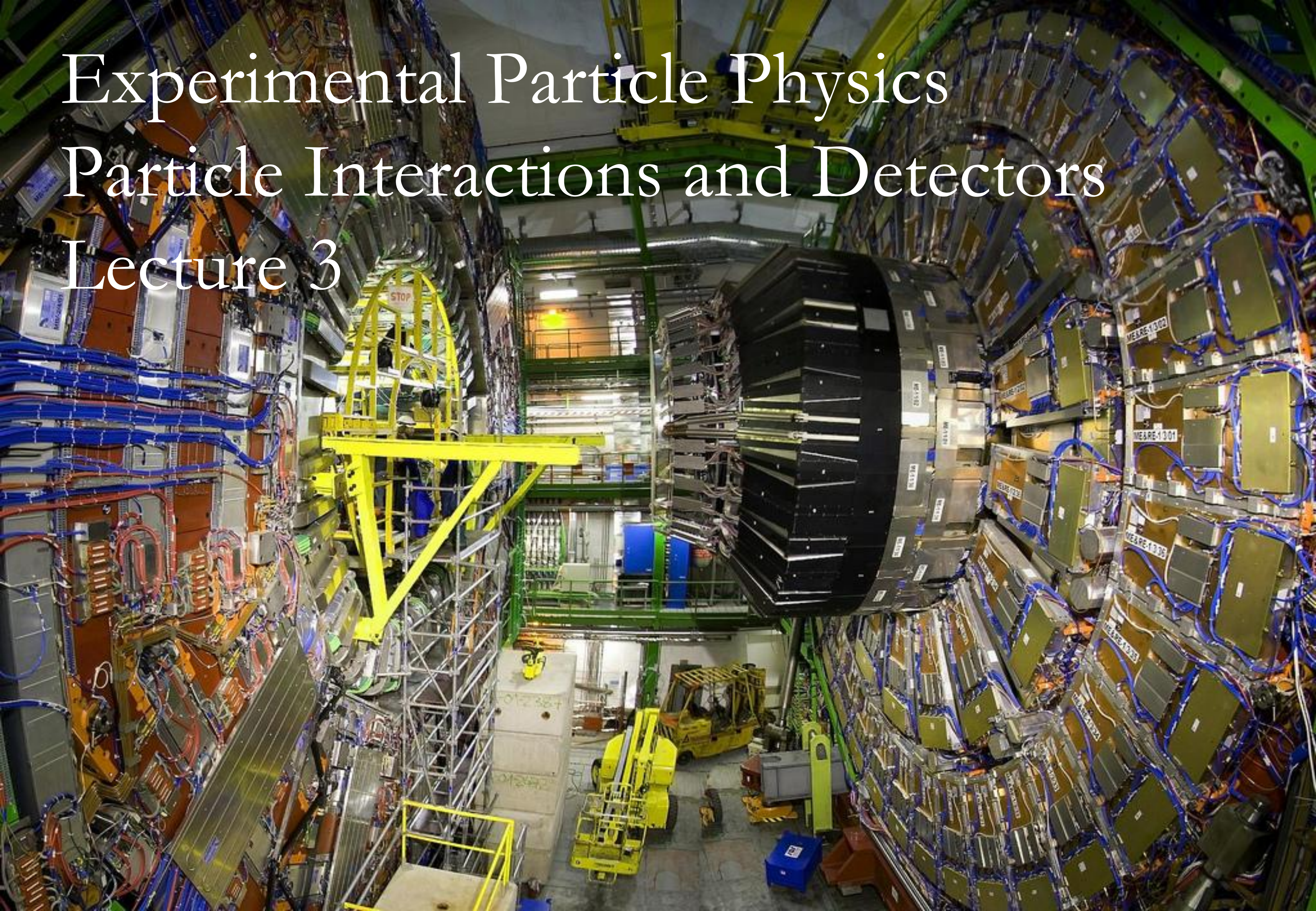
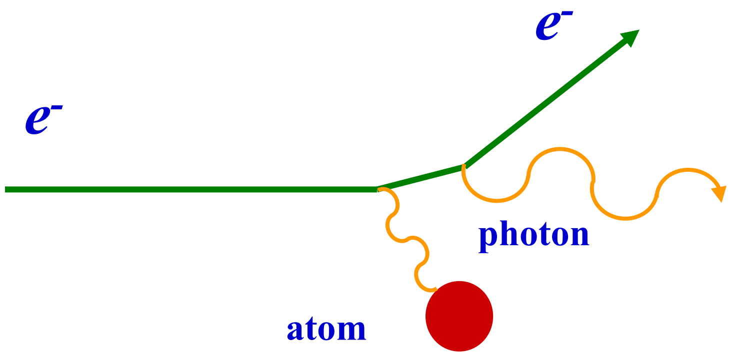
Experimental Particle Physics
Particle Interactions and Detectors
Lecture 3



Interactions and Detectors

- Last lecture
  - Ionisation Losses and charged particle detectors
- This lecture
  - Photon absorption
  - Electromagnetic Showers
  - Hadronic Showers
  - Multiple Scattering

Radiation Loss for electrons



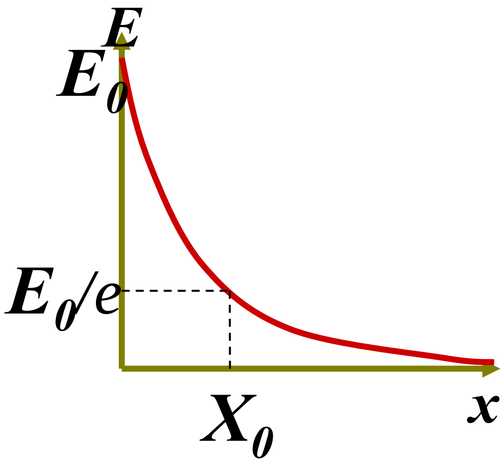
- Bremsstrahlung: electromagnetic radiation produced by the deceleration of a charged particle, such as an electron, when deflected by another charged particle, such as an atomic nucleus.
- Photon can be very energetic.

