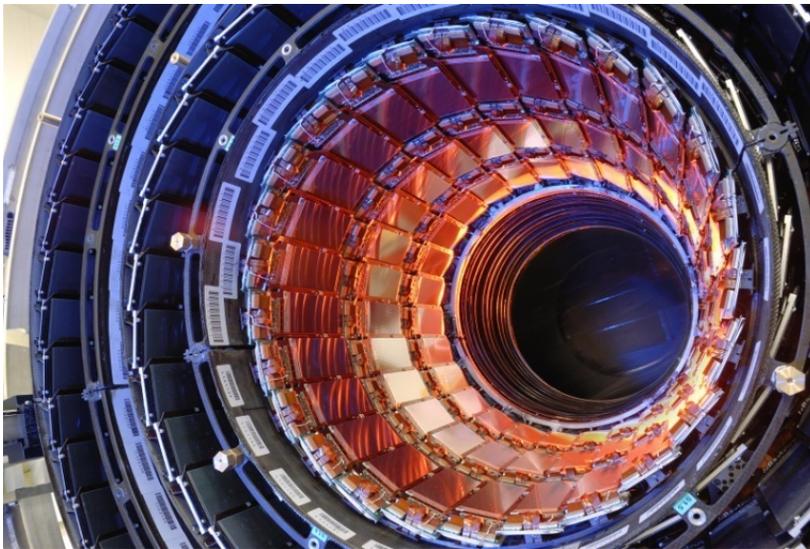


# Solid State Detectors and Fibers

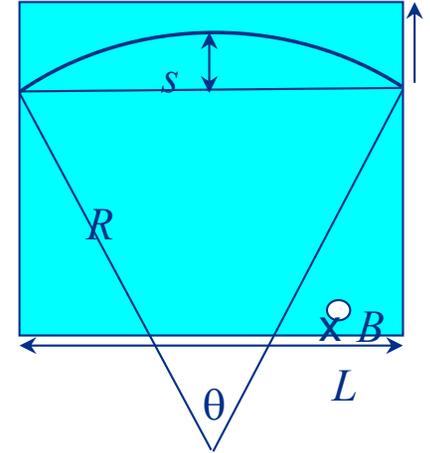
- Vertex detectors, microstrips, pixel detectors, fibers
  - Radiation hard (very important!)
- Silicon detectors have many nice features
  - Commercially produced
  - Can make fine granularity



CMS  
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# Resolution – How good is your tracker?



- Note that most trackers are in a magnetic field

- $p_T \text{ (Gev/c)} = 0.3 B R$

- How well can we measure R?

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

- Depends on a variety of things, including the magnetic field

- For three hits in a tracker:

$$\left. \frac{\sigma(p_T)}{p_T} \right|^{meas.} = \frac{\sigma_s}{s} = \frac{\sigma_x}{s} \sqrt{3/2} = \frac{\sigma_x \cdot p_T}{0.3 \cdot B L^2} \sqrt{96}$$

- Note this equation improves with length squared and improves with magnetic field. It degrades with position resolution and the momentum

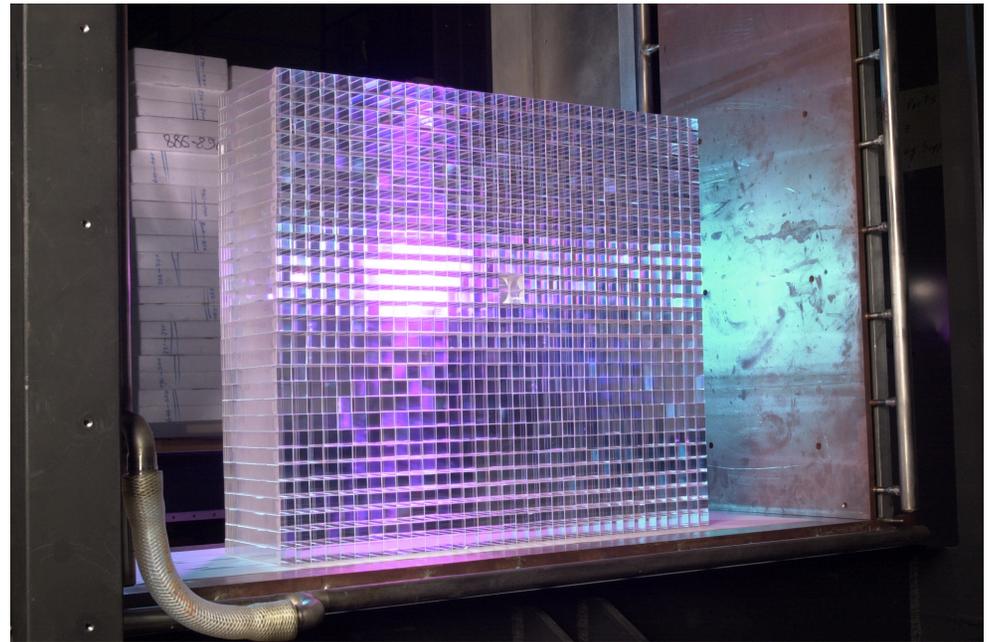
- A rough estimate of how well we can measure resolution:  $\frac{\sigma(p_T)}{p_T^2}$

