Lecture 3: Particle Interactions with Matter (Part II) & Particle ID

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Detectors and Particle Interactions

- Understanding the LHC detectors (and their differences) requires a basic understanding of the interaction of high energy particles and matter
- Also required for understanding how experimentalists identify particles and make physics measurements/discoveries
- Particles can interact with:
  - atoms/molecules
  - atomic electrons
  - nucleus
- Results in many effects:
  - Ionization (inelastic)
  - Elastic scattering (Coulomb)
  - Energy loss (Bremsstrahlung)
  - Pair-creation
  - etc.

Important to understand interactions of:
- Charged Particles
  - Light: Electrons
  - Heavy: All Others (π, μ, K, etc.)
- Neutral Particles
  - Photons
  - Neutrons

Lot's of sources. Main one used here is the PDG: pdg.lbl.gov

Radiation Length

- The radiation length (X_0) is th characteristic length that describes the energy decay of a beam of electrons:

$$X_0 = \frac{716.4 \text{ g cm}^{-2} \, A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Distance over which the electron energy is reduced by a factor of 1/e due to radiation losses only
- Radiation loss is approx. independent of material when thickness expressed in terms of X_0
- Higher Z materials have shorter radiation length
  - want high-Z material for an EM calorimeter
  - want as little material as possible in front of calorimeter
- Example:
  lead: ρ = 11.4 g/cm^3 so X_0 = 5.5 mm
- The energy loss by brem is:

$$\boxed{-\frac{dE}{dx} = \frac{E}{X_0}}$$

material	X_0 g/cm^2
H_2	63
Al	24
Fe	13.8
Pb	6.3

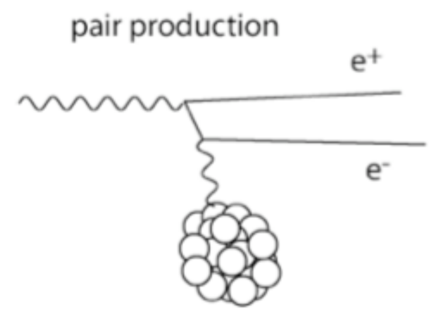
Energy Loss of Photons and EM Showers

- High-energy photons predominately lose energy in matter by e+e− pair production
- The mean free path for pair production by a high-energy photon

$$\lambda = \frac{9}{7} X_0$$

- **Note for electrons $\lambda = X_0$**

- But then we have high energy electrons…so the process repeats!
  - This is an electromagnetic shower!
  - An electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy



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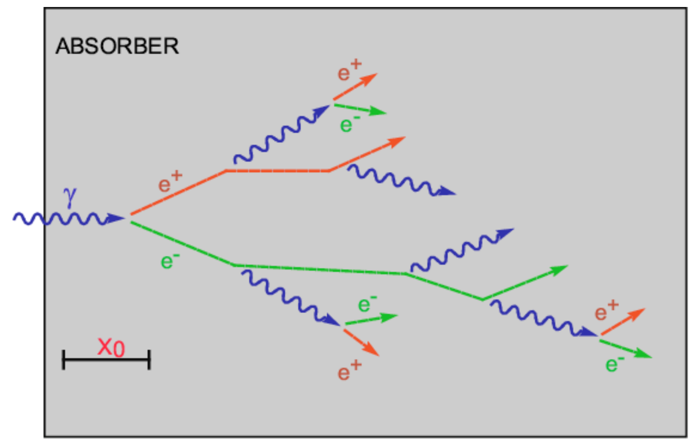


T. Dorigo

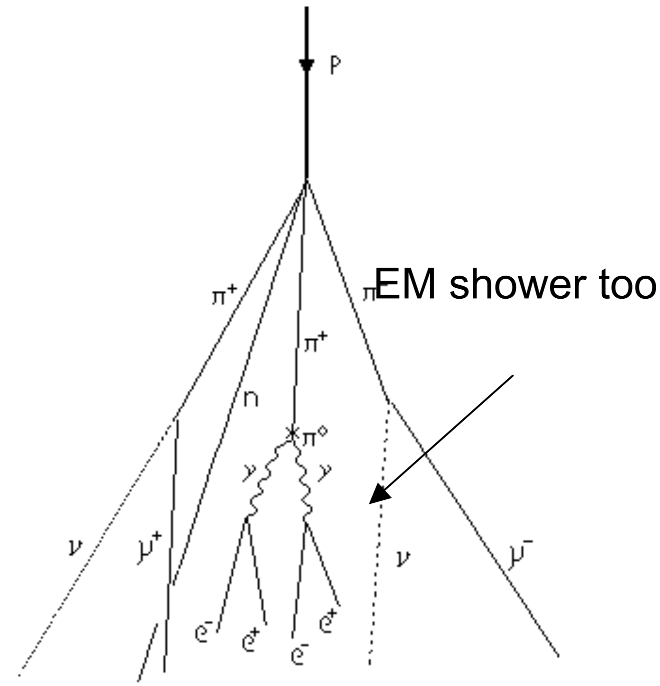
Hadronic Showers

- Interactions of heavy particles with nuclei can also produce hadronic showers
- Described by the **nuclear interaction length**

$$\lambda_n \approx 35\, g cm^{-2} A^{1/3}$$

- For heavy (high Z) materials we see that the nuclear interaction length is a lot longer than the electromagnetic one, $\lambda_n > X_0$
- So hadronic showers start later than electromagnetic showers and are more diffuse

- Example: lead ~ steel = 17 cm



material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

Pictures of EM and Had Showers!