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

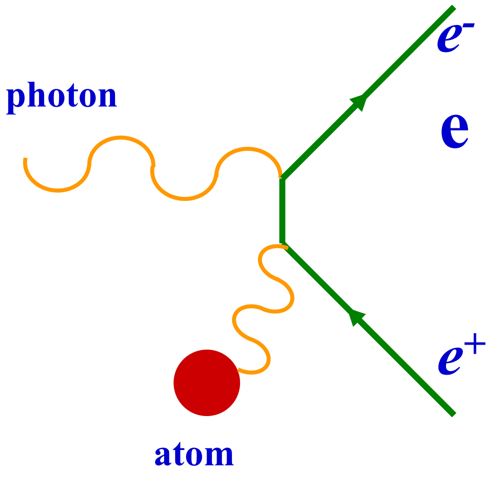
Radiation Length

(gcm^{-2})

$$\Leftrightarrow E = E_0 e^{-x/X_0}$$



Photon Absorption



- Electron-positron pair production
- Exponential absorption
- Length scale 9/7 × X_0

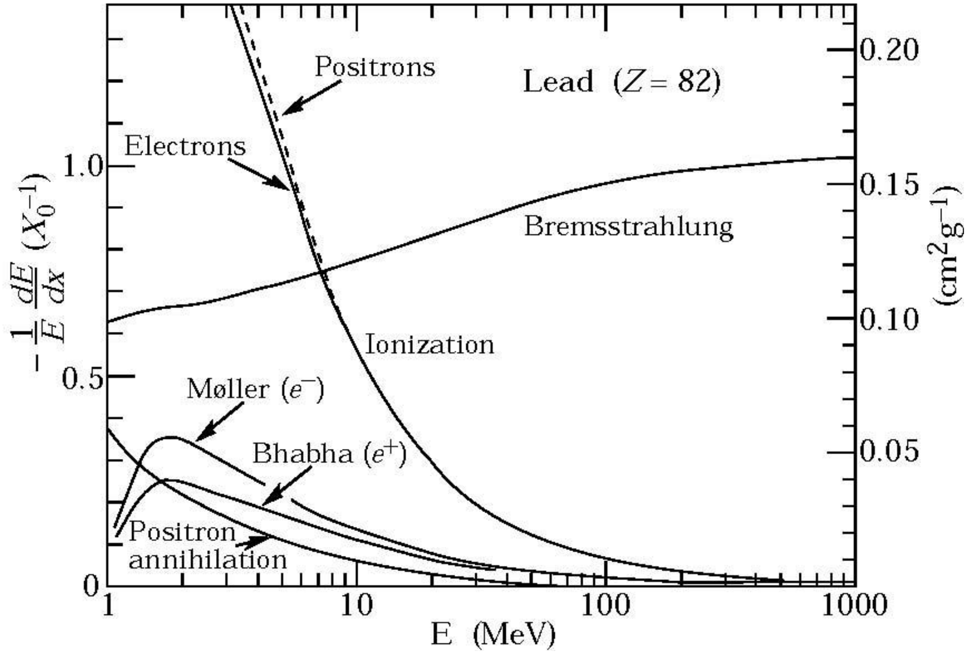
$$-\frac{dE}{dx} = \frac{7E}{9X_0}$$

Radiation Length for electrons and photons

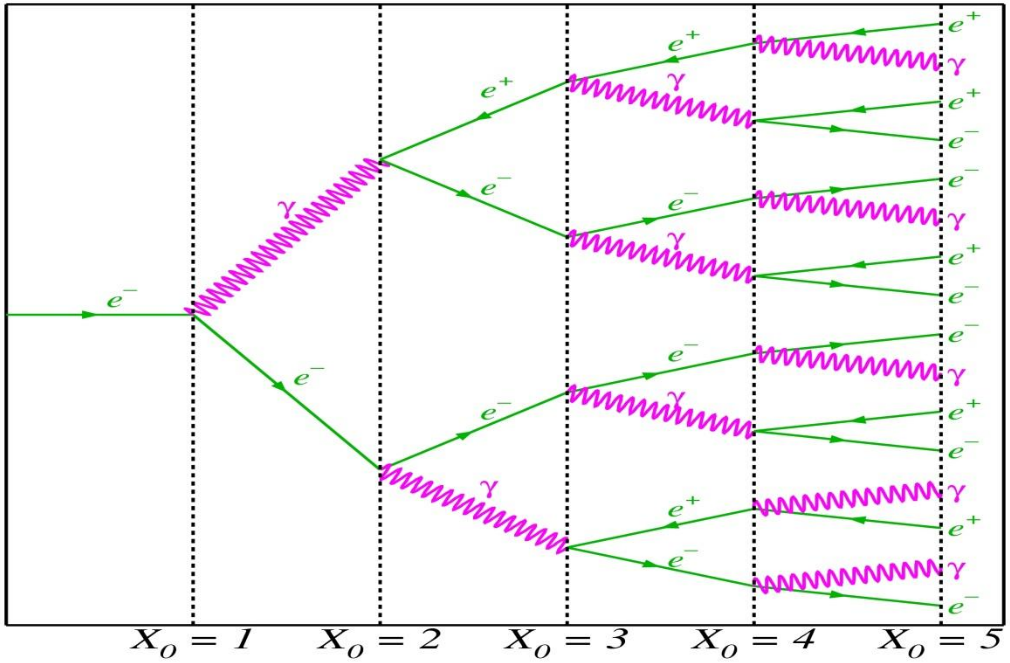
- Radiation Length X_o has 2 definitions:
  - "Mean distance over which high-energy electron loses all but 1/e of its energy by Bremsstrahlung."
  - "7/9ths of the mean free path for pair production by a high-energy photon."

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \quad (\mathrm{gcm}^{-2})$$

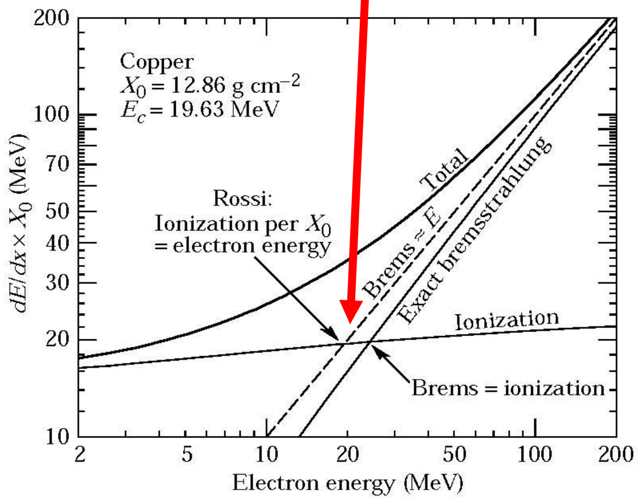
	X_0 (g cm^{-2})	X_0 (cm)
Air	37	30,000
Silicon	22	9.4
Lead	6.4	0.56



