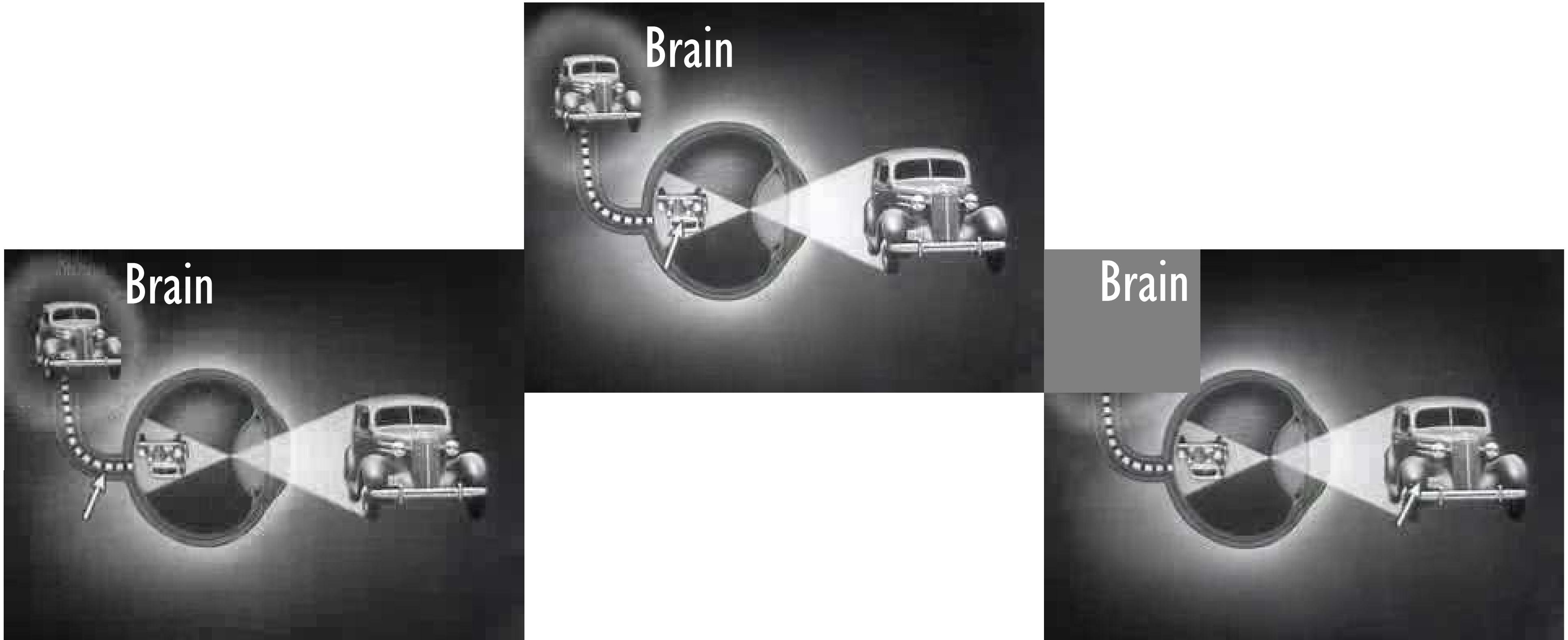
# Lecture 1

# Detector Instrumentation

## Introduction

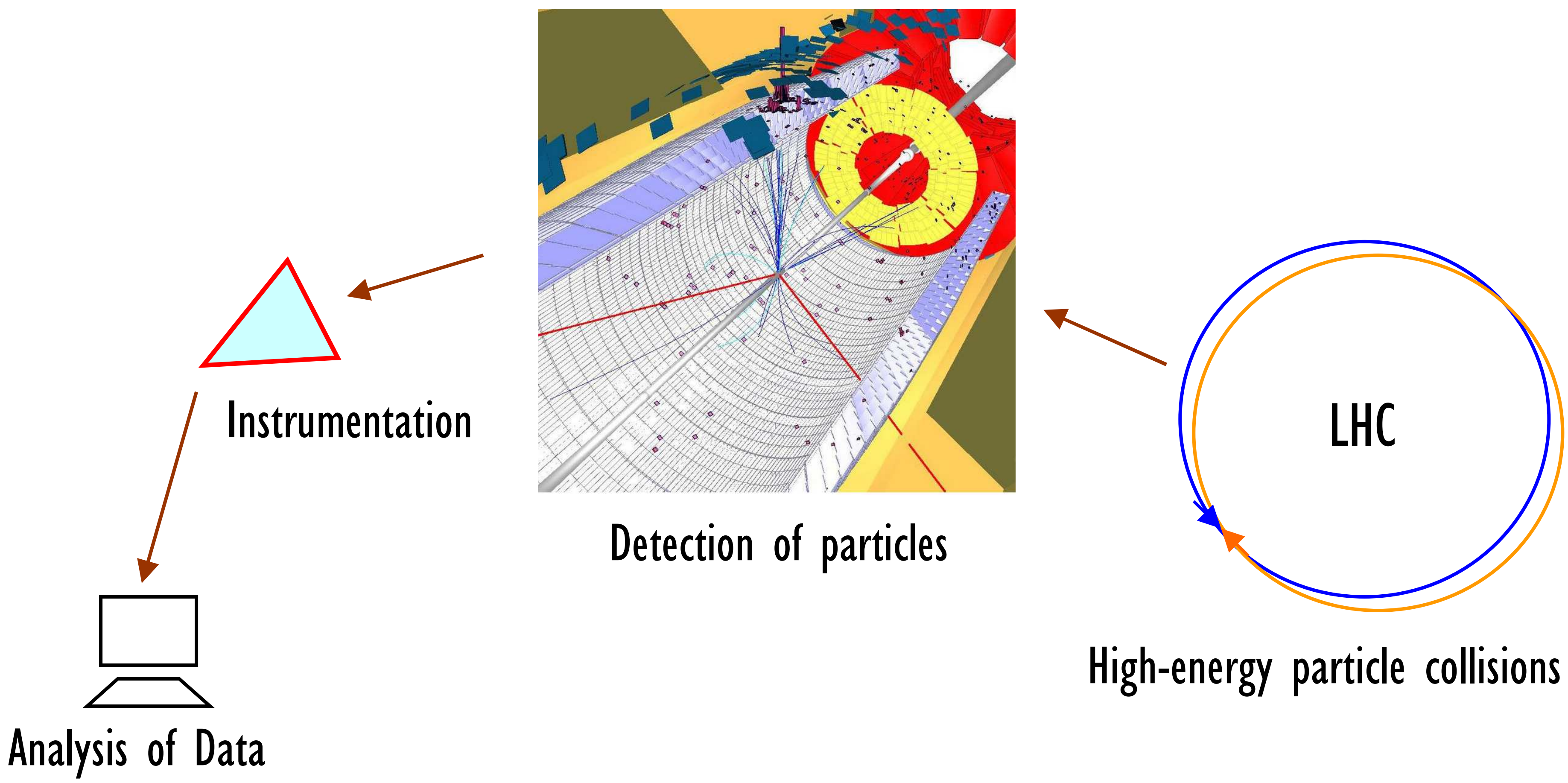
*Reference for this lecture series:*
*William Leo, Techniques of Nuclear and Particle Physics*