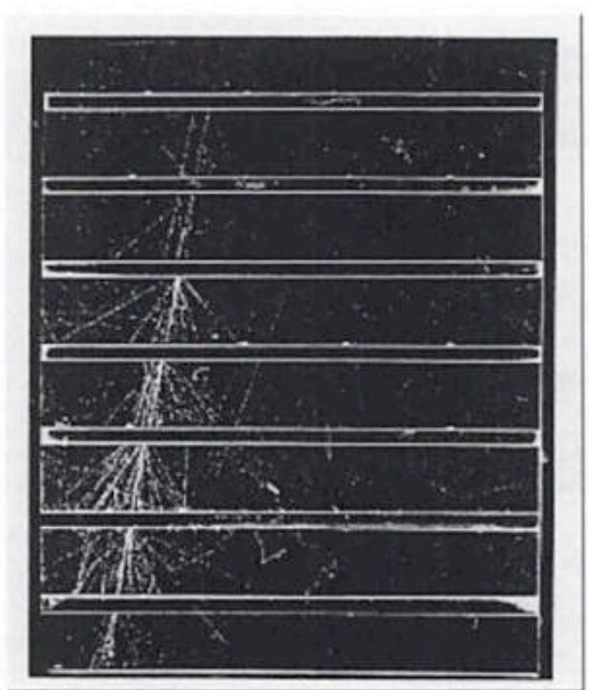


Figure 2.5 A photograph of the development of an electromagnetic shower in Pb plates. The number of particles in the shower builds up geometrically. After reaching a maximum, the shower then slowly dies off due to ionization loss ([2] – with permission).

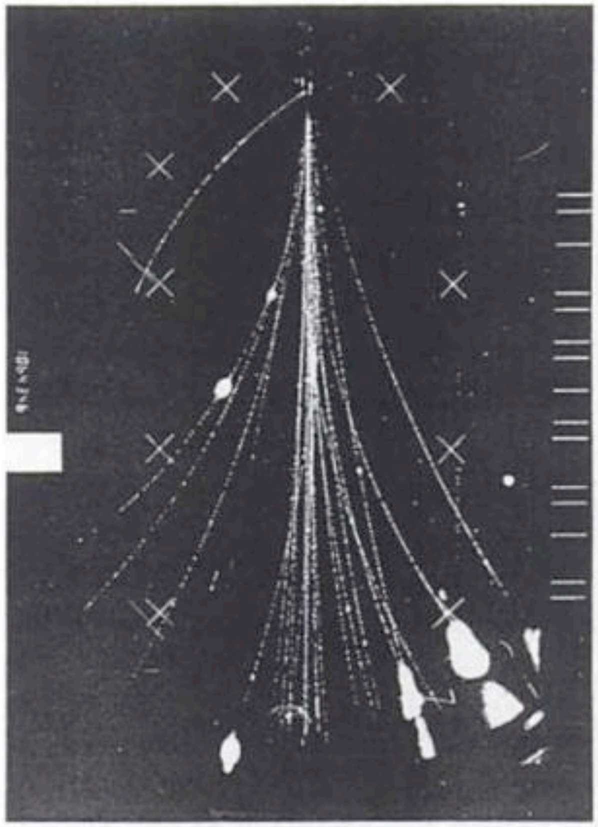
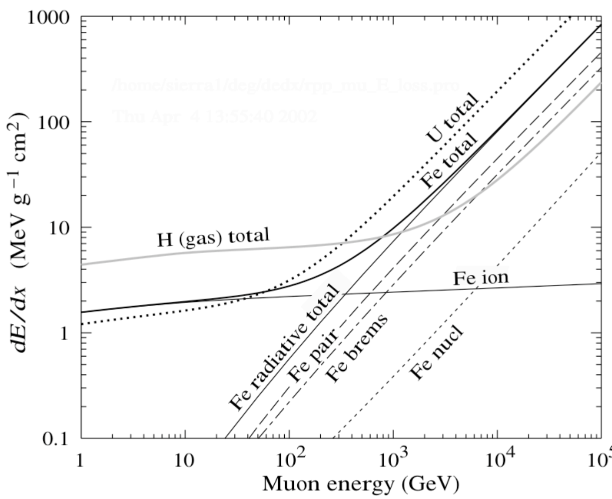


Figure 2.10 Photograph of a 200 GeV pion interaction ([5] – with permission).