Simple Electromagnetic (EM) Shower



E_c Critical Energy



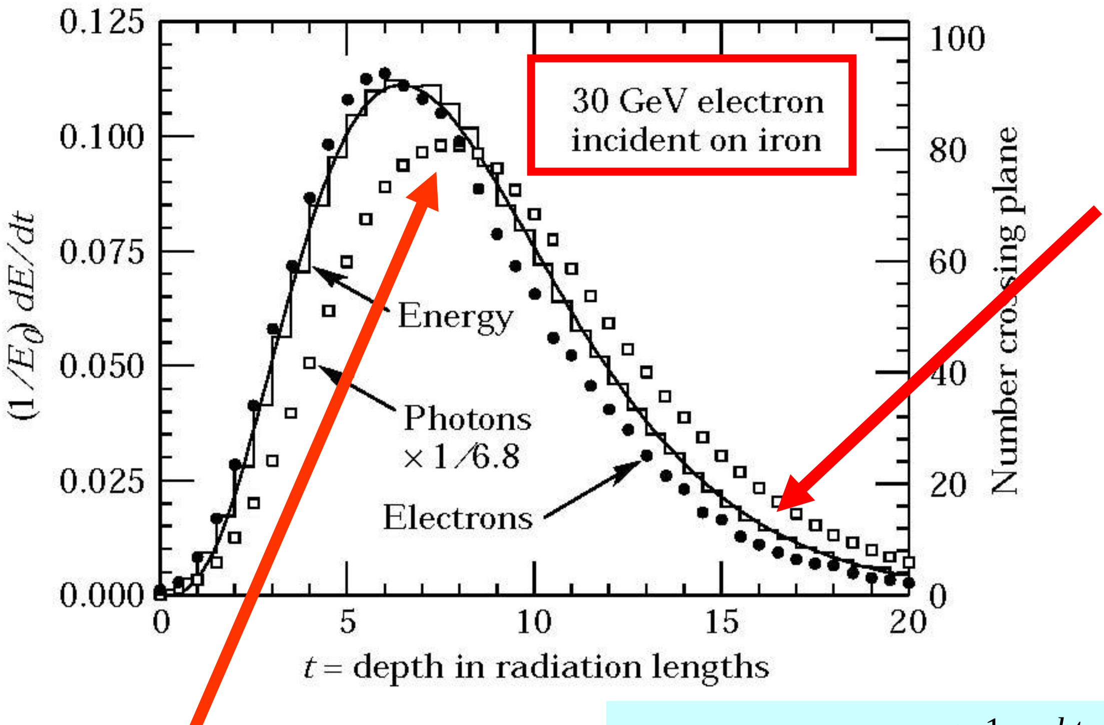
x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
$<E>$	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$<E_c$

- Start with electron or photon
- Depth ~ ln(E_0)
- Most energy deposited as ionisation.

Real EM Shower

- Shape dominated by fluctuations

As depth of shower increases more energy is carried by photons



Tail

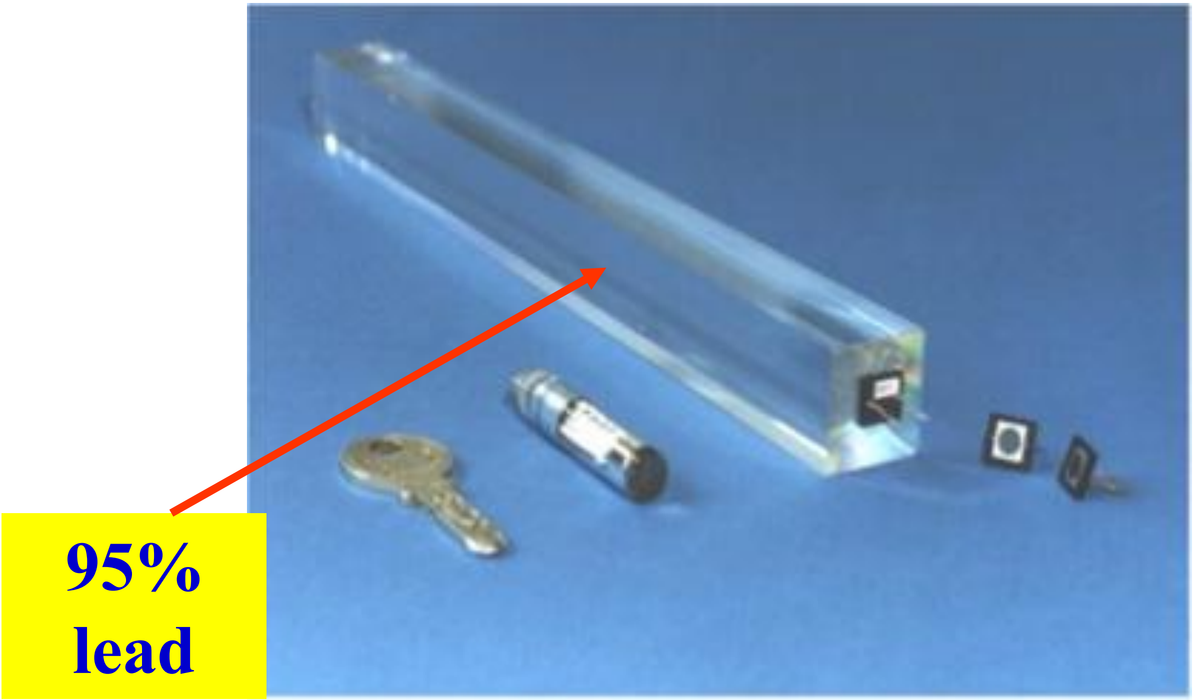
Maximum close to naïve depth expectation

$$\frac{dE}{dt} \approx E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}, \quad t = \frac{x}{X_0}$$