# How do you see ?




Instrumentation ← Detection ← Phenomenon

# Detector instrumentation



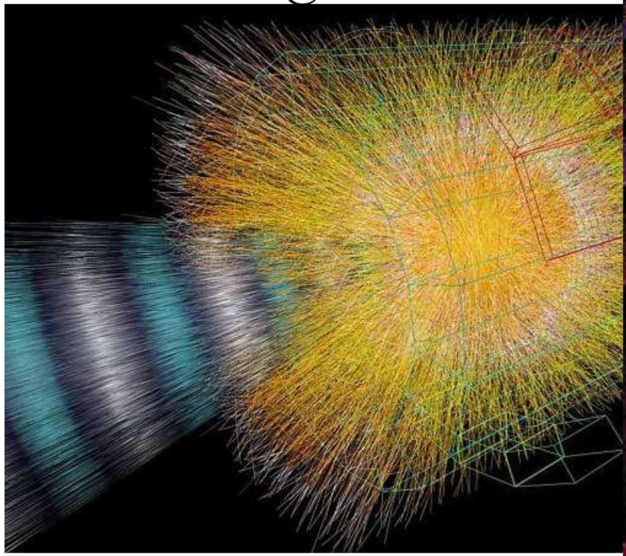
# Why do you want to study fundamental particles ?

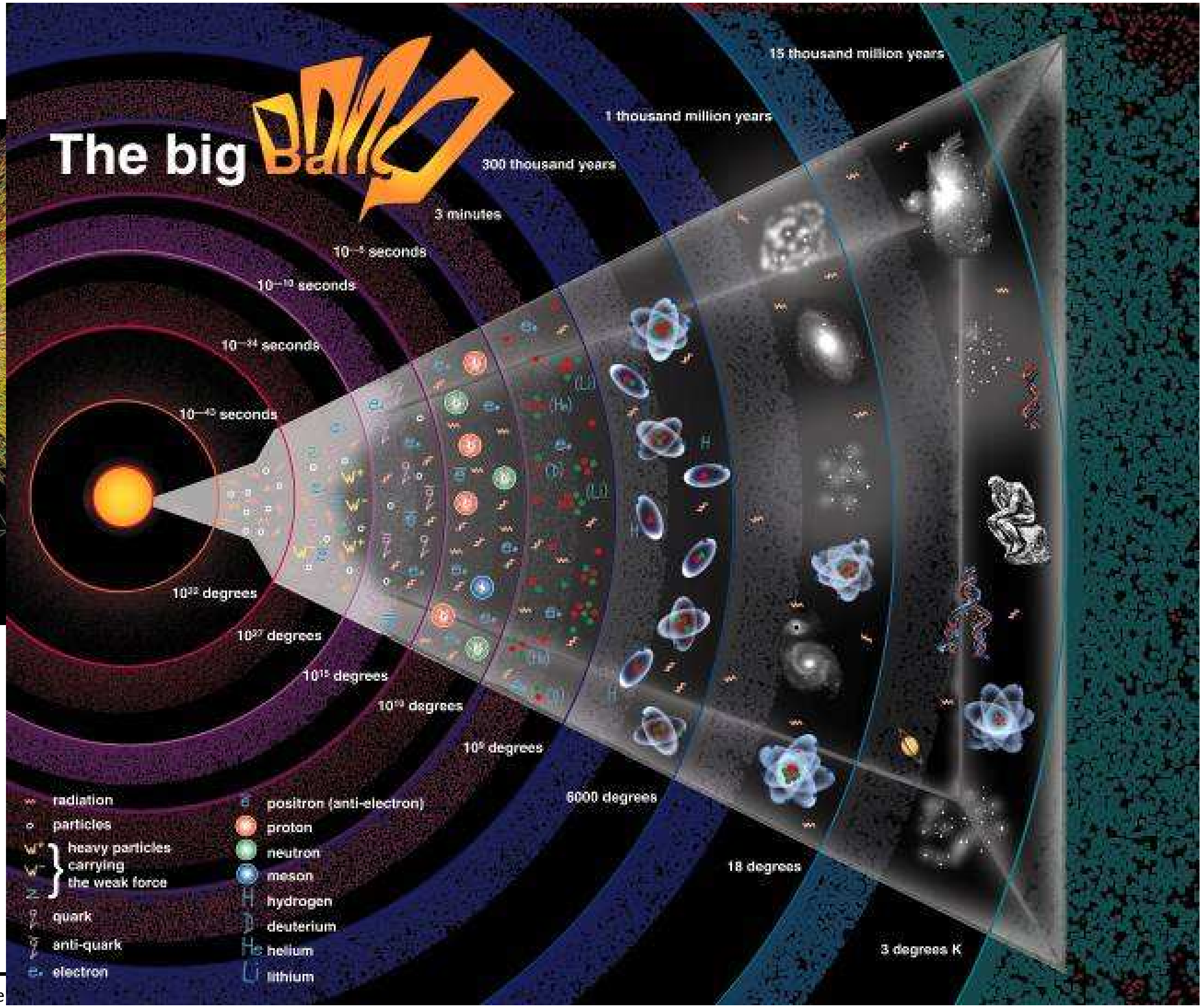
- $^{208}$Pb + $^{208}$Pb nuclei collide at high energy: 416 nucleons go in, $\sim$ 7000 fundamental particles come out.
- Two protons collide at high energy (7 TeV c.o.m energy for LHC), $\sim$ 80 fundamental particles come out