From “High p_T physics at hadron colliders” By Dan Green

Muons

- Because of it's long lifetime, the muon for our purposes is like a stable particle
  (cτ ~ 700 m)
- As we saw it is a MIP
- Also, does not feel the strong interaction
  - No hadron shower, only MIP
- Therefore, they are very penetrating
- However, at high energies muons can sometimes behave more like electrons!
  - At high energies radiative losses begin to dominate and muons can brem
  - The effective radiation length decreases at high energy and so (late) EM showers can develop in the detector

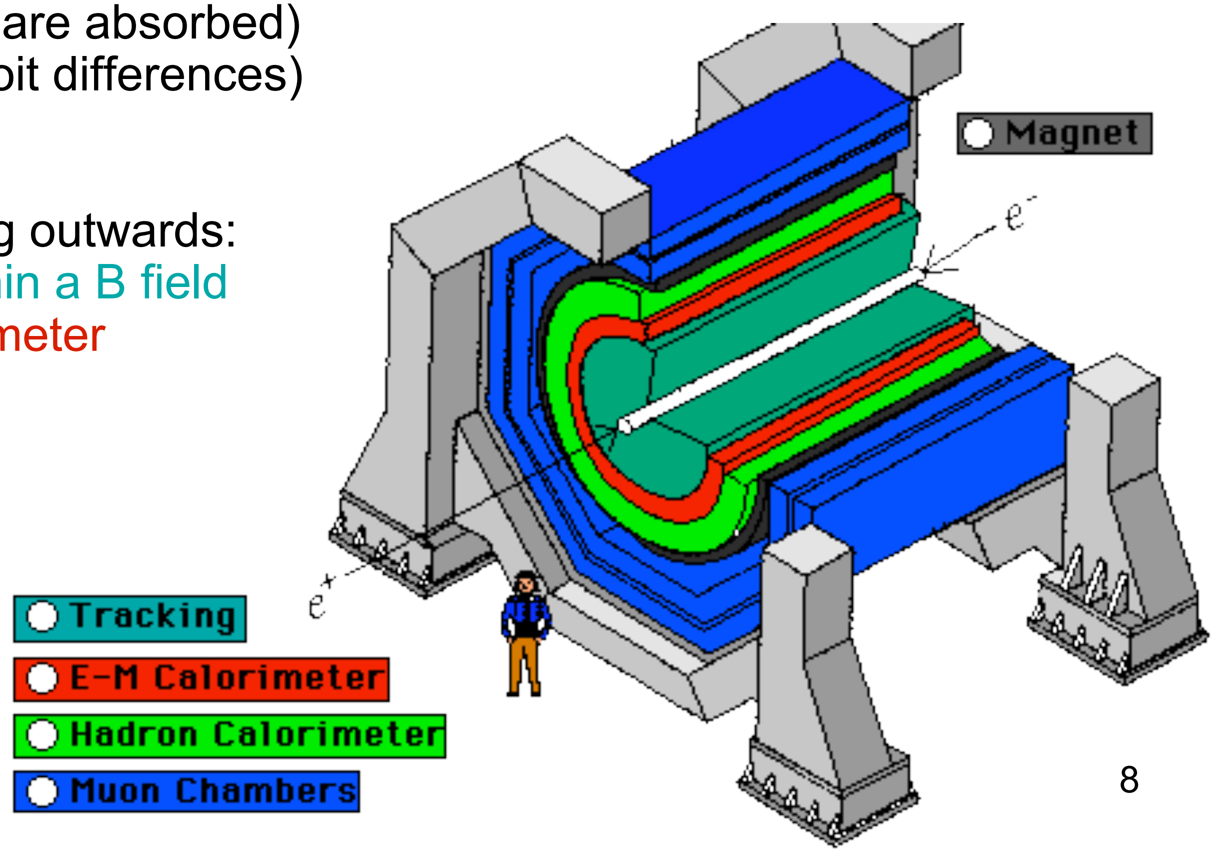


PDG

Particle Detectors

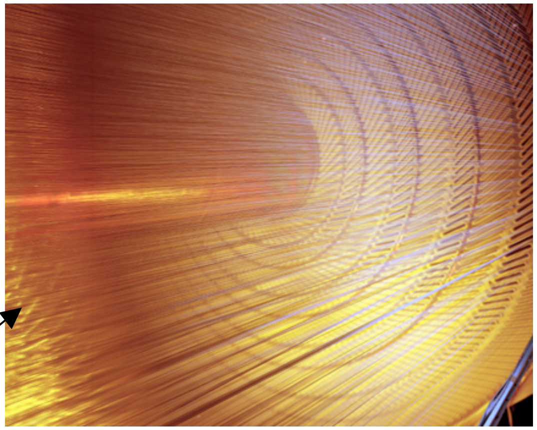
- Goal is to completely surround collision by arranging different types of detectors in layers.
- We know how particles interact with matter and we identify them (to the best of our ability!) by exploiting differences in showering, interaction with matter
- What do we want to know about the particles?
  - Their momentum and charge (magnetic field)
  - Their energy (particles are absorbed)
  - Their species (we exploit differences)

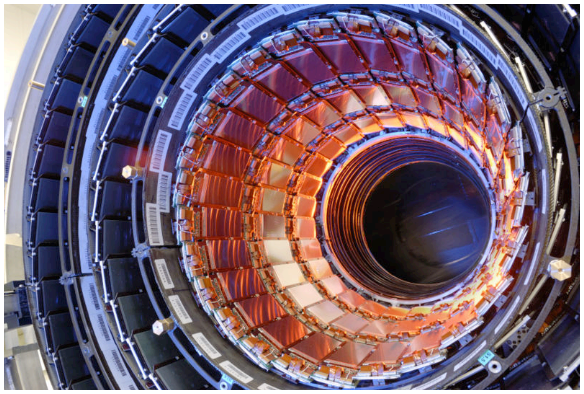
- Starting from center moving outwards:
  - Tracking detectors within a B field
  - Electromagnetic calorimeter
  - Hadronic calorimeter
  - Muon chambers