Calorimetry 1 - Homogeneous

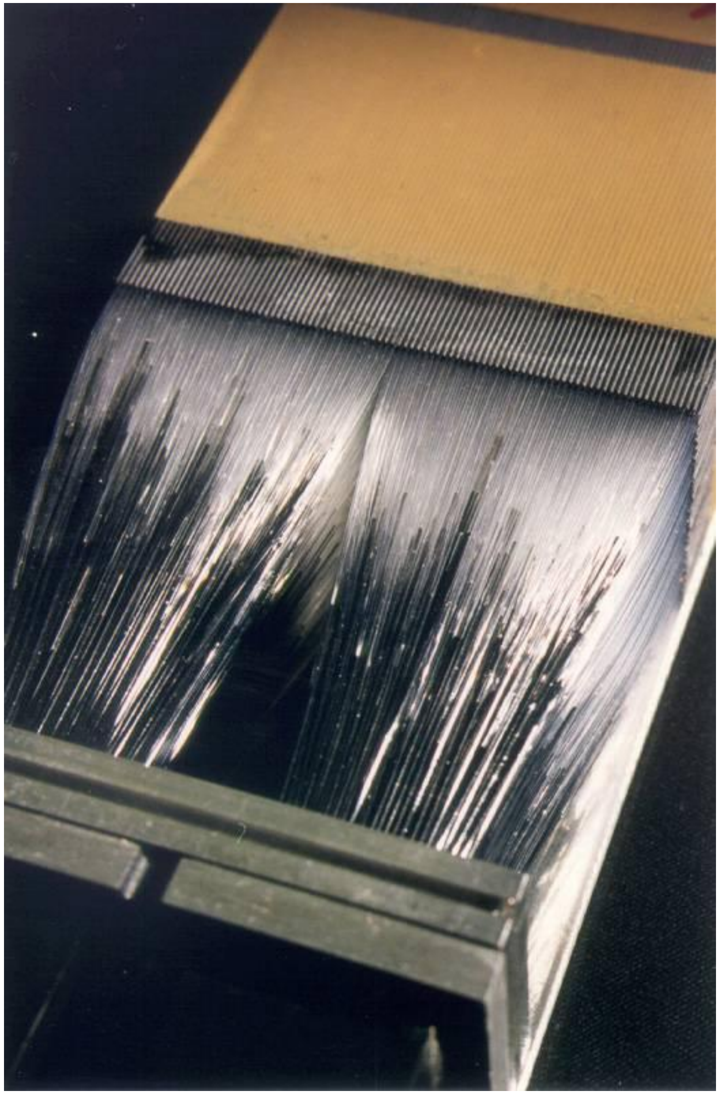
In homogeneous calorimeters the functions of passive particle absorption and active signal generation and readout are combined in a single material. Such materials are almost exclusively used for electromagnetic calorimeters, e.g. crystals, composite materials (like lead glass, $PbWO_4$) or liquid noble gases.

- Crystal, glass, liquid
- Acts as absorber and scintillator
- Light detected by photodetector
- E.g. $PbWO_4$ ($X_0 \approx 0.9$ cm)



95% lead

Calorimetry 2 – Sampling



- In sampling calorimeters the functions of particle absorption and active signal readout are separated. This allows optimal choice of absorber materials and a certain freedom in signal treatment.
- Heterogeneous calorimeters are mostly built as sandwich counters, sheets of heavy-material absorber (e.g. lead, iron, uranium) alternating with layers of active material (e.g. liquid or solid scintillators, or proportional counters).
- Only the fraction of the shower energy absorbed in the active material is measured.
- Hadron calorimeters, needing considerable depth and width to create and absorb the shower, are necessarily of the sampling calorimeter type (see next slide).

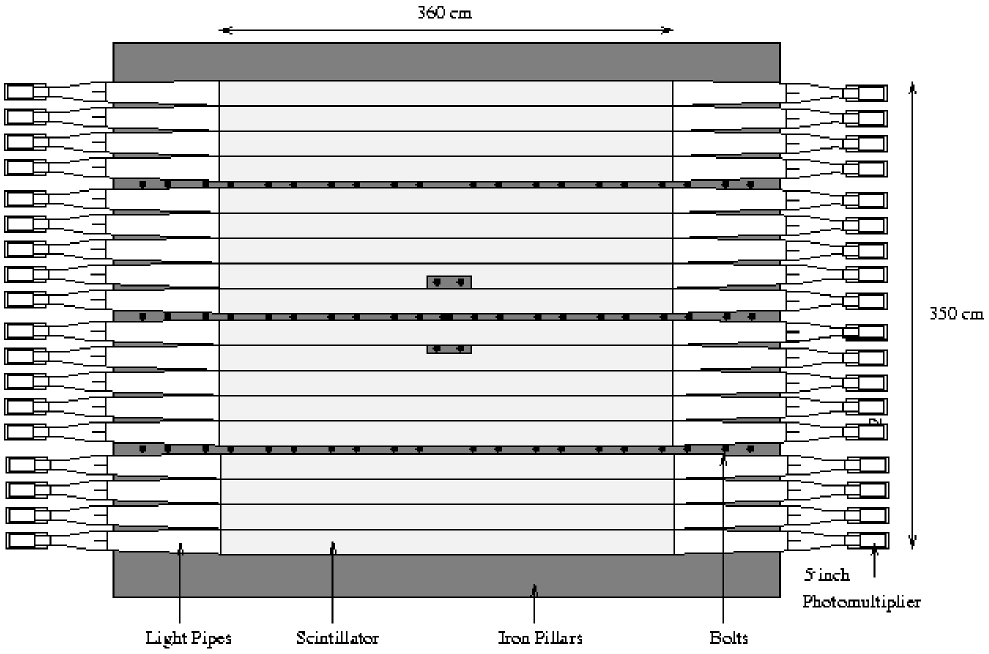
Hadronic Showers

- Nuclear interaction length >> radiation length

$$\lambda \approx 35 \mathrm{g.cm}^{-2} A^{1/3}$$

e.g. Lead: $X_0 = 0.56$ cm, $\lambda = 17$ cm

- Hadron showers wider, deeper, less well understood
- Need much larger calorimeter to contain hadron shower
  - Always sampling
  - Dense metals still good as absorbers
  - Mechanical/economic considerations often important
  - Uranium, steel, brass…