- The collision converts ordinary matter to pure energy, which then coalesces back out into fundamental particles
- *This is similar to what happened at the Big Bang: start with pure energy, and produce fundamental particles.*
- *So we are recreating conditions of the early universe in these collisions*

# Why do you want to study fundamental particles ?

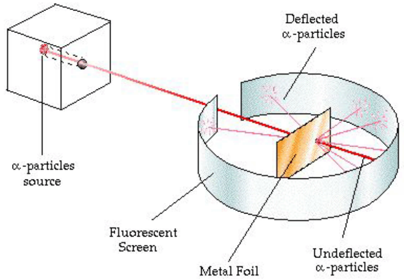
*$^{208}Pb+^{208}Pb$ @ 7 TeV*



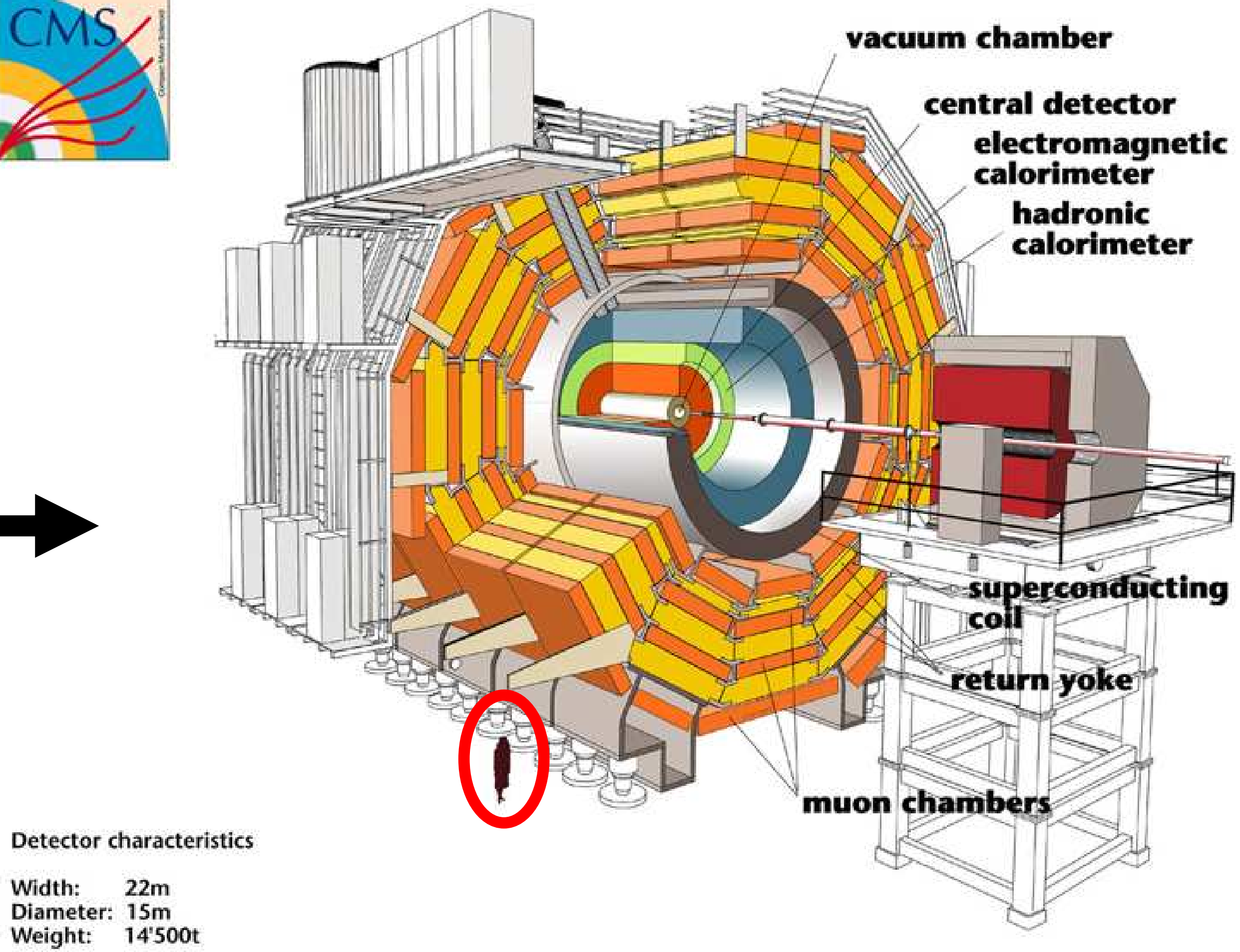



*Recreate conditions soon after the BigBang & understand how matter formed out of pure energy*