# 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

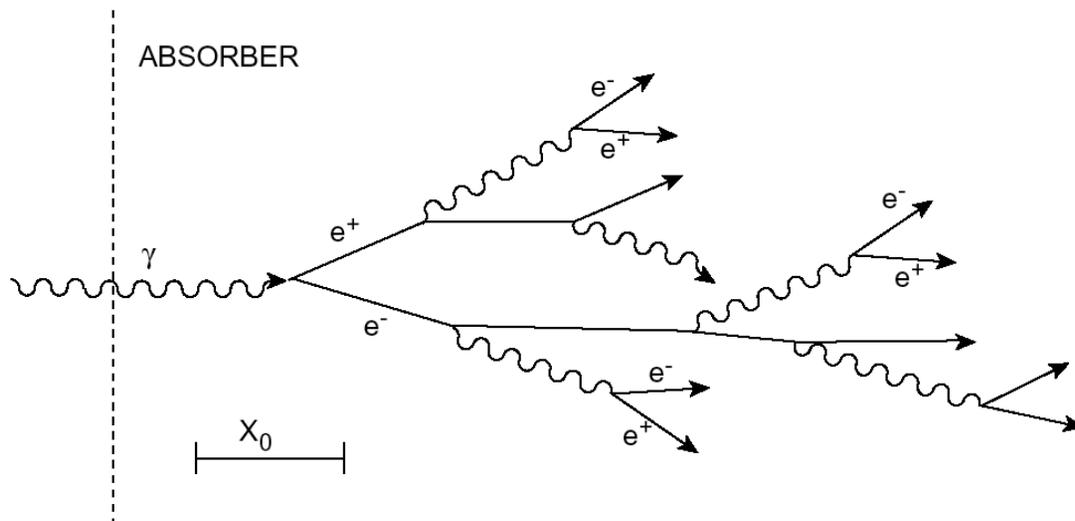
- **Used for:**
  - Energy measurements
  - Mass measurements
- **Main concepts**
  - Ionization
  - Nuclear interactions = “showering”
- **What type of calorimeters are there?**
  - Electromagnetic calorimeters
  - Hadronic calorimeters
  - Sampling vs homogeneous



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



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Figure 5: Schematic development of an electromagnetic shower.

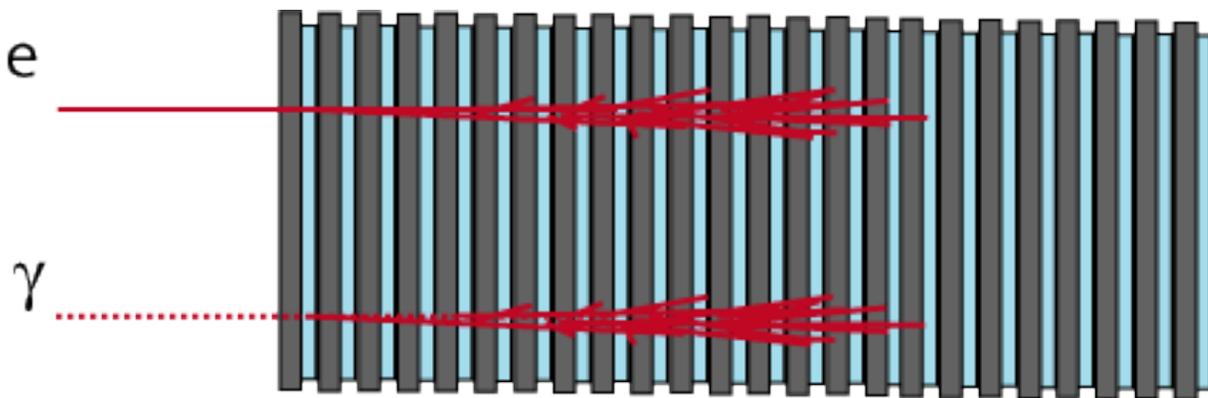
# How does a calorimeter work?

- 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:
  - $X_0 = 180 (A/Z^2) \text{ (g/cm}^2\text{)}$
- Critical energy: When the loss of energy from Bremsstrahlung equals the ionization loss of Energy:  $E_c = 800/(Z + 1.2) \text{ (MeV)}$
- Moliere radius: Contains 90% of the shower and characterizes the width of the shower
  - $r = 21.2 \text{ (MeV)} X_0/E_c$
- Max shower:  $S_{\max} = \ln(E_{\text{incoming}}/E_c)$