Hadronic Calorimeter from NOMAD experiment

Hadronic Calorimeter

CMS Barrel Calorimeter

Alternating layers of steel and readout

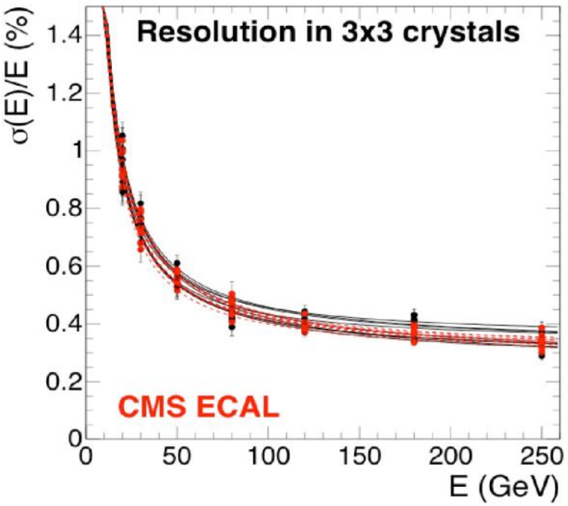
CDF

CMS Endcap Calorimeter

Energy Resolution Limitations

- EM Calorimeter
  - the intrinsic limitation in resolution results from variations in the net track length of charged particles in the cascade.
  - Sampling Fluctuations
  - Landau Distribution

$$\frac{\sigma(E)}{E} \approx \frac{1\% - 3\%}{\sqrt{E}}$$

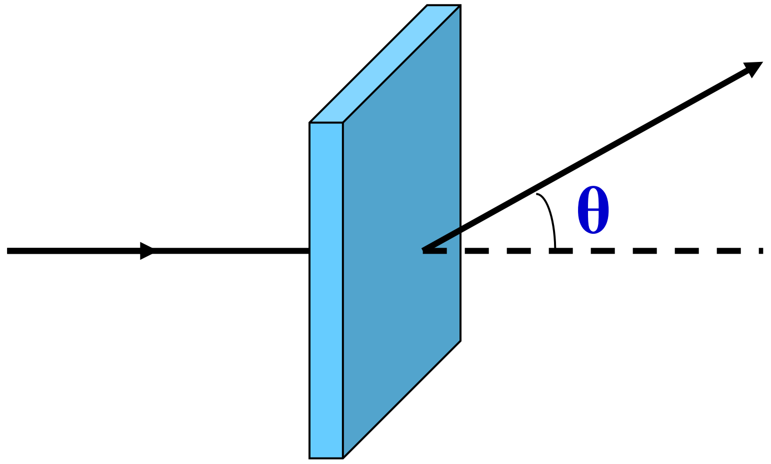


- Hadronic Calorimeter
  - A fluctuating π^0 component among the secondaries which interacts electromagnetically without any further nuclear interaction ($\pi^0 \rightarrow \gamma\gamma$). Showers may develop with a dominant electromagnetic component.
  - A sizeable amount of the available energy is converted into excitation and breakup of nuclei. Only a small fraction of this energy will eventually appear as a detectable signal and with large event-to-event fluctuations.
  - A considerable fraction of the energy of the incident particle is spent on reactions which do not result in an observable signal. Such processes may be energy leakage of various forms, like:
    - Backscattering
    - Nuclear excitation
    - slow neutrons, neutrinos

$$\frac{\sigma(E)}{E} \approx \frac{30\%}{\sqrt{E}}$$

Multiple Scattering

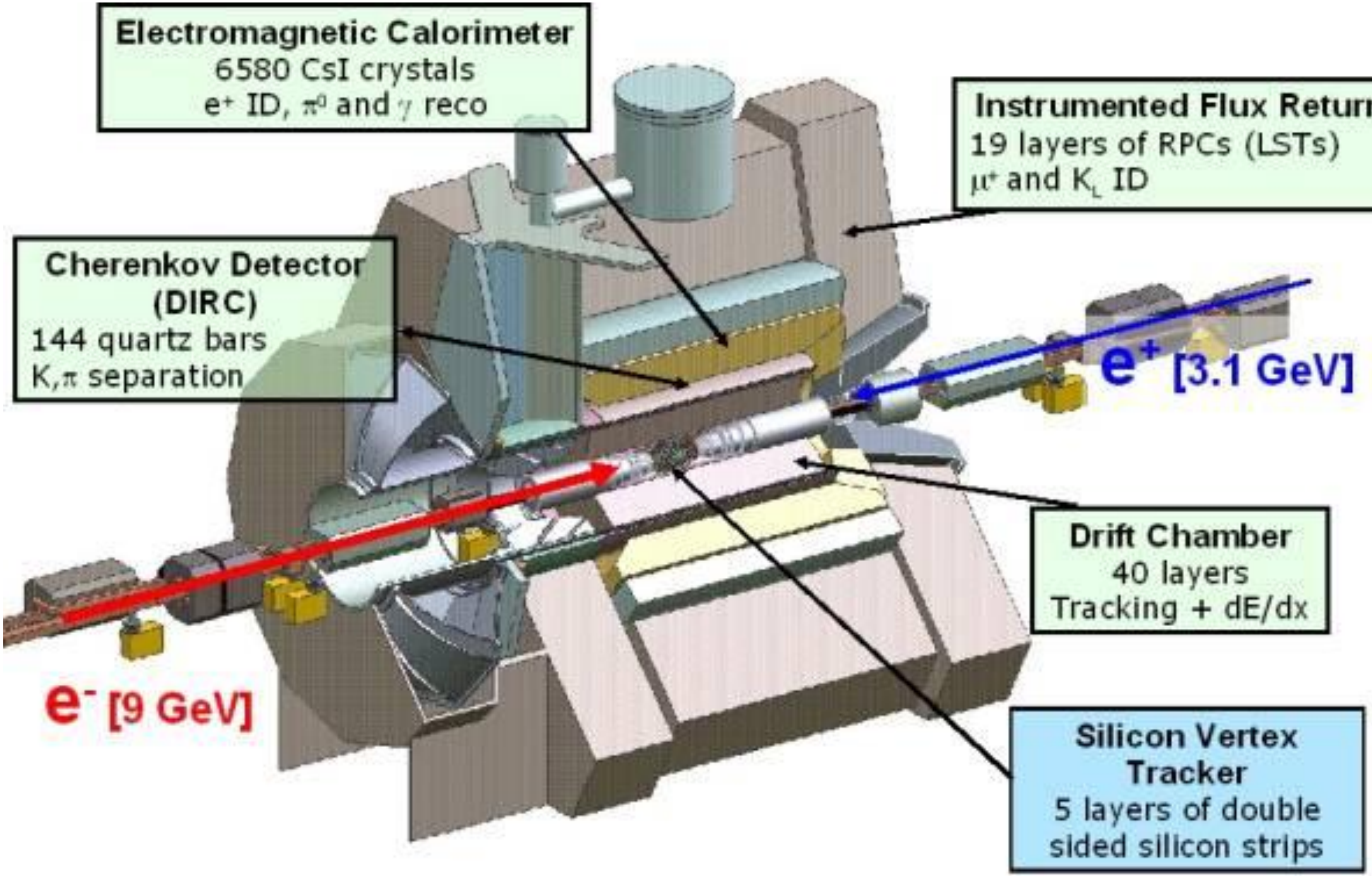
- Elastic scattering from nuclei causes angular deviations:



$$\theta_{RMS} \approx \frac{13.6\mathrm{MeV}}{\beta cp} q\sqrt{x / X_0}$$

- Approximately Gaussian
- Can disrupt measurements in subsequent detectors
- If you want to:
  - Measure momentum : make detector as light as possible
  - Measure energy: make detector as heavy as possible
- Measure momentum before energy!

