Chapter 1 Introduction

Purpose: **provide a brief introduction to:**

1. The Standard Model
2. An overview of the fundamental particles
3. The relationship between the particles and the forces
4. The interactions of particles in matter

Fundamental Particles:

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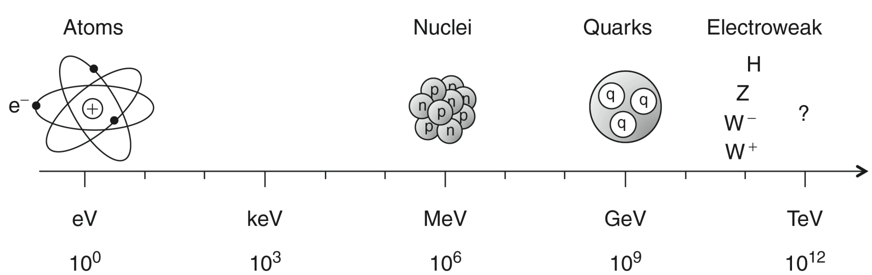

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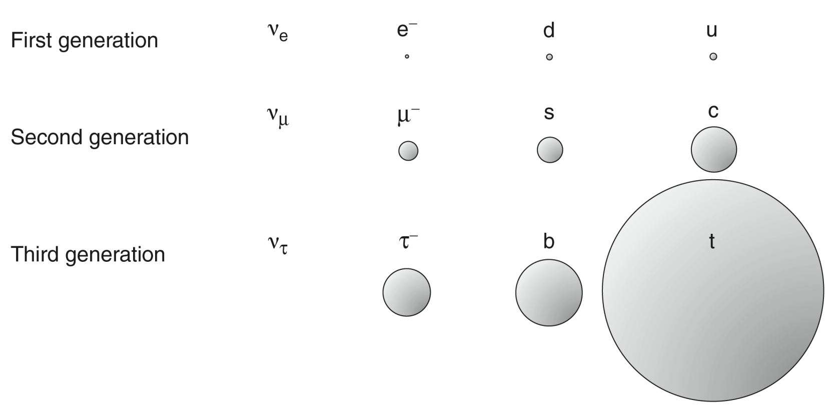
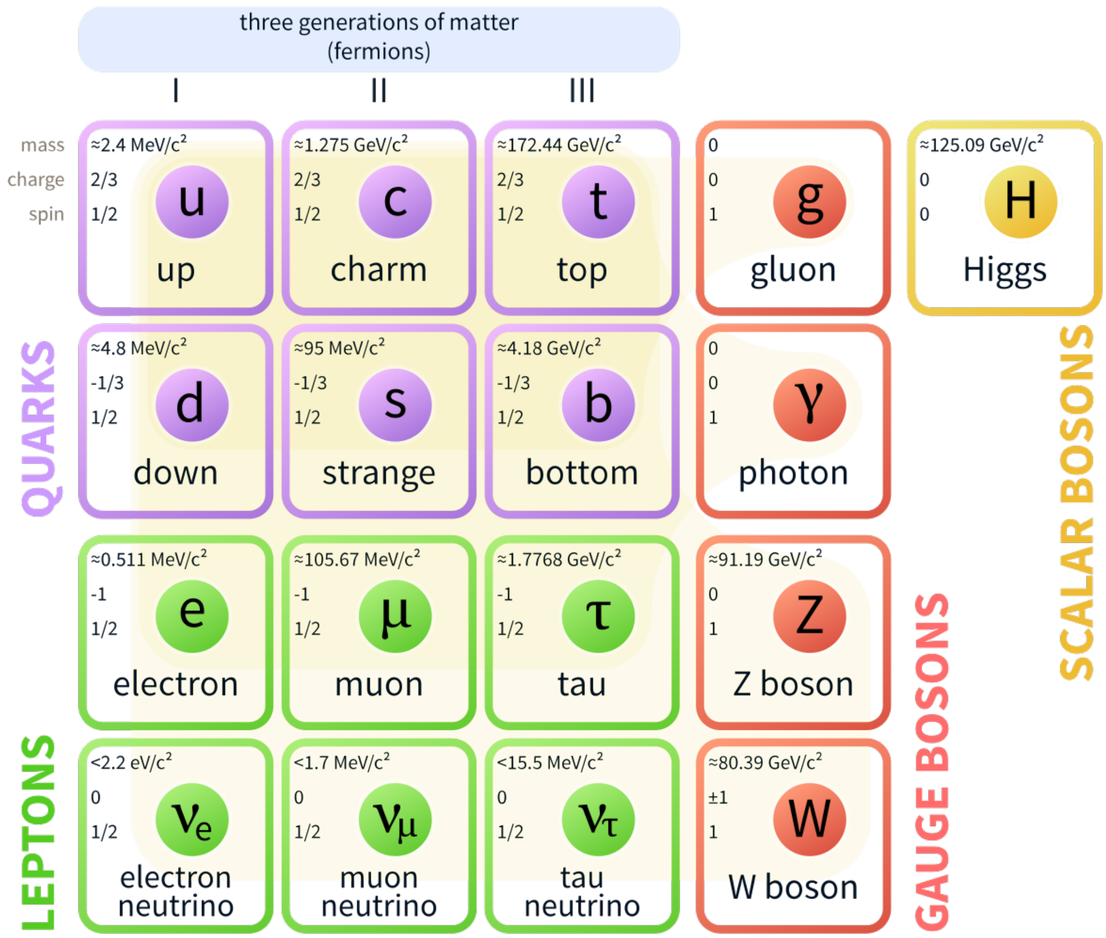


Standard Model of Elementary Particles



The Forces experienced by different particles

			Strong	E.M.	Weak
Quarks	down-type up-type	d, s, b u, c, t	Yes	Yes	Yes
Leptons	charged	e^-, μ^-, τ^-	No	Yes	Yes
	neutrinos	ν_e, ν_μ, ν_τ	No	No	Yes

The Fundamental Forces:

In modern particle physics, each force is described by a Quantum Field Theory (QFT).