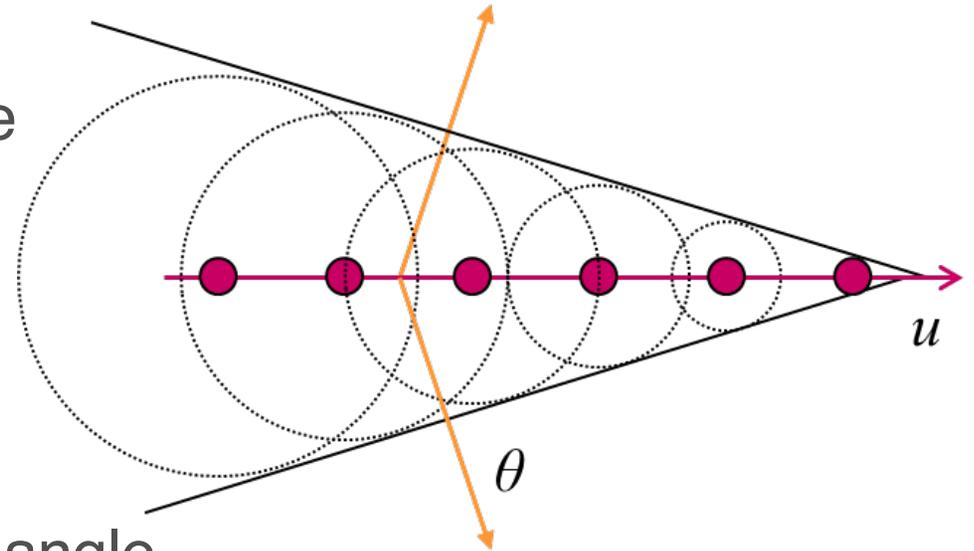


# HCal: Definitions of Parameters

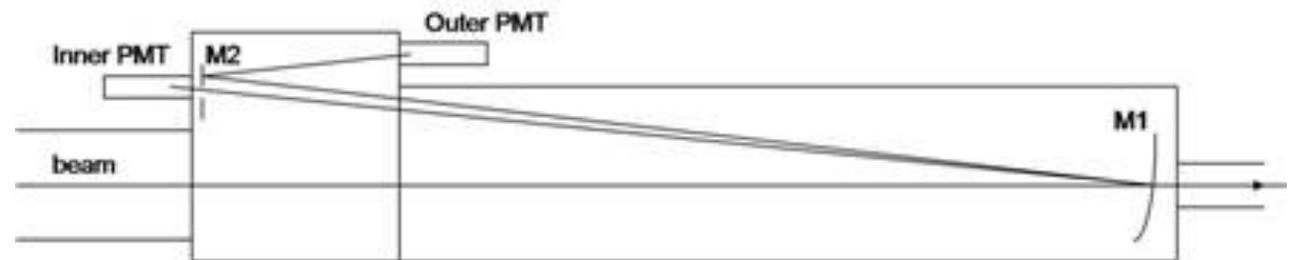
- Defined by nuclear interaction lengths instead of radiation lengths
  - $\Lambda = A / (\text{cross section}) * \text{Number of atoms}$
- Much more complicated, no easy formulas to use to define various concepts (shower max, etc)
- Several orders of magnitude bigger than EM interactions
  - Might need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

# Cherenkov Detectors

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

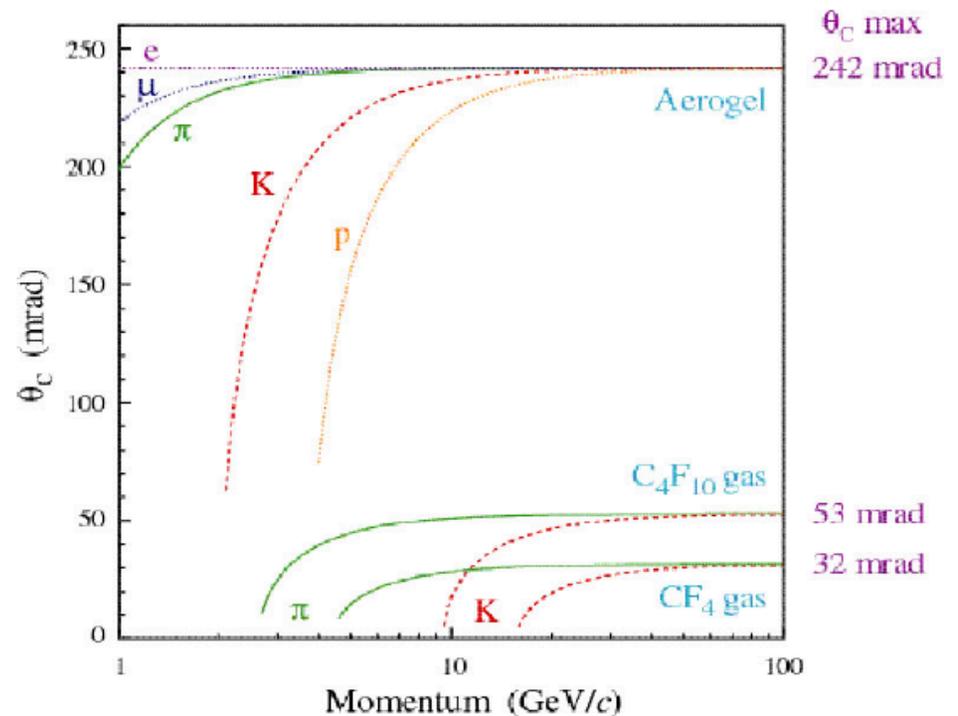


- Main parameter: Cherenkov angle
  - $\cos(\theta) = 1/(n \cdot \beta)$
  - Dependent of velocity of particle and the index of refraction for the material



# Cherenkov and Transition Radiation detectors

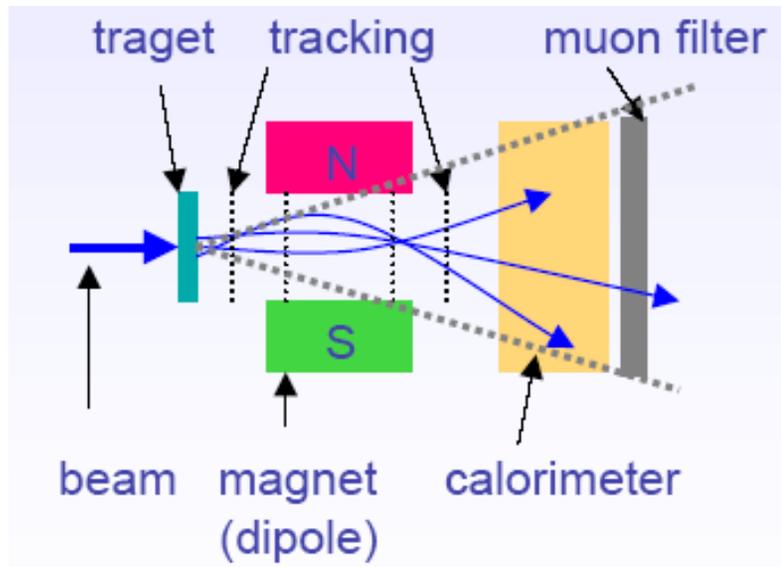
- Both used for Time of Flight and particle identification
  - Depending on mass and speed of particle, it will arrive in different places
- Important piece of the whole detector