Creating a detector from the components



Electromagnetic Calorimeter
6580 CsI crystals
e^+ ID, π^0 and γ reco

Instrumented Flux Return
19 layers of RPCs (LSTs)
μ^+ and K_L ID

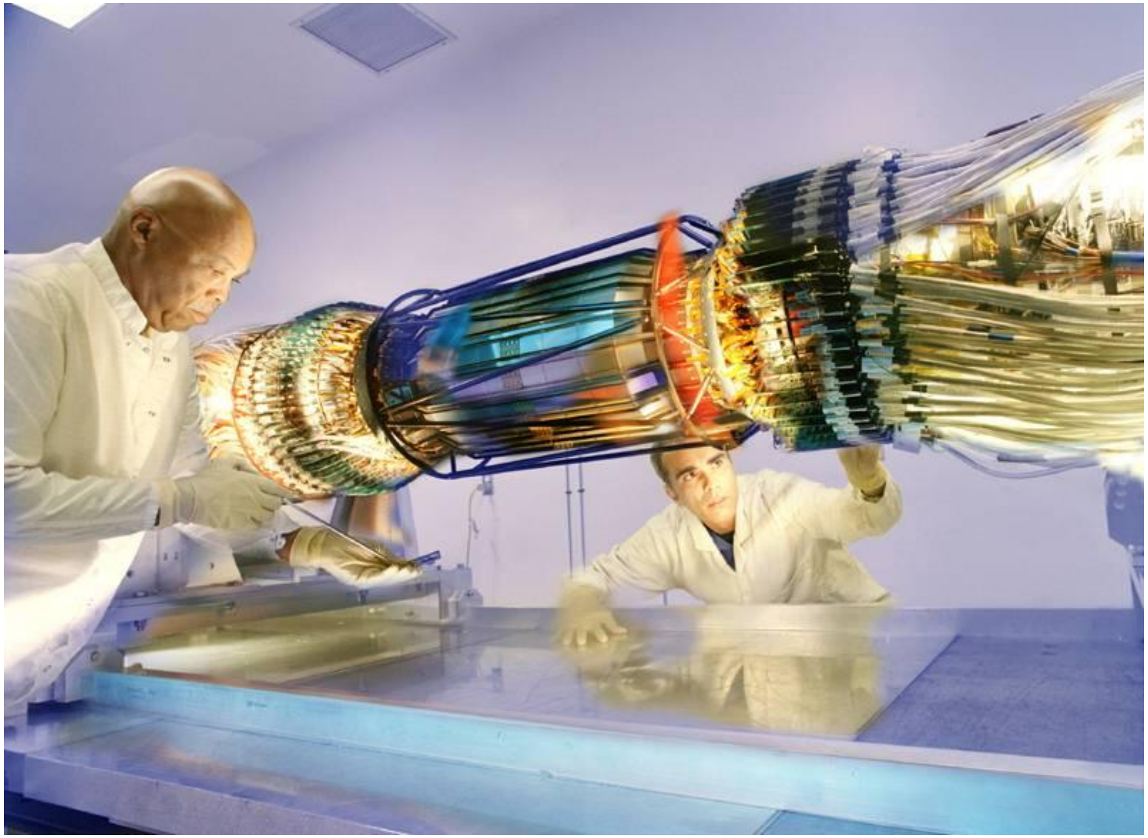
Cherenkov Detector (DIRC)
144 quartz bars
K,π separation

Drift Chamber
40 layers
Tracking + dE/dx

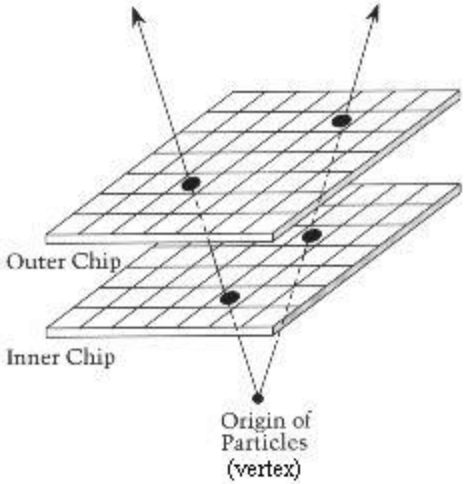
Silicon Vertex Tracker
5 layers of double sided silicon strips

1) Vertex Detectors

Purpose: Ultra-high precision trackers close to interaction point to measure vertices of charged tracks



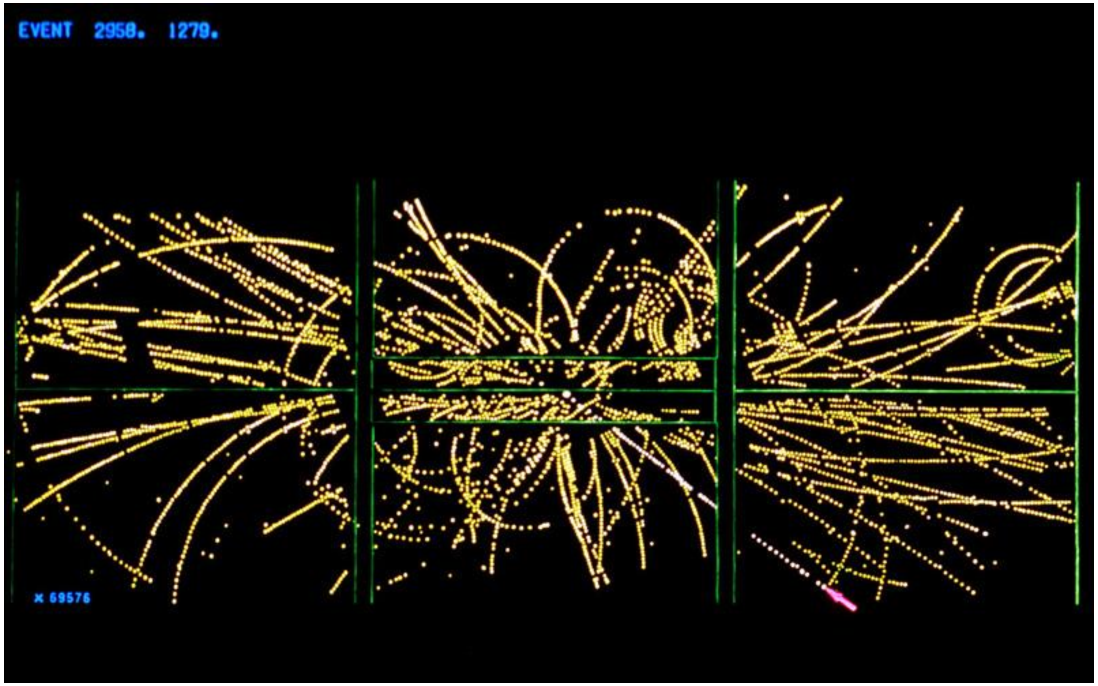
- Spatial resolution a few microns
- Low mass
- *A few layers of silicon*