Tracking Detectors

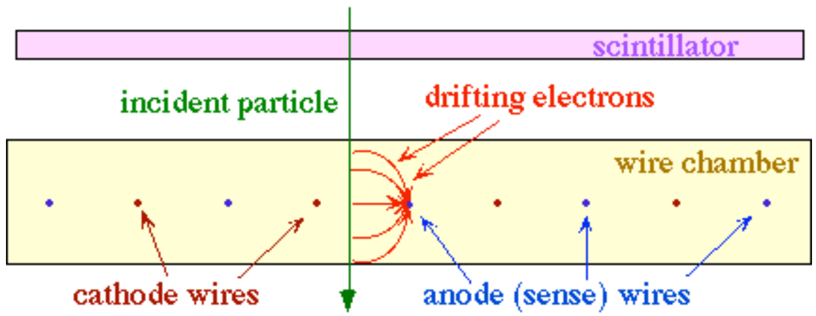
- Purpose: measure momentum and charge of charged particles
- To minimize multiple scattering, we want tracking detectors to contain as little material as possible
- Two main technologies:
  - gas/wire drift chambers (like CDF's COT)
  - solid-state detectors (silicon)
- Silicon is now the dominant sensor material in use for tracking detectors at the LHC (especially CMS)

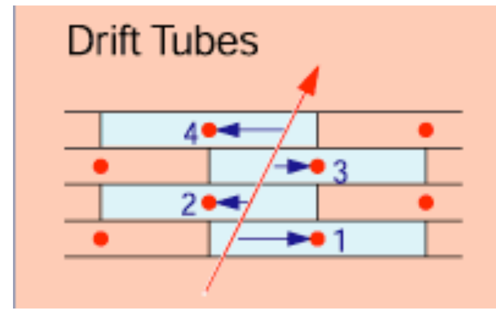




CMS

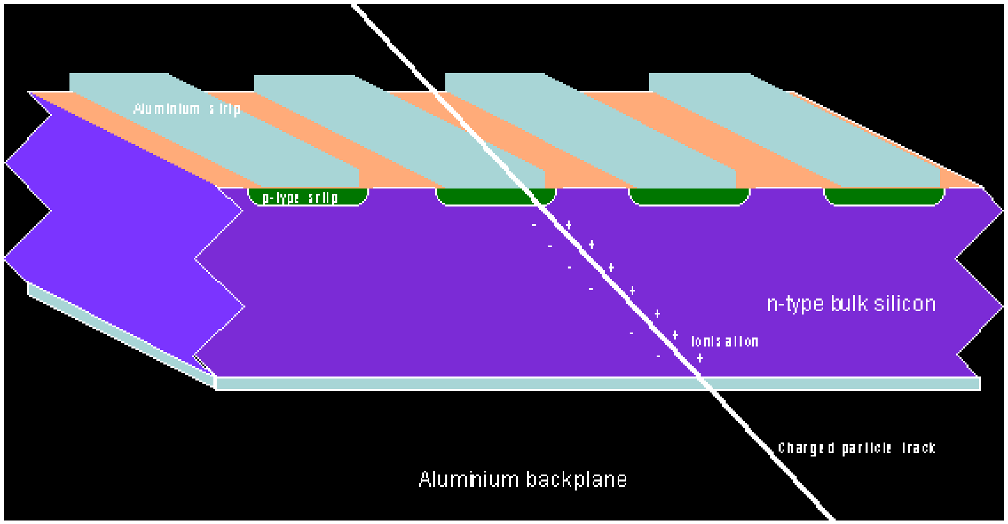
Gas/Wire Drift Chambers





- Wires in a volume filled with a gas (such as Argon/Ethan)
- Measure where a charged particle has crossed
  - charged particle ionizes the gas.
  - electrical potentials applied to the wires so electrons drift to the sense wire
  - electronics measures the charge of the signal and when it appears.
- To reconstruct the particles track several chamber planes are needed
- Example:
  - CDF COT: 30 k wires, 180 µm *hit* resolution
- Advantage:
  - low thickness (fraction of X_0)
  - traditionally preferred technology for large volume detectors

Silicon Detectors



~300μm

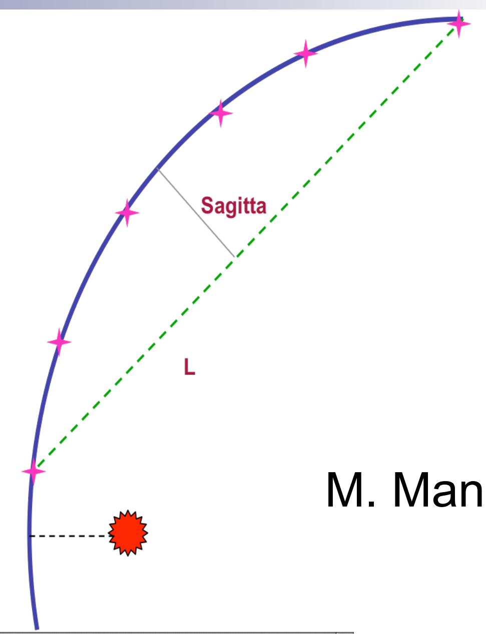
- Semi-conductor physics:
  - doped silicon: p-n junction
  - apply very large reverse-bias voltage to p-n junction
    - "fully depleted" the silicon, leaving E field
- Resolution 1-2% @ 100 GeV
- Important for detection secondary vertices
  - b-tagging (more on this later)