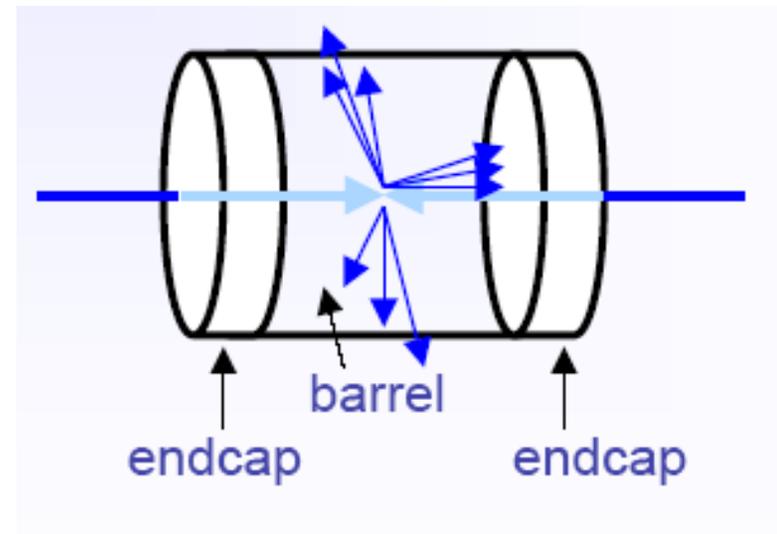
# Putting it all together

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

## Fixed Target Geometry

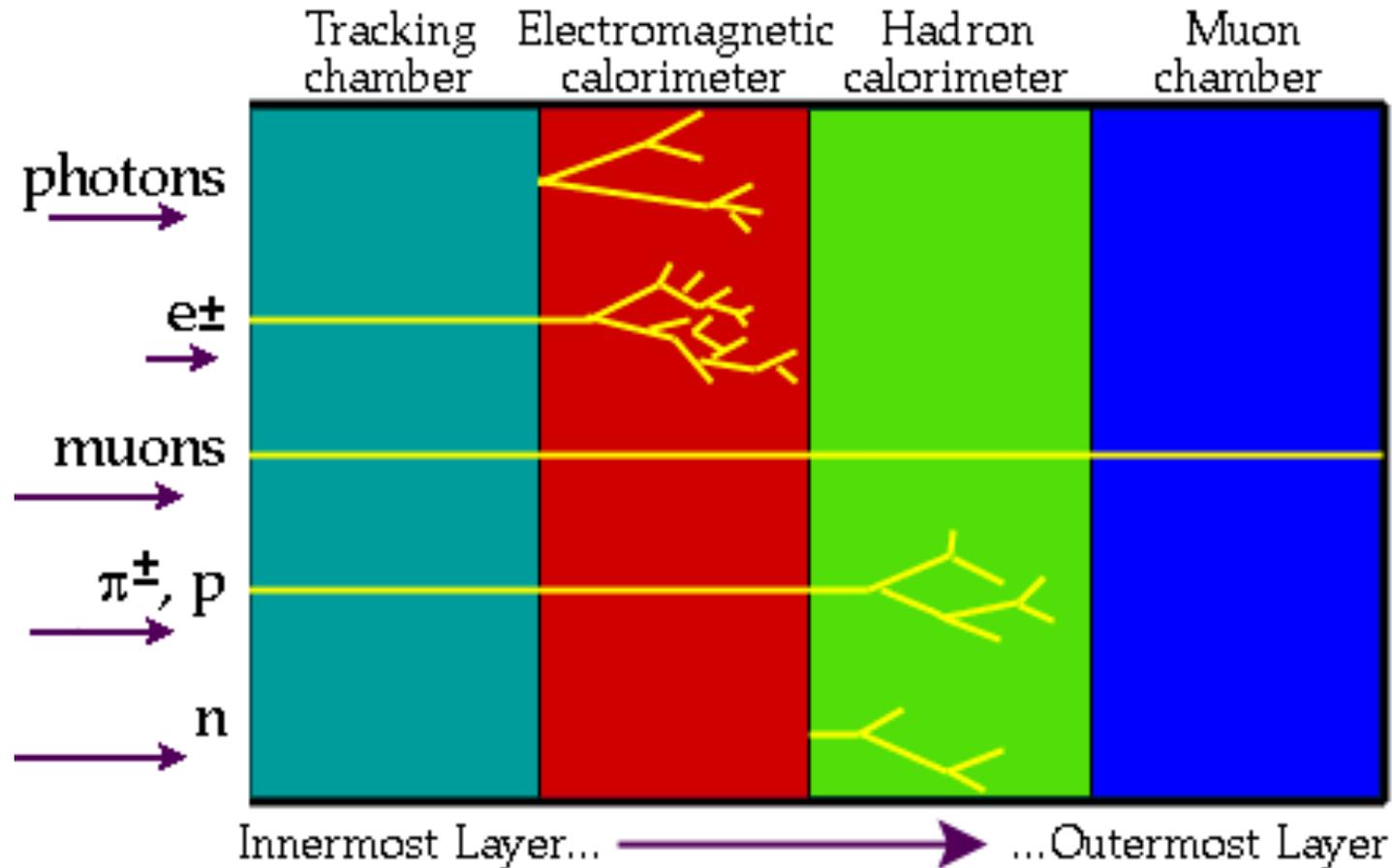


## Collider Geometry



# What do events look like?

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

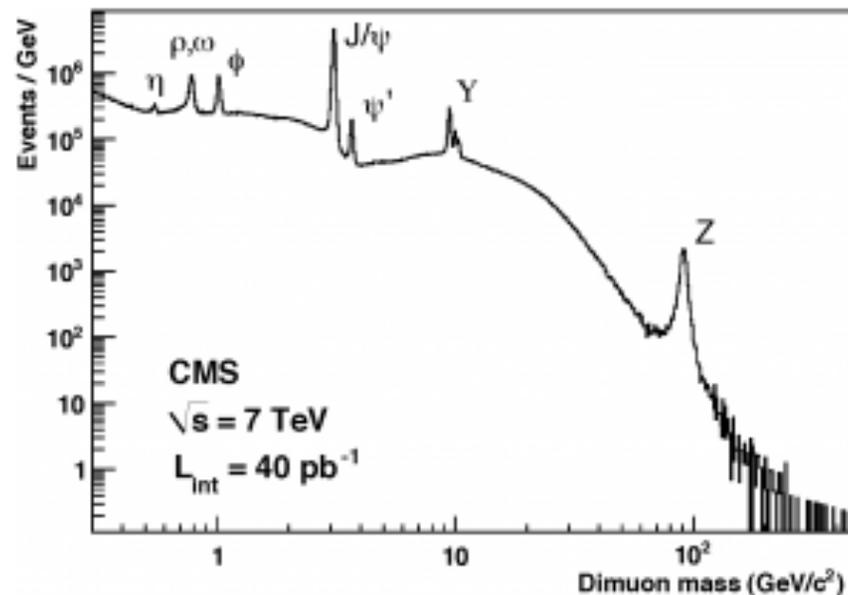


# More information on what they look like

Signature	Detector Type	Particle
Jet of hadrons	Calorimeter	$u, c, t \rightarrow Wb,$ $d, s, b, g$
'Missing' energy	Calorimeter	$\nu_e, \nu_\mu, \nu_\tau$
Electromagnetic shower, $X_0$	EM Calorimeter	$e, \gamma, W \rightarrow e\nu$
Purely ionization interactions, $dE/dx$	Muon Absorber	$\mu, \tau \rightarrow \mu\nu\nu$
Decays, $c\tau \geq 100\mu\text{m}$	Si tracking	$c, b, \tau$