2) Tracking Detectors

Purpose: Measure trajectories of charged particles

- Low mass
  - Reduce multiple scattering
  - Reduce shower formation
- High precision
- Multiple 2D or 3D points
- *Drift chamber, TPC, silicon...*
- Can measure momentum in magnetic field ($p = 0.3qBR$)

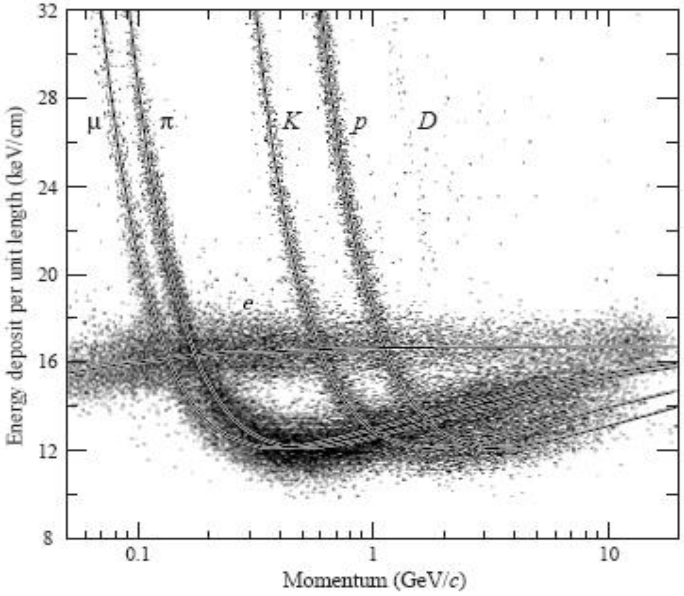


3) Particle ID

Purpose: Distinguish different charged “stable” particles

- Muon, pion, kaon, proton
- Measured momentum and energy: $m^2 = E^2 - p^2$
  - Difficult at high energy $E \sim p$
- Different *dE/dx* in tracking detectors
  - Only for low energy β^{-2} region, no good for MIPs

- Measure time-of-flight, gives β
  - *Fast scintillator*
- Measure β directly
  - *Cerenkov radiation*
- Measure γ directly
  - *Transition radiation*

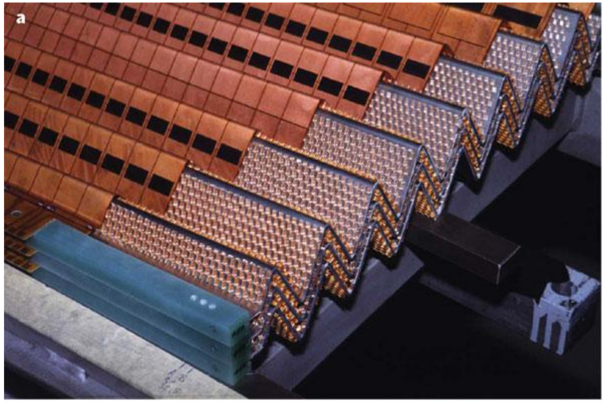


4) EM Calorimeter

Purpose: Identify and measure energy of electrons and photons

- Need ~ 10 X_0
  - 10 cm of lead
- Will see some energy from muons and hadrons
- Homogenous
  - *Crystal*
  - *Doped glass*
- Sampling
  - *Absorber + scintillator/MWPC/…*

ATLAS: Liquid Argon + Lead

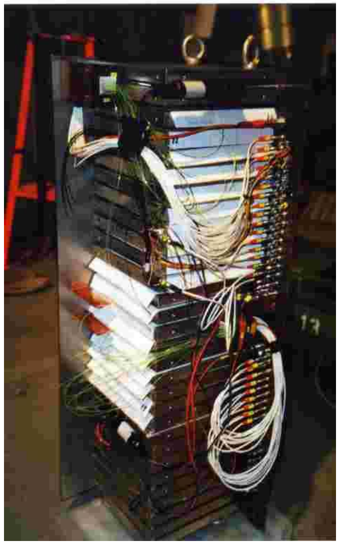


CMS: Lead-Tungstate crystal

5) Hadron Calorimeter

Purpose: Identify and measure energy of all hadrons

- Need ~ 10 λ
  - 2 m of lead
- Both charged and neutral
- Will see some energy from muons
- Sampling
  - *Heavy, structural metal absorber*
  - *Scintillator, MWPC detector*