Momentum and Charge Measurement

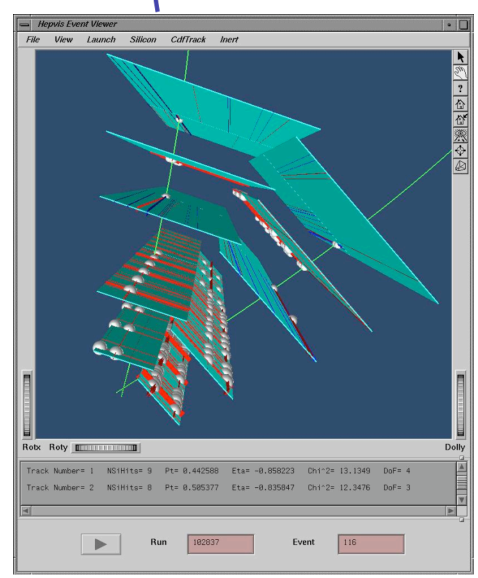
- Since a B field is applied, by measuring a few points of the particle's track we can reconstruct the curvature of the track
  - $p_T \propto$ radius of curvature
- sagitta depends on tracking length L, p_T, and B

$$s \approx \frac{BL^2}{13.3 p_T}$$

- Example:
  - If B = 4 T, L = 1 m, p_T = 100 GeV we get a sagitta = 3 mm
- Momentum resolution $\propto p_T^2$
  - It gets worse at high p_T!



M. Mannelli



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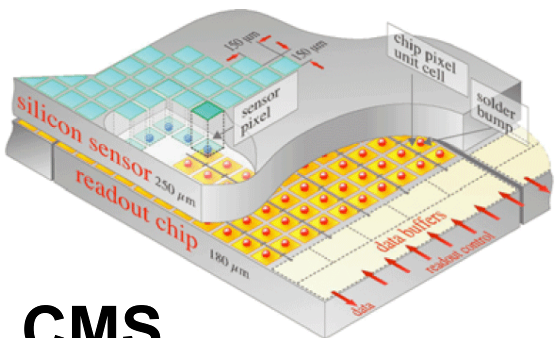
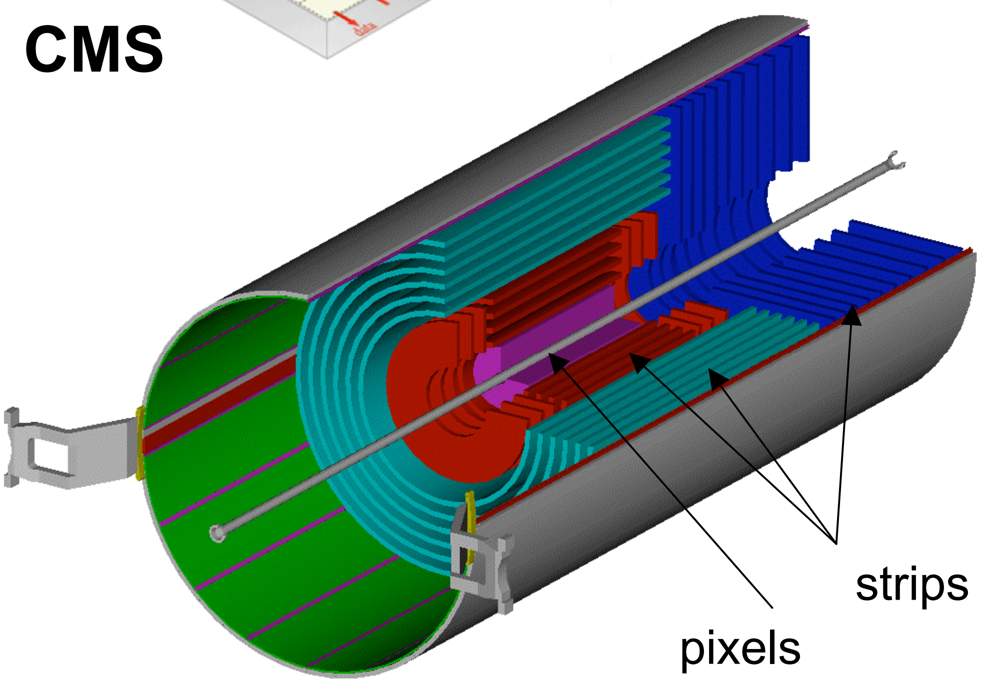
Silicon Pixel Detectors

- These detectors provide very high granularity, high precision set of measurements as close to the interaction point as possible.