# Why such big experiments?




Rutherford ~ 1m
α experiment

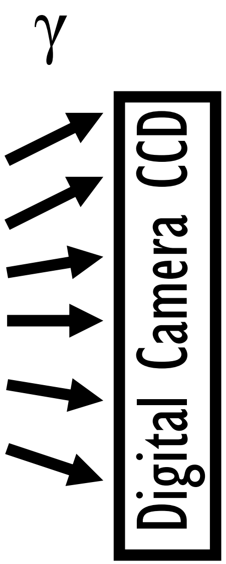


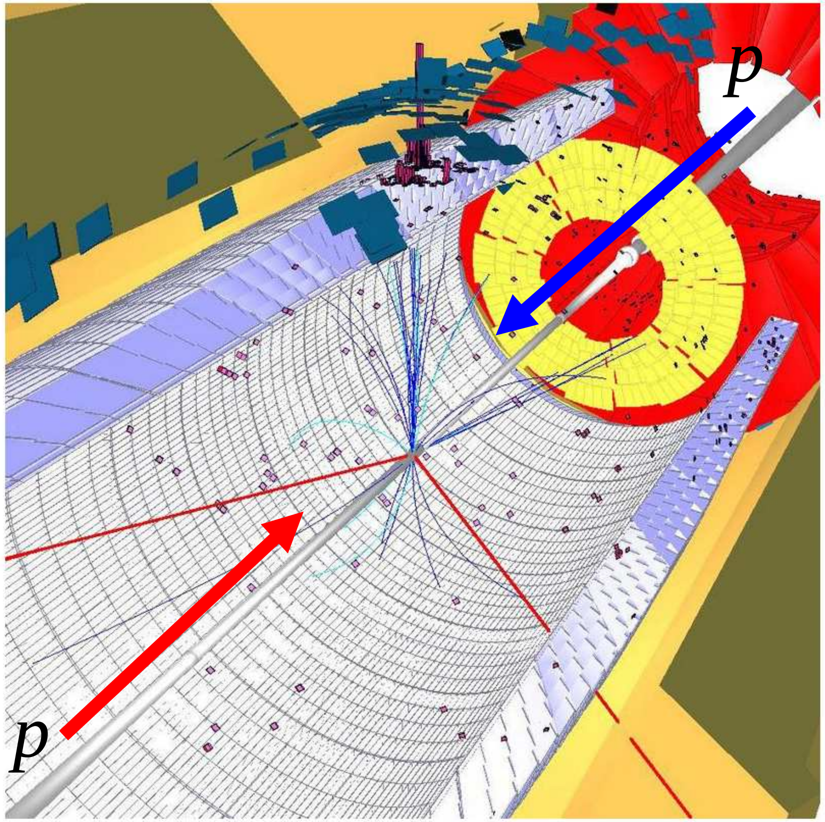



http://cms.web.cern.ch/cms/Detector/WhyBig/index.html

# Digital Camera=2D image of photons at low energy

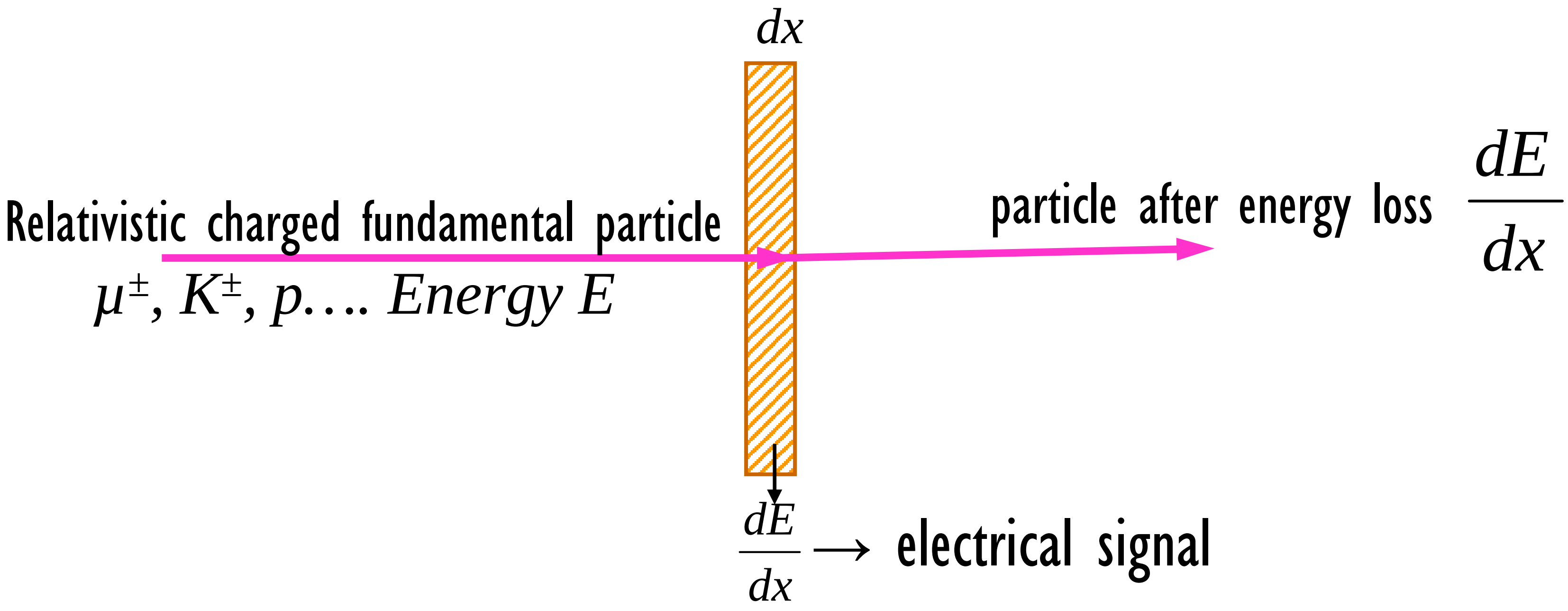
## Particle detector=3D image of collision of high energy particles with tracking, energy measurements



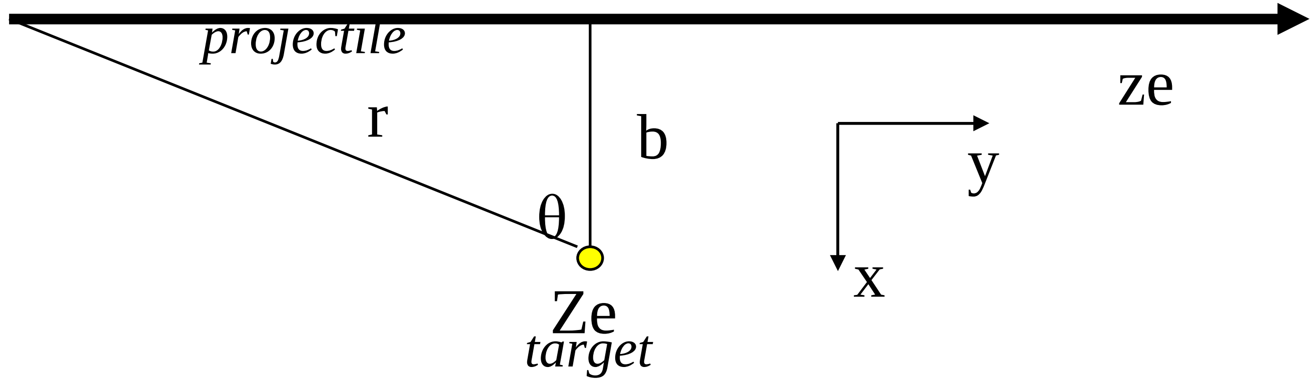
# Basic principle of particle detection

<u>All particles lose energy when passing through a material</u>




There is a fundamental equation that determines $\frac{dE}{dx}$ for all charged particles