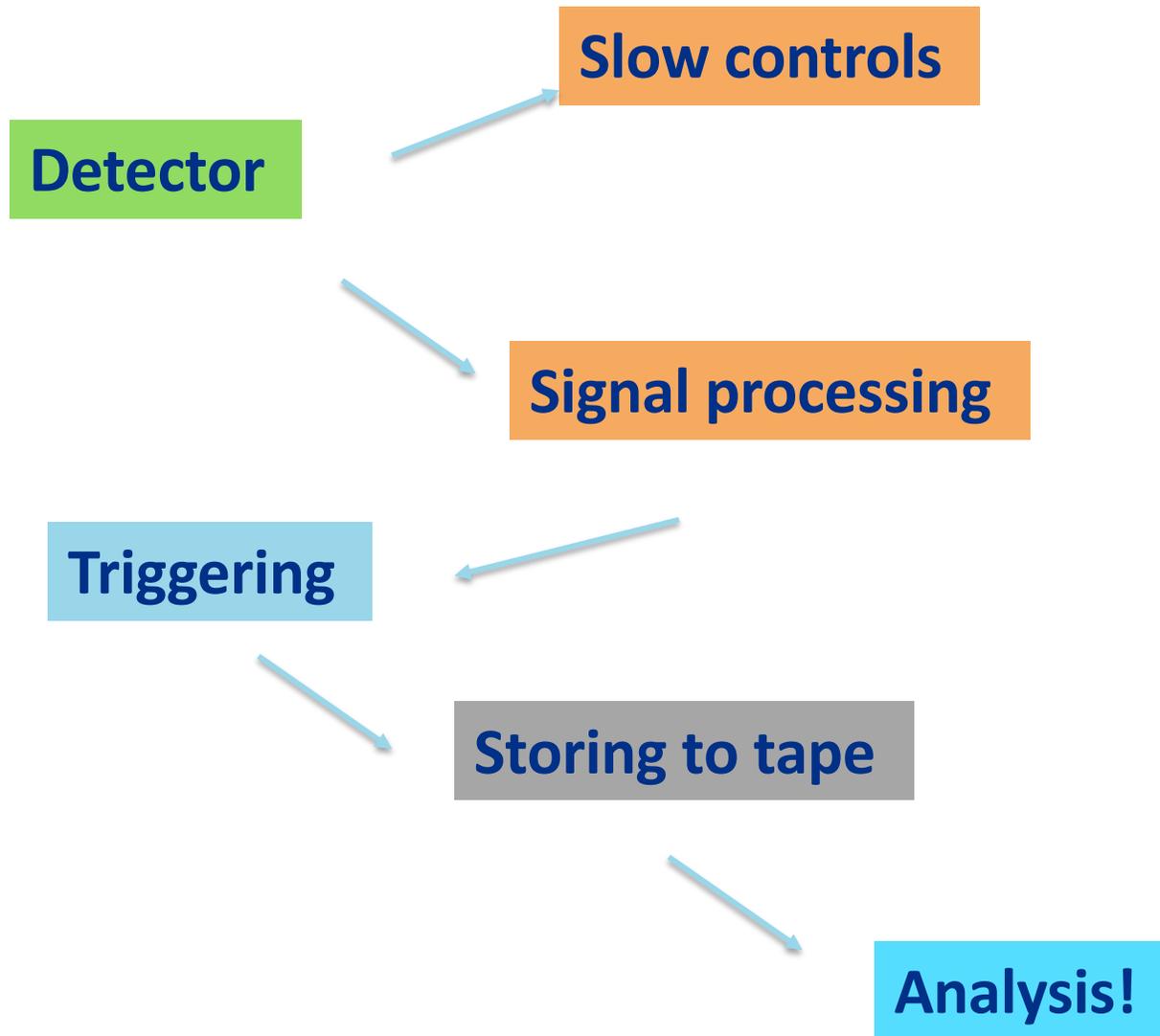
# DAQ and electronics

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



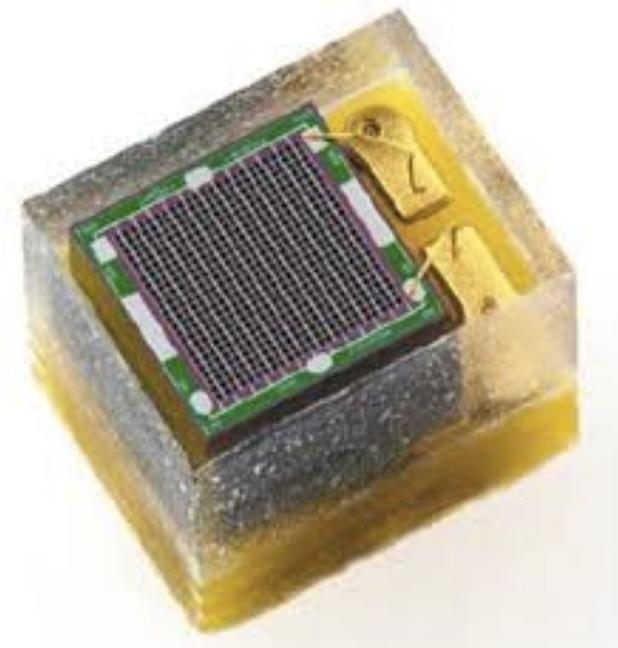
- How do we get from trackers and calorimeters to this?