	CMS	ATLAS
# Pixels	65 million	80 million

CMS



ATLAS

EM Calorimeters

- Purpose: measure energy of EM particles (charged or neutral)
- How?
  - Use heavy material to cause EM shower (brem/pair production)
  - Total absorption / stop particles
  - Important parameter is X_0 (usually 15-30 X_0 or a high Z material)
  - There is little material before the calorimeter (tracker)
- Two types of calorimeters:
  - Sampling
  - Homogeneous
- Relative energy uncertainty decreases with E !

CMS EM Cal (PbWO)

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Add terms in quadrature

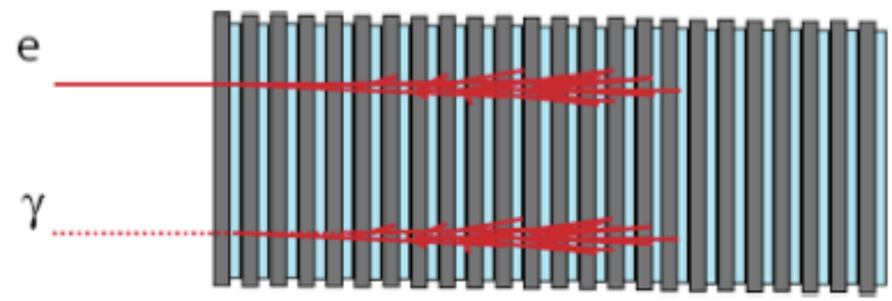
a: stochastic term (photon counting)

b: constant term

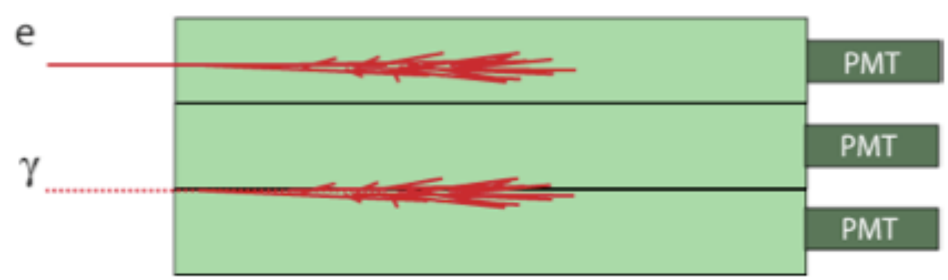
c: noise (electronics)

Sampling vs. Homogeneous Calorimeters

- Sampling calorimeter
  - active medium which generates signal
    - scintillator, an ionizing noble liquid, a Cherenkov radiator…
  - a passive medium which functions as an absorber
    - material of high density, such as lead, iron, copper, or depleted uranium.
    - σE/E ~ 10%

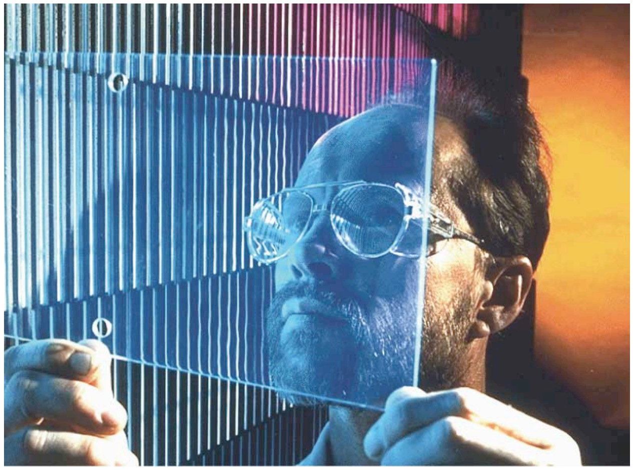


- Homogeneous calorimeter
  - the entire volume generates signal.
  - usually electromagnetic
  - inorganic heavy (high-Z) scintillating crystals
    - CsI, NaI, and PWO, ionizing noble liquids…
    - σE/E ~ 1%



Hadronic Calorimeters

- Purpose: measure energy of hadronic/heavy particles
- How?
  - Similar to EM calorimeters but important parameter is λ_n (usually 5-8 λ_n)
  - Typically sampling calorimeters
  - Larger and coarser in sampling depth
- Resolutions typically a lot worse than EM cal.
  - Stochastic term 30-50% and higher (~80% at CDF)

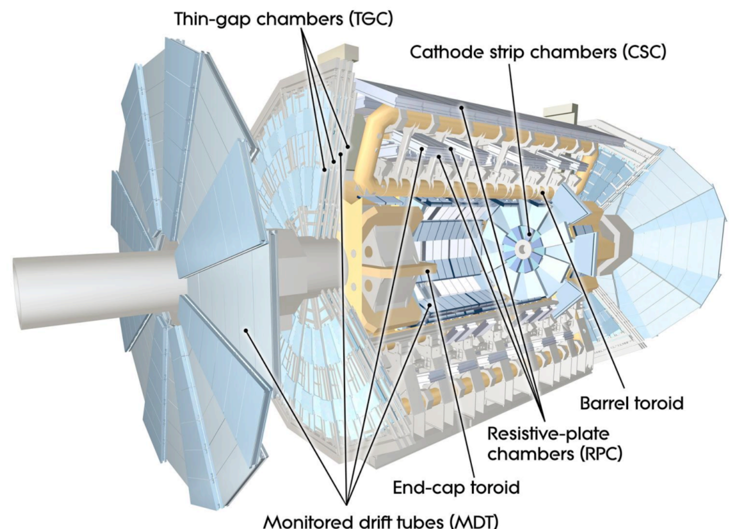


Atlas Tile Cal.