# Simplified calculation of $\left\langle \frac{dE}{dx} \right\rangle$




*Force on projectile*

$$F_x = \frac{Zze^2}{4\pi\varepsilon_0 r^2}\cos\theta = \frac{Zze^2}{4\pi\varepsilon_0 b^2}\cos^3\theta$$

*Force on projectile / target*

$$\Delta p = \int_{-\infty}^{\infty} dt F_x = \frac{Zze^2}{2\pi\varepsilon_0 \beta c}\frac{1}{b}$$

*Energy transferred*

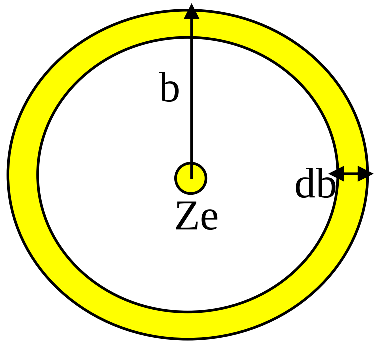
$$\Delta E = \frac{\Delta p^2}{2M} = \frac{Z^2 z^2 e^4}{2M(2\pi\varepsilon_0)^2(\beta c)^2}\frac{1}{b^2}$$

*target! $M_{nucleus} >> M_{electron}$*
*So scattering is off atomic electrons!*

# Simplified calculation of $\left\langle \frac{dE}{dx} \right\rangle$

*Energy transferred ΔE is a function of the impact parameter 'b':*

*Integrate over all b's and figure out the average number of electrons as the projectile goes through material of thickness Δx*




$$\frac{dn}{db} = 2\pi b \times (\text{number of electrons / unit area })$$

$$= 2\pi b \times Z \frac{N_A}{A} \rho \Delta x$$

$$\overline{\Delta E} = \int_{b_{\min}}^{b_{\max}} \mathrm{d}b \frac{\mathrm{d}n}{\mathrm{d}b} E_e(b) = 2C \frac{m_e c^2}{\beta^2} \frac{Zz^2}{A} \rho \Delta x \left[ \ln b \right]_{b_{\min}}^{b_{\max}}$$

$$= C \frac{m_e c^2}{\beta^2} \frac{Zz^2}{A} \rho \Delta x \left[ \ln E \right]_{E_{\min}}^{E_{\max}}$$

$$\text{with } C = 2\pi N_A \left( \frac{e^2}{4\pi \varepsilon_0 m_e c^2} \right)$$

$$\boxed{E_{\max} = \frac{2\gamma^2 \beta^2 m_e c^2}{1 + 2\gamma \frac{m_e}{M} + \left( \frac{m_e}{M} \right)^2} \approx 2\gamma^2 \beta^2 m_e c^2}$$

*Maximum energy that a particle with speed β can transfer to a target with mass m at rest in an elastic collision*

# Bethe-Bloch equation (1930-33)

Our Simplified:

$$\boxed{\left\langle \frac{dE}{dx} \right\rangle = 2C \frac{m_e c^2}{\beta^2} z^2 \frac{Z}{A} \rho \ln\left( \frac{2\beta^2 \gamma^2 m_e c^2}{I_0} \right)}$$

Detailed analysis with quantum mechanics gives:

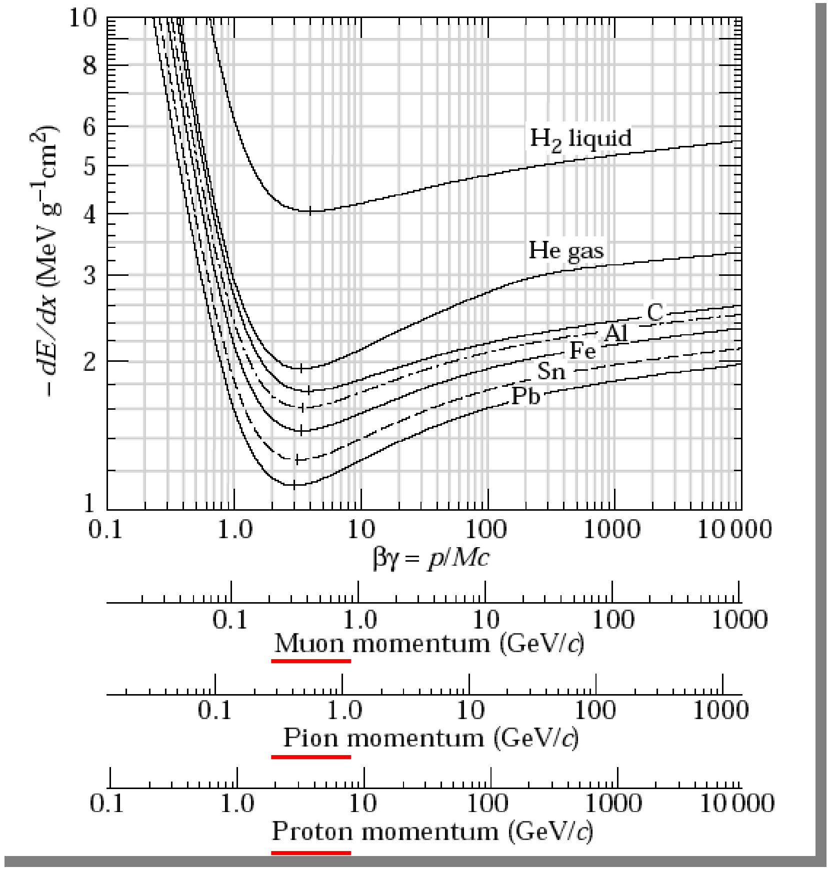
$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I} - \beta^2 - \frac{\delta}{2}]$$