# Data Acquisition Process

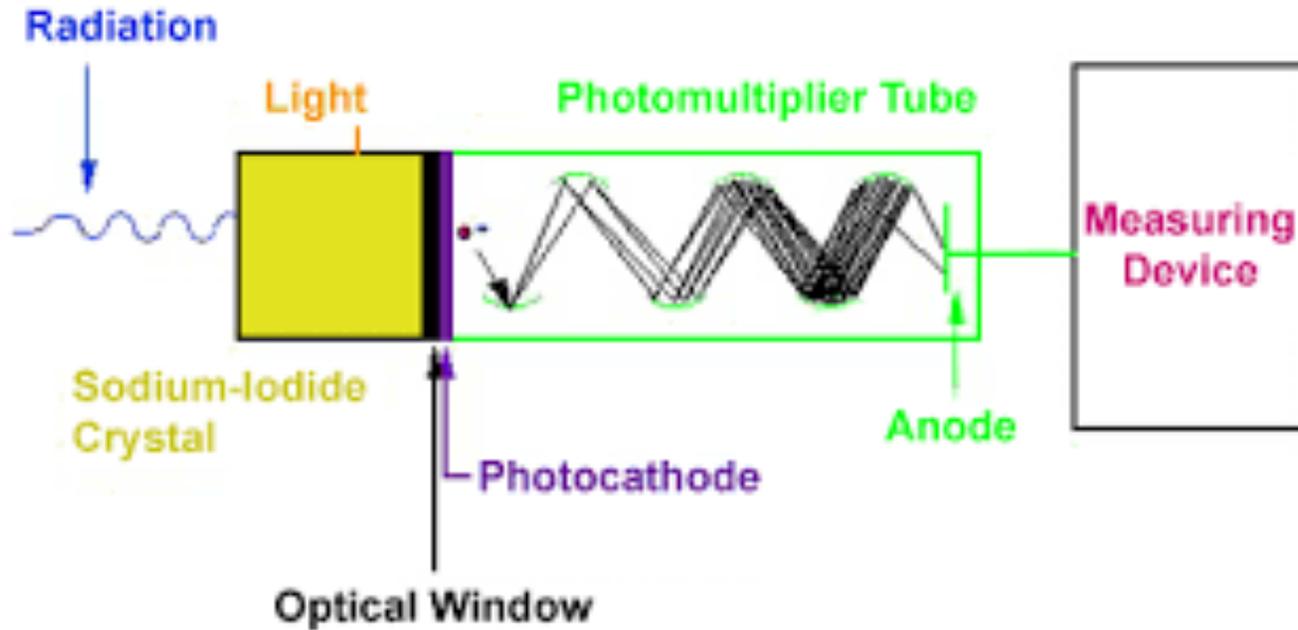


# Detector signals

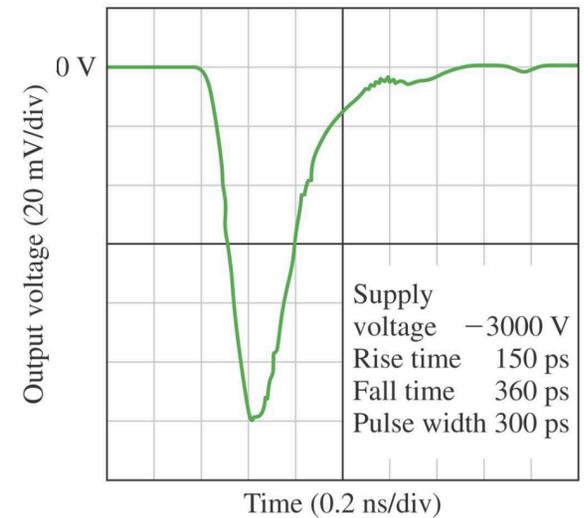
- Trackers, calorimeters, TPCs all have “eyes”
  - Photomultiplier tubes
  - Silicon Photomultiplier tubes
  - Sense wires that collect charge