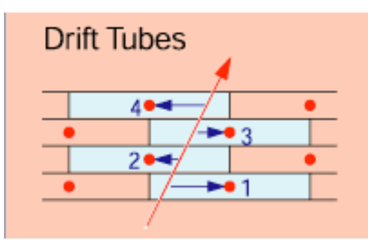
Muon Chambers

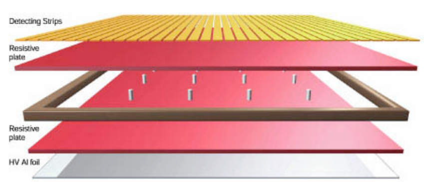
- Purpose: measure momentum / charge of muons
- Recall that the muon signature is extraordinarily penetrating
- Muon chambers are the outermost layer
- Measurements are made combined with inner tracker

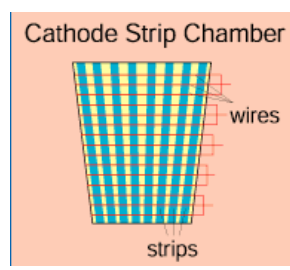
- Muon chambers in LHC experiments:
  - Series of tracking chambers for precise measurements
    - RPC's: Resistive Plate Chambers
    - DT's: Drift Tubes
    - CSC's: Cathode Strip Chambers
    - TGC's: Thin Gap Chambers