# Universal features of Bethe-Bloch Energy Loss

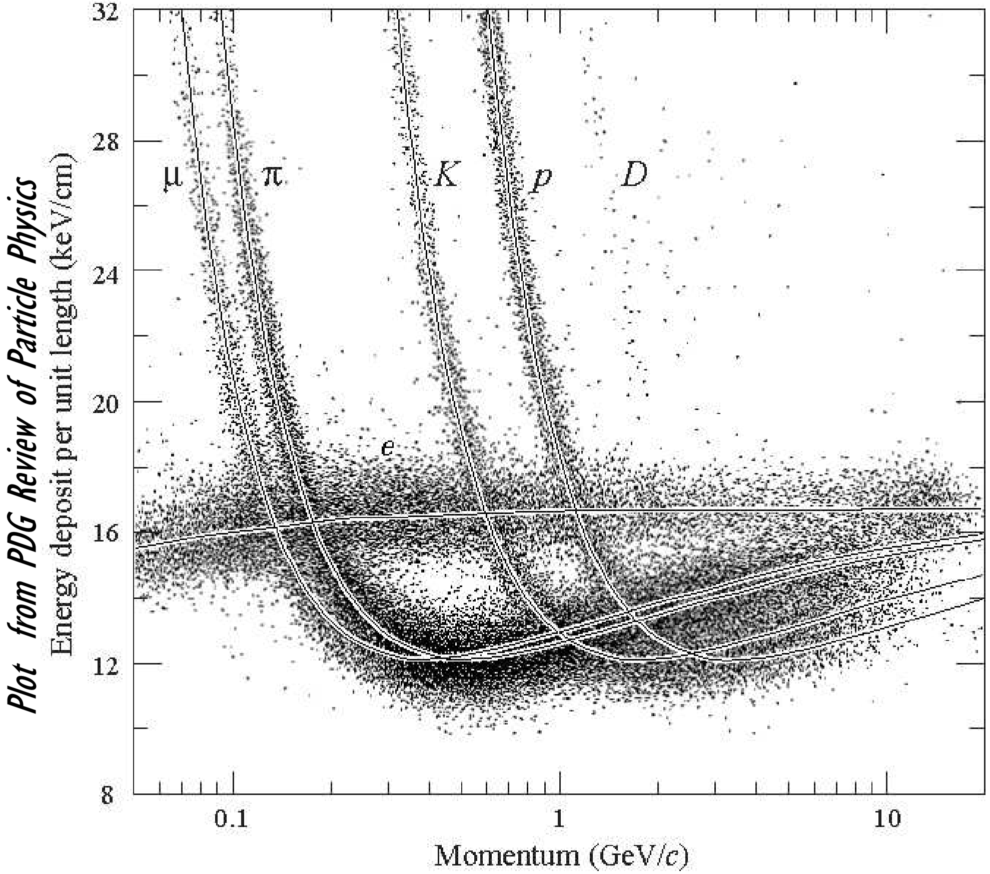
For a relativistic charged particle going through detector material:

1. Shape of energy loss curve is <u>independent</u> of material type & projectile particle ($\pi^{\pm}$,$K^{\pm}$,$p$..)

2. Function of *particle momentum*
   *Z/A of material*
   constants and corrections

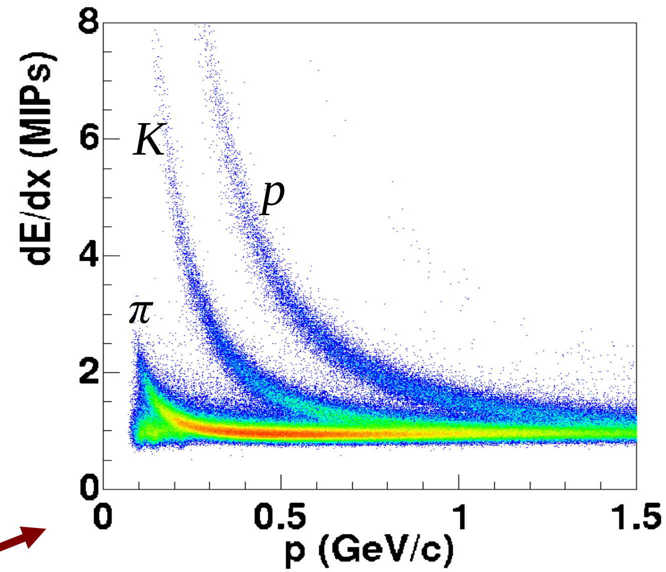


# Why is Bethe-Bloch so important?




Different particles have different dE/dx in same detector material (due to $\beta\gamma$ factor)

→Particle Identification!




*Plot from Pradeep Sarin, PhD thesis, 300 $\mu$m thin Silicon pixel detector.*

# What are the fundamental particles we study?

| | | |
|---|---|---|
| $p$ | $P_{11}$ | **** |
| $n$ | $P_{11}$ | **** |
| $N(1440)$ | $P_{11}$ | **** |
| $N(1520)$ | $D_{13}$ | **** |
| $N(1535)$ | $S_{11}$ | **** |
| $N(1650)$ | $S_{11}$ | **** |
| $N(1675)$ | $D_{15}$ | **** |
| $N(1680)$ | $F_{15}$ | **** |
| $N(1700)$ | $D_{13}$ | *** |
| $N(1710)$ | $P_{11}$ | *** |
| $N(1720)$ | $P_{13}$ | **** |
| $N(1900)$ | $P_{13}$ | ** |
| $N(1990)$ | $F_{17}$ | ** |
| $N(2000)$ | $F_{15}$ | ** |
| $N(2080)$ | $D_{13}$ | ** |
| $N(2090)$ | $S_{11}$ | * |
| $N(2100)$ | $P_{11}$ | * |
| $N(2190)$ | $G_{17}$ | **** |
| $N(2200)$ | $D_{15}$ | ** |
| $N(2220)$ | $H_{19}$ | **** |
| $N(2250)$ | $G_{19}$ | **** |
| $N(2600)$ | $I_{1,11}$ | *** |
| $N(2700)$ | $K_{1,13}$ | ** |