# Example – Photomultiplier Tube

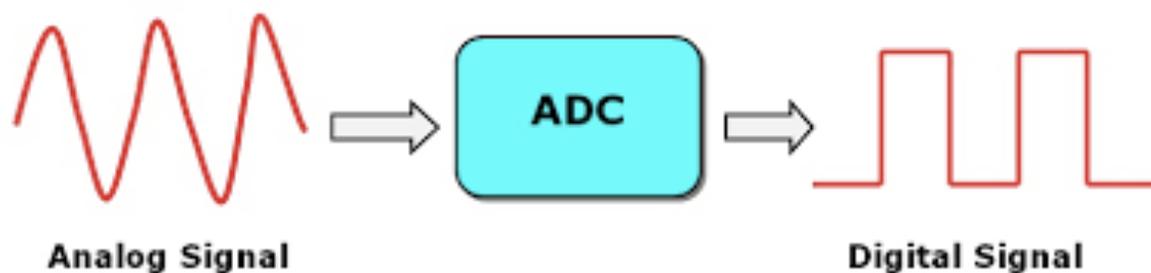


The output signal from a single photon



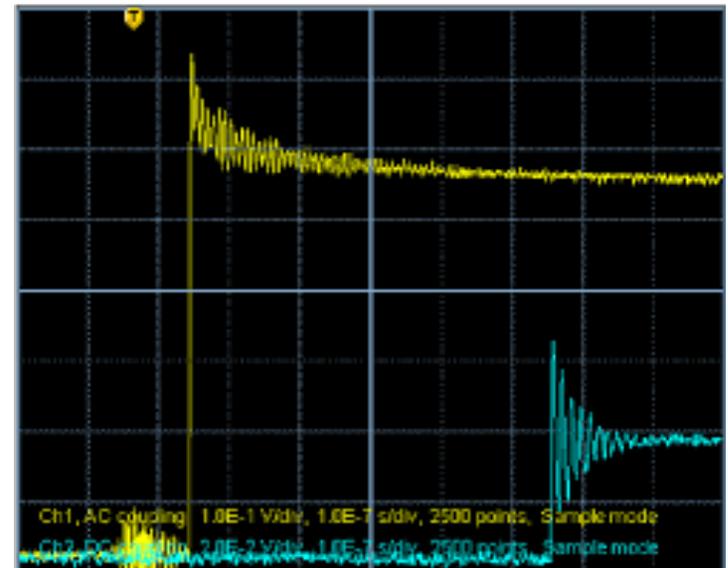
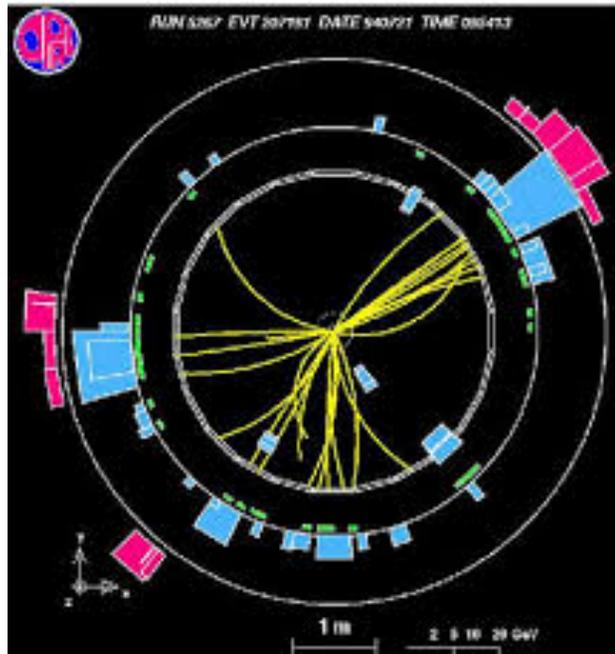
# Signal processing

- 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

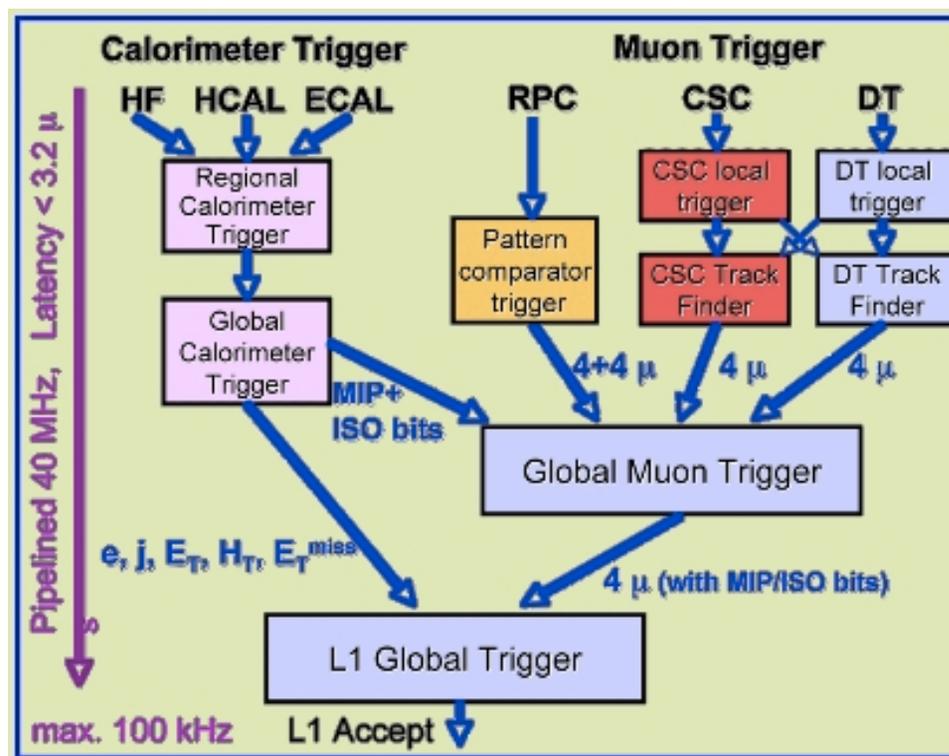
- We've turned those particle interactions into electronic signals