ATLAS Muon system



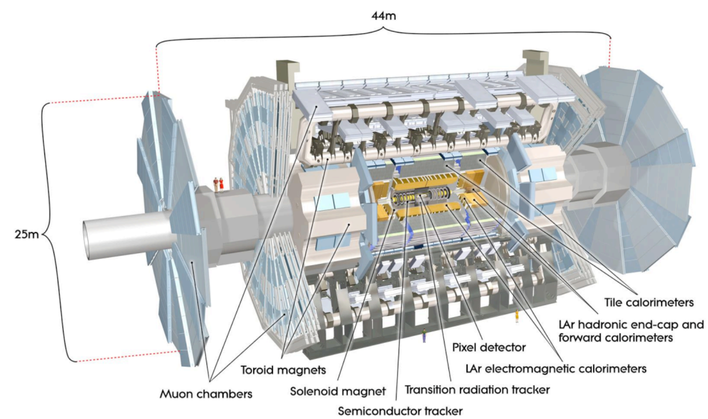




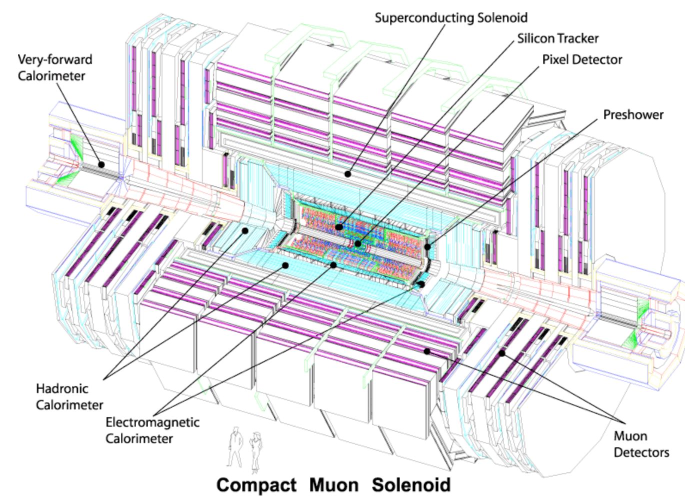

CMS Muon chambers

ATLAS and CMS Detectors Revisited

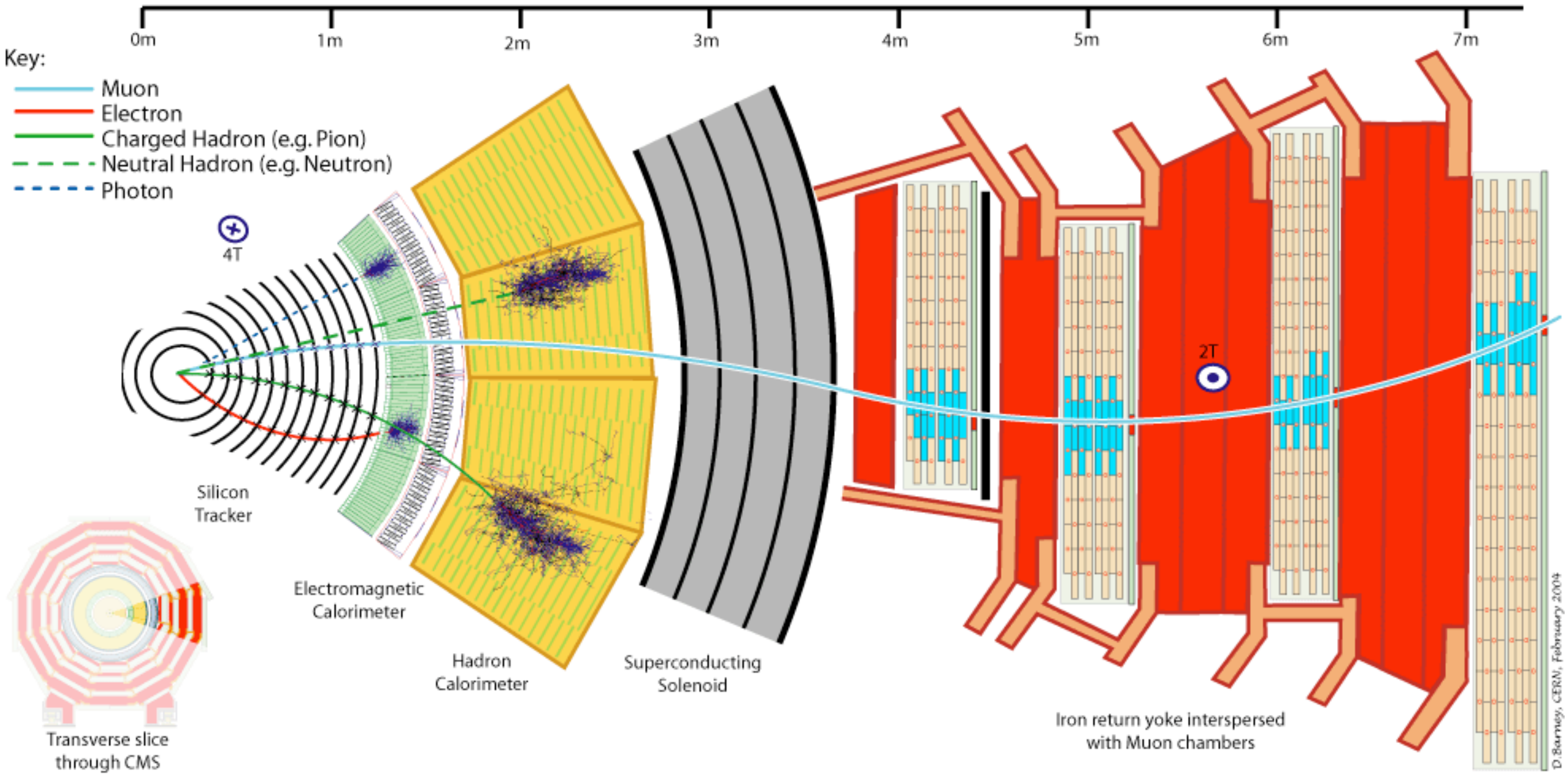
- Two different approaches for detectors
- Both need to be very radiation hard



	ATLAS	CMS
tracking	silicon/gas	silicon
em cal	liquid Ar	PbWO
had cal	steel/scint.	brass/scint.
muon	RPCs/drift	RPCs/drift
Magnet	Solenoid (inner) /Toroid (outer)	Solenoid
B Field	~2 Tesla /4Tesla	~4 Tesla



Animation



0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Backup

Table 27.1: Summary of variables used in this section. The kinematic variables β and γ have their usual meanings.

Symbol	Definition	Units or Value
α	Fine structure constant $(e^2/4\pi\epsilon_0\hbar c)$	$1/137.035\,999\,11(46)$
M	Incident particle mass	MeV/c^2
E	Incident part. energy γMc^2	MeV
T	Kinetic energy	MeV
m_ec^2	Electron mass $\times\, c^2$	$0.510\,998\,918(44)$ MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_ec^2$	$2.817\,940\,325(28)$ fm
N_A	Avogadro's number	$6.022\,1415(10) \times 10^{23}\ \mathrm{mol}^{-1}$
ze	Charge of incident particle	
Z	Atomic number of absorber	
A	Atomic mass of absorber	$\mathrm{g\ mol}^{-1}$
K/A	$4\pi N_A r_e^2 m_ec^2/A$	$0.307\,075\ \mathrm{MeV\ g}^{-1}\ \mathrm{cm}^2$ for $\mathrm{A} = 1\ \mathrm{g\ mol}^{-1}$
I	Mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	
$\hbar\omega_p$	Plasma energy $(\sqrt{4\pi N_e r_e^3}\ m_ec^2/\alpha)$	$28.816\sqrt{\rho\langle Z/A\rangle}\ \mathrm{eV}^{(a)}$
N_c	Electron density	(units of r_e)$^{-3}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
—	$4\alpha r_e^2 N_A/A$	$(716.408\ \mathrm{g\ cm}^{-2})^{-1}$ for $A = 1\ \mathrm{g\ mol}^{-1}$
X_0	Radiation length	$\mathrm{g\ cm}^{-2}$
E_c	Critical energy for electrons	MeV
$E_{\mu c}$	Critical energy for muons	GeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\ m_ec^2$	21.2052 MeV
R_M	Molière radius	$\mathrm{g\ cm}^{-2}$

$^{(a)}$ For ρ in $\mathrm{g\ cm}^{-3}$.