| | | |
|---|---|---|
| $\Delta(1232)$ | $P_{33}$ | **** |
| $\Delta(1600)$ | $P_{33}$ | *** |
| $\Delta(1620)$ | $S_{31}$ | **** |
| $\Delta(1700)$ | $D_{33}$ | **** |
| $\Delta(1750)$ | $P_{31}$ | * |
| $\Delta(1900)$ | $S_{31}$ | ** |
| $\Delta(1905)$ | $F_{35}$ | **** |
| $\Delta(1910)$ | $P_{31}$ | **** |
| $\Delta(1920)$ | $P_{33}$ | *** |
| $\Delta(1930)$ | $D_{35}$ | *** |
| $\Delta(1940)$ | $D_{33}$ | * |
| $\Delta(1950)$ | $F_{37}$ | **** |
| $\Delta(2000)$ | $F_{35}$ | ** |
| $\Delta(2150)$ | $S_{31}$ | * |
| $\Delta(2200)$ | $G_{37}$ | * |
| $\Delta(2300)$ | $H_{39}$ | ** |
| $\Delta(2350)$ | $D_{35}$ | * |
| $\Delta(2390)$ | $F_{37}$ | * |
| $\Delta(2400)$ | $G_{39}$ | ** |
| $\Delta(2420)$ | $H_{3,11}$ | **** |
| $\Delta(2750)$ | $I_{3,13}$ | ** |
| $\Delta(2950)$ | $K_{3,15}$ | ** |
| | | |
| $\Lambda$ | $P_{01}$ | **** |
| $\Lambda(1405)$ | $S_{01}$ | **** |
| $\Lambda(1520)$ | $D_{03}$ | **** |
| $\Lambda(1600)$ | $P_{01}$ | *** |
| $\Lambda(1670)$ | $S_{01}$ | **** |
| $\Lambda(1690)$ | $D_{03}$ | **** |
| $\Lambda(1800)$ | $S_{01}$ | *** |
| $\Lambda(1810)$ | $P_{01}$ | *** |
| $\Lambda(1820)$ | $F_{05}$ | **** |
| $\Lambda(1830)$ | $D_{05}$ | **** |
| $\Lambda(1890)$ | $P_{03}$ | **** |
| $\Lambda(2000)$ | | * |
| $\Lambda(2020)$ | $F_{07}$ | * |
| $\Lambda(2100)$ | $G_{07}$ | **** |
| $\Lambda(2110)$ | $F_{05}$ | *** |

| | | |
|---|---|---|
| $\Sigma^+$ | $P_{11}$ | **** |
| $\Sigma^0$ | $P_{11}$ | **** |
| $\Sigma^-$ | $P_{11}$ | **** |
| $\Sigma(1385)$ | $P_{13}$ | **** |
| $\Sigma(1480)$ | | * |
| $\Sigma(1560)$ | | ** |
| $\Sigma(1580)$ | $D_{13}$ | * |
| $\Sigma(1620)$ | $S_{11}$ | ** |
| $\Sigma(1660)$ | $P_{11}$ | *** |
| $\Sigma(1670)$ | $D_{13}$ | **** |
| $\Sigma(1690)$ | | ** |
| $\Sigma(1750)$ | $S_{11}$ | *** |
| $\Sigma(1770)$ | $P_{11}$ | * |
| $\Sigma(1775)$ | $D_{15}$ | **** |
| $\Sigma(1840)$ | $P_{13}$ | * |
| $\Sigma(1880)$ | $P_{11}$ | ** |
| $\Sigma(1915)$ | $F_{15}$ | **** |
| $\Sigma(1940)$ | $D_{13}$ | *** |
| $\Sigma(2000)$ | $S_{11}$ | * |
| $\Sigma(2030)$ | $F_{17}$ | **** |
| $\Sigma(2070)$ | $F_{15}$ | * |
| $\Sigma(2080)$ | $P_{13}$ | ** |
| $\Sigma(2100)$ | $G_{17}$ | * |
| $\Sigma(2250)$ | | *** |
| $\Sigma(2455)$ | | ** |
| $\Sigma(2620)$ | | ** |
| $\Sigma(3000)$ | | * |
| $\Sigma(3170)$ | | * |

| | | |
|---|---|---|
| $\Xi^0$ | $P_{11}$ | **** |
| $\Xi^-$ | $P_{11}$ | **** |
| $\Xi(1530)$ | $P_{13}$ | **** |
| $\Xi(1620)$ | | * |
| $\Xi(1690)$ | | *** |
| $\Xi(1820)$ | $D_{13}$ | *** |
| $\Xi(1950)$ | | *** |
| $\Xi(2030)$ | | *** |
| $\Xi(2120)$ | | * |
| $\Xi(2250)$ | | ** |
| $\Xi(2370)$ | | ** |
| $\Xi(2500)$ | | * |
| | | |
| $\Omega^-$ | | **** |
| $\Omega(2250)^-$ | | *** |
| $\Omega(2380)^-$ | | ** |
| $\Omega(2470)^-$ | | ** |

| | |
|---|---|
| $\Lambda_c^+$ | **** |
| $\Lambda_c(2595)^+$ | *** |
| $\Lambda_c(2625)^+$ | *** |
| $\Lambda_c(2765)^+$ | * |
| $\Lambda_c(2880)^+$ | *** |
| $\Lambda_c(2940)^+$ | *** |
| $\Sigma_c(2455)$ | **** |
| $\Sigma_c(2520)$ | *** |
| $\Sigma_c(2800)$ | *** |
| $\Xi_c^+$ | *** |
| $\Xi_c^0$ | *** |
| $\Xi_c'^+$ | *** |
| $\Xi_c'^0$ | *** |
| $\Xi_c(2645)$ | *** |
| $\Xi_c(2790)$ | *** |
| $\Xi_c(2815)$ | *** |
| $\Xi_c(2930)$ | * |
| $\Xi_c(2980)$ | *** |
| $\Xi_c(3055)$ | ** |
| $\Xi_c(3080)$ | *** |
| $\Xi_c(3123)$ | * |
| $\Omega_c^0$ | *** |
| $\Omega_c(2770)^0$ | *** |
| | |
| $\Xi_{cc}^+$ | * |
| | |
| $\Lambda_b^0$ | *** |
| $\Sigma_b$ | *** |
| $\Sigma_b^*$ | *** |
| $\Xi_b^0$, $\Xi_b^-$ | *** |
| $\Omega_b^-$ | *** |

*Particle Data Book lists ~ 200 known "stable" fundamental particles "Particle Zoo"*