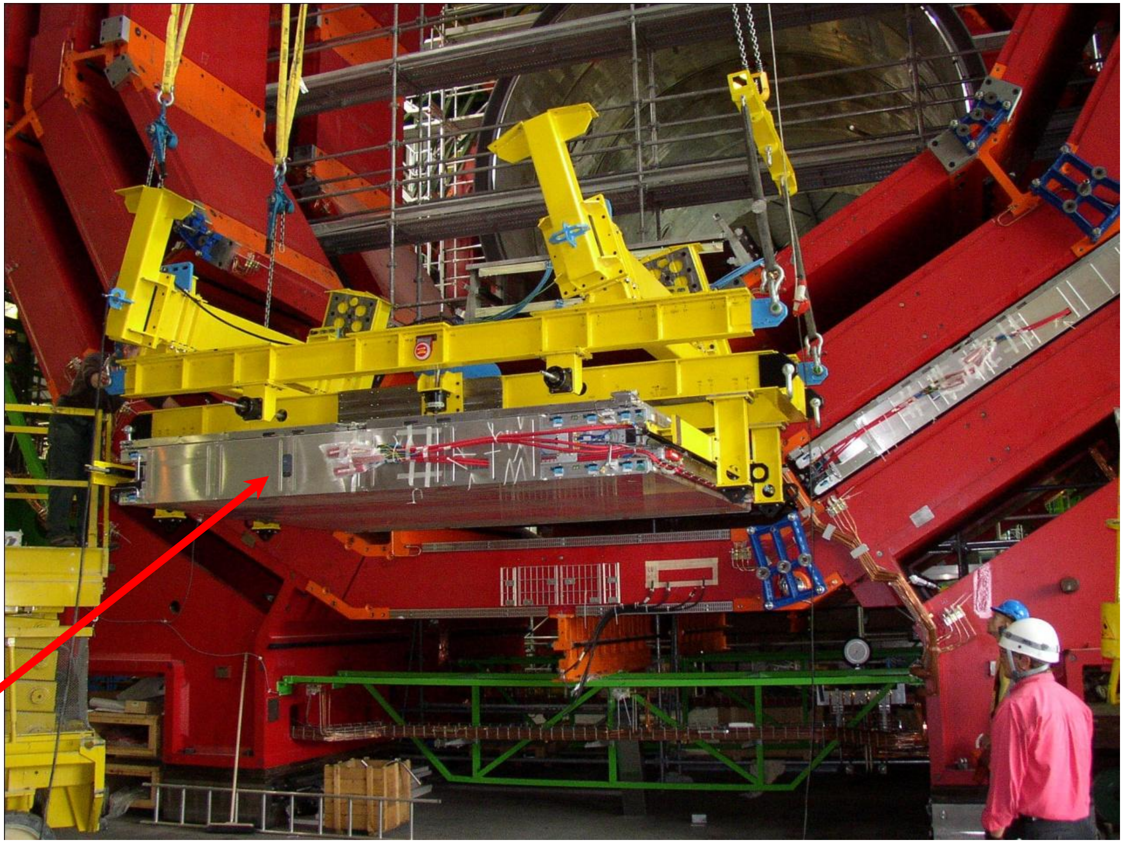
6) Muon Detectors

Purpose: Identify muons

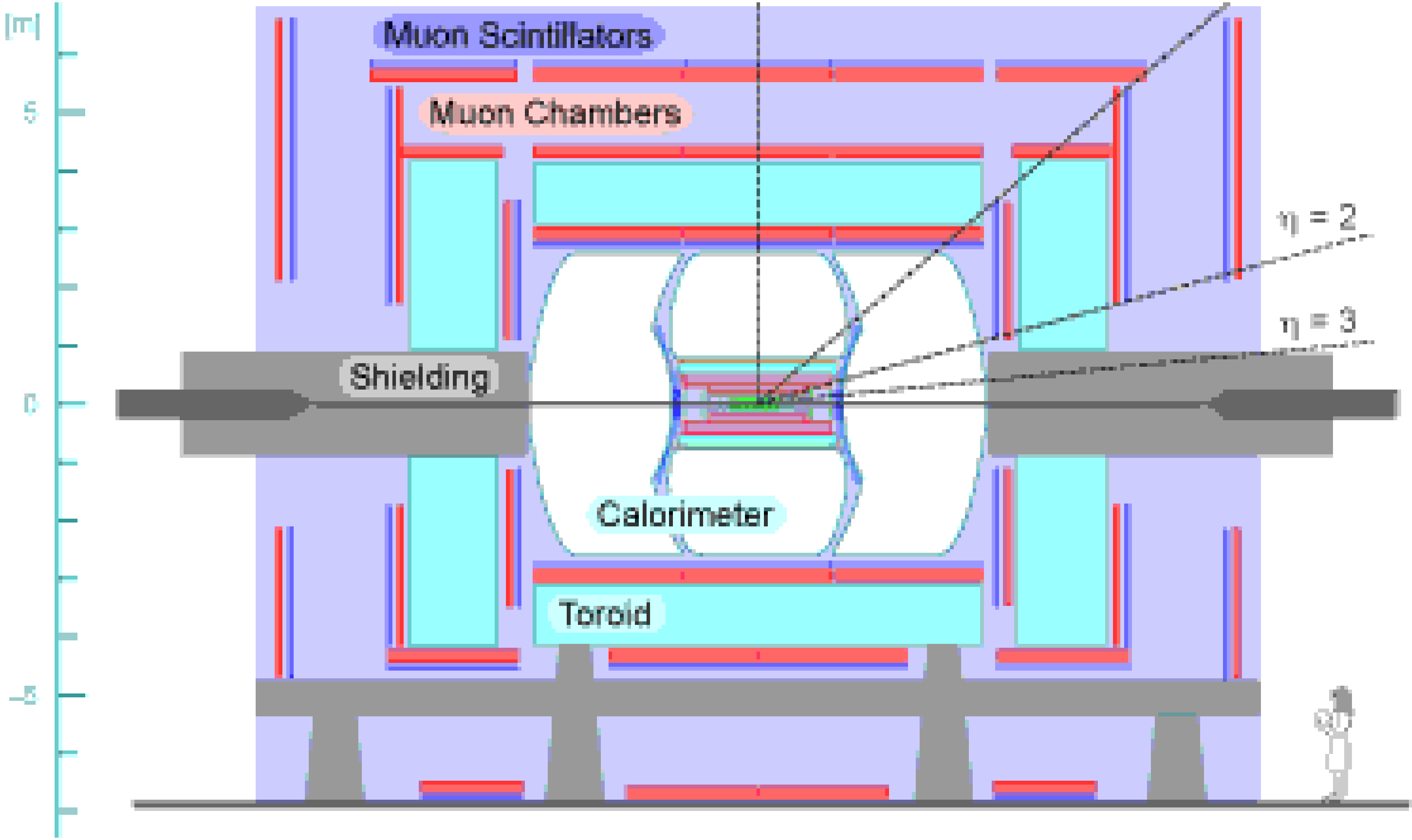
CMS

- Muons go where other particles cannot reach:
  - No nuclear interactions
  - Critical energies >> 100 GeV
    - Always a MIP
  - Stable (τ = 2.2 μs)

- A shielded detector can identify muons
  - "shielding" is often calorimeters or the magnet iron return yoke
  - *Scintillator, MWPC, drift chambers…*



Putting them all together



Next Time...

Putting it all together

- building a particle physics experiment