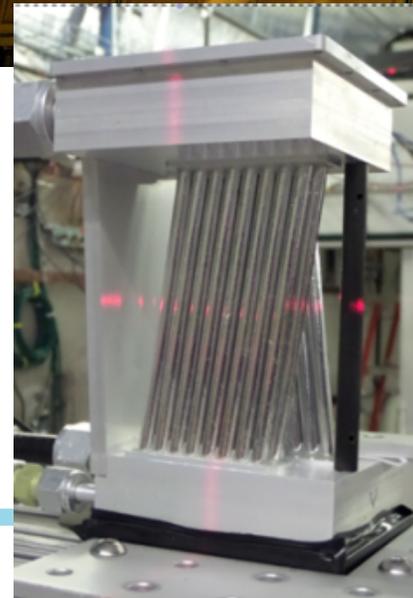
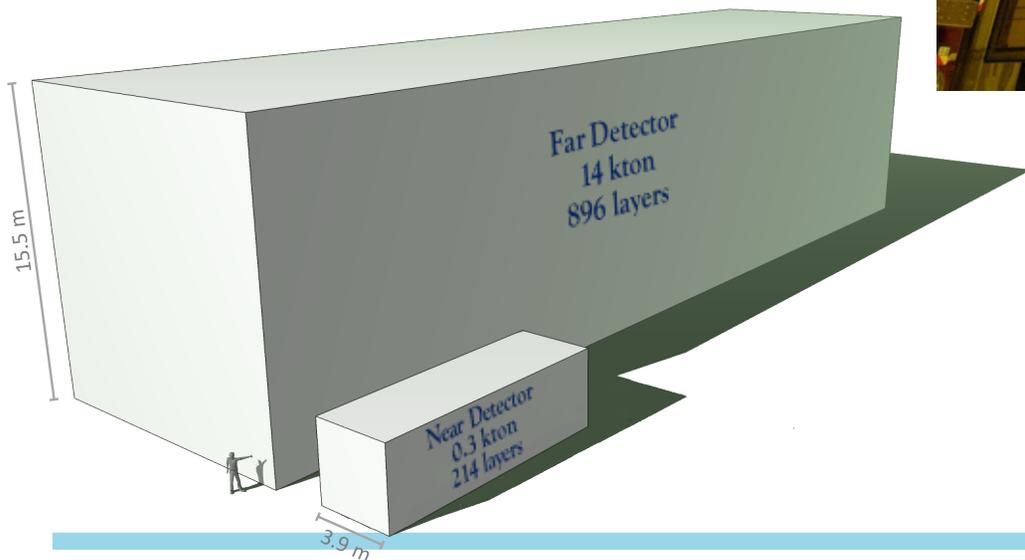
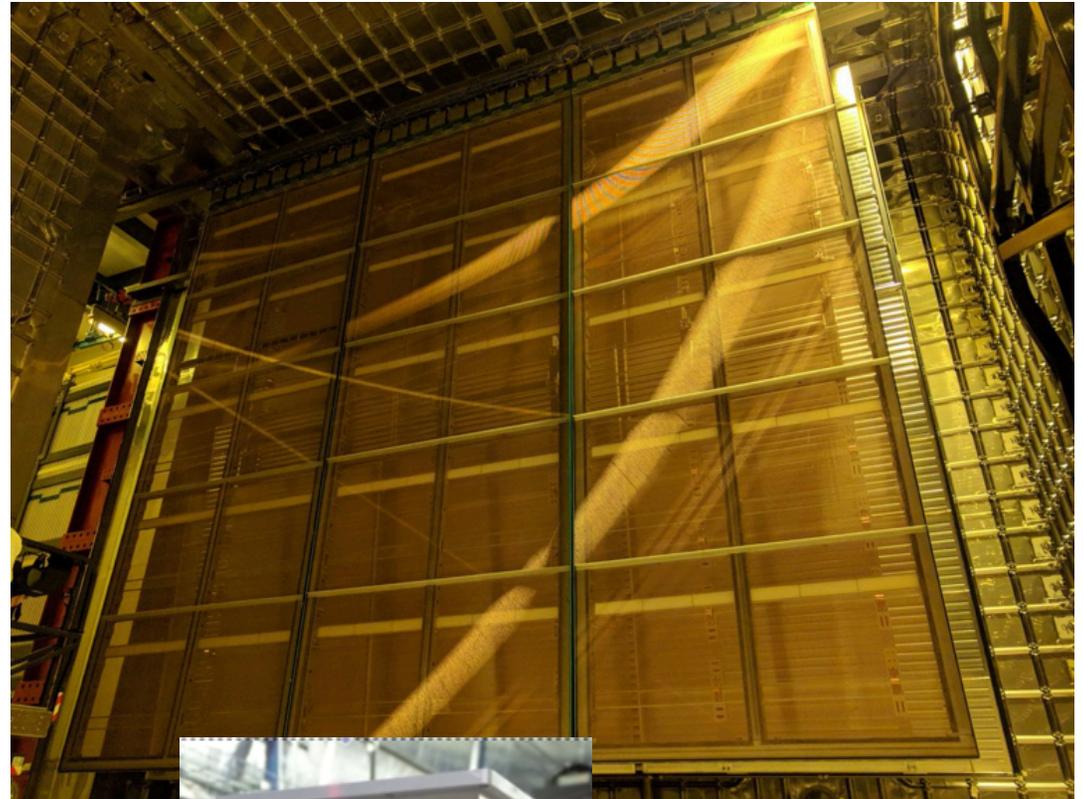
# Trigger systems

- 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

# References

- Interesting Lecture notes:
  - [physics.ucdavis.edu/Classes/Physics252b/Lectures/252b\\_lecture3.ppt](http://physics.ucdavis.edu/Classes/Physics252b/Lectures/252b_lecture3.ppt)
  - [http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/Lectures\\_SS2012.htm](http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/Lectures_SS2012.htm)
  - [https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma\\_InteractionsWithMatter\\_1.pdf](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>