# Most of those particles don't travel far

## Distance a particle travels (and can be detected be before it decays) <u>depends on it's energy.</u>

## Example 1: $\mu \rightarrow e^- + \overline{\nu_e} + \nu_\mu$ lifetime $\tau = 2.2 \times 10^{-6}$ s

- *Cosmic ray μ 's produced by cosmic rays colliding with p,He, Li in upper atmosphere: altitude ~ 10 km.*
- *In it's rest frame $\tau \sim 2.2 \cdot 10^{-6}$ s. At speed ~ c expect μ to travel ~ cτ ~ 660 m before decaying to $e^-$. $m_\mu c^2$=105 MeV*
- ***<u>But</u>*** *$E_\mu$~2 GeV so it has a Lorentz boost of $E_\mu = \gamma\,(m_\mu c^2)$ so γ~ 20 gives mean range of μ before decay s = cγτ ~ 12 km*

## Example 2:

*π has shorter lifetime $2.6 \cdot 10^{-8}$ s $\rho_0$ lifetime $\sim 6 \cdot 10^{-24}$ s*

# Reducing the Zoo membership in a $p+p$ collider @ 7 TeV

1. From the ~ 200 fundamental particles listed by the PDG, only **<u>27</u>** have a $c\gamma\tau > \sim 1\mu m$ so they can be seen as 'tracks' in a detector.

2. **<u>13</u>** of these have a $c\gamma\tau < 500\ \mu m$, *i.e. very short tracks* that must be measured indirectly with high precision vertex detectors.

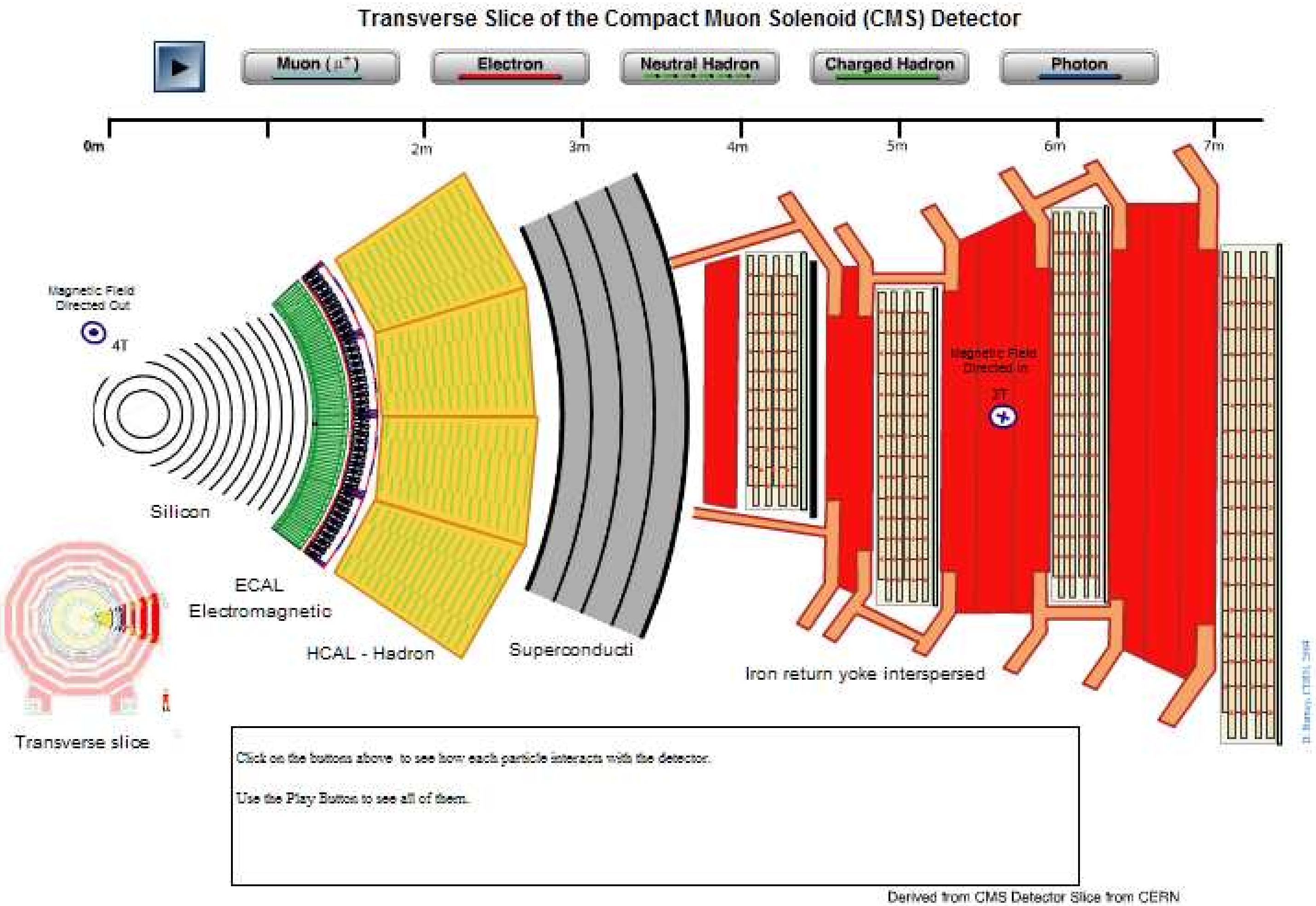
3. Of the **<u>14</u>** remaining particles only **<u>8</u>** typically have energies high enough to have $c\gamma\tau >$ *few tens of meters* to make it all the way through most detectors:

$$e^{\pm}, \mu^{\pm}, \gamma^{0}, \pi^{\pm}, K^{\pm}, K^{0}, p^{\pm}, n$$

*<u>These are the common 'bread and butter' of particle physics.</u>*

# Particle detection at work

## A slice through the CMS detector



# What are the measurements we make?

- Energy ***E***

  through energy deposition and/or calorimetry

- Momentum ***p***

  make charged particles bend in a magnetic field

- $(E^2 - p^2) = m^2$ uniquely identifies particles

- Can also measure spin, polarization in specialized experiments.

# Summary

In this lecture we have looked at:

- Why we do high energy Particle & Nuclear physics
- What are the common fundamental particles we deal with
- Principle of particle detection through energy loss