QED	Quantum Electrodynamics	the photon γ
QCD	Quantum Chromodynamics	the gluon g
EW	Electroweak Interactions	$\gamma,\ W^{+},\ W^{-},\ Z^{0}$

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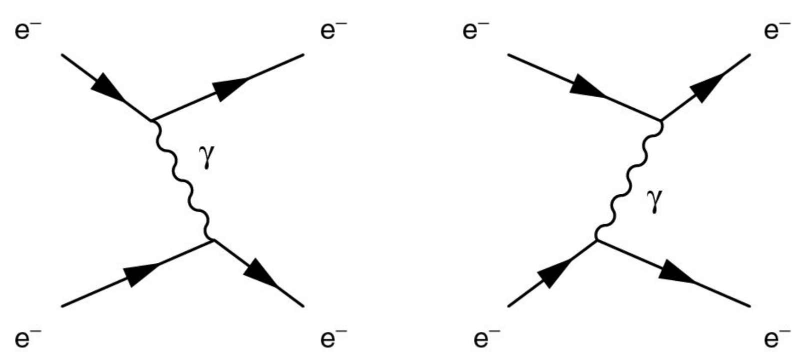

In QFT, each of the three forces correspond to the exchange of a spin-1 force-carrying particle, known as a *gauge boson*.

Four Forces at a distance of 1 fm (roughly the size of a proton)

Force	**particle**	**relative strength**	**Mass (GeV/c^2)**
Electromagnetic	Photon γ	1/137	0
Gravitational	Graviton G	10^{-37}	0
Weak nuclear	$W^{\pm}$, Z^{o}	10^{-8}	80.4, 90.2
Strong nuclear	Gluon g	1	0

The Standard Model Interaction vertices

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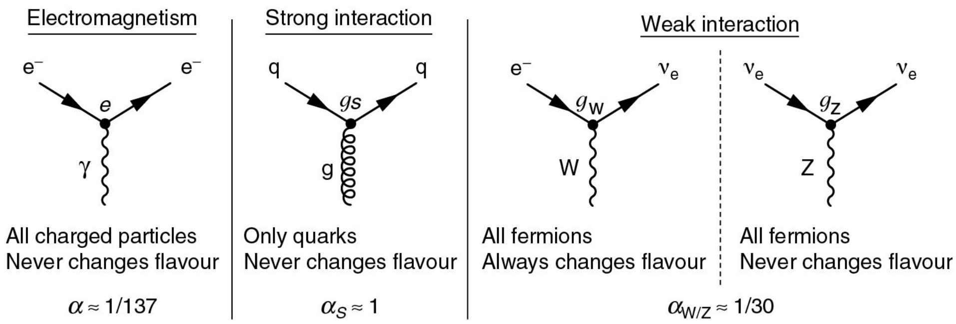


The nature of the forces is determined by the properties of the bosons of the associated QFT and the way in which the gauge bosons couple to the spin-half fermions.

For each type of interaction there is an associated coupling strength. For QED the coupling strength is simply the electron charge, $g_{QED} = e \equiv +|e|$

A particle couples to a force-carrying boson only if it carries the charge of the interaction.

- Only electrically-charged particles couple to the photon
- Only color-charged particles couple to the gluon.

The $W^{\pm}$ (weak charged-current) only couples together pairs of fundamental fermions that differ by one unit of electric charge, $\pm e$. The weak interaction couples a charged lepton with its corresponding neutrino.

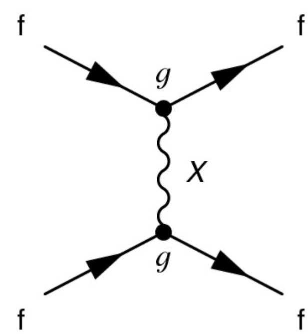
$$\binom{\nu_e}{e^-}, \quad \binom{\nu_\mu}{\mu^-}, \quad \binom{\nu_\tau}{\tau^-}$$

Likewise, for quarks, the weak charged-current ($W^{\pm}$) couples quark combinations that differ by one unit of electric charge, ±*e*.

$$\binom{u}{d}, \binom{u}{s}, \binom{u}{b}, \binom{c}{d}, \binom{c}{s}, \binom{c}{b}, \binom{t}{d}, \binom{t}{s}, \binom{t}{b}$$

The strength of the weak charged-current coupling between up-type quarks $\left(+\frac{2}{3}e\right)$ and down-type quarks $\left(-\frac{1}{3}e\right)$ is greatest for quarks of the same generation. Weak charged-current interactions (W±) are particularly important when considering particle decays that change flavor.

The scattering of two fermions (*f*) by the exchange boson (*X*) is shown in the figure below. The strength of the fundamental interaction at each of the two three-point vertices (*ffX*) is denoted by the coupling constant *g*.



The strength of the fundamental interaction between the gauge boson and a fermion is determined by the coupling constant *g*.

The quantum mechanical transition matrix element ($\mathcal{M}$) for an interaction process includes a factor of the coupling constant *g* for each interaction vertex.

$$\mathcal{M} \propto g^2$$

In the above figure, the interaction probability is proportional to the matrix element squared $|\mathcal{M}|^2 \propto g^4$. In QED, the quantum-mechanical probability of the interaction includes a single factor of α for each interaction vertex, so, $\alpha \propto e^2$, and $|M|^2 \propto \alpha^2$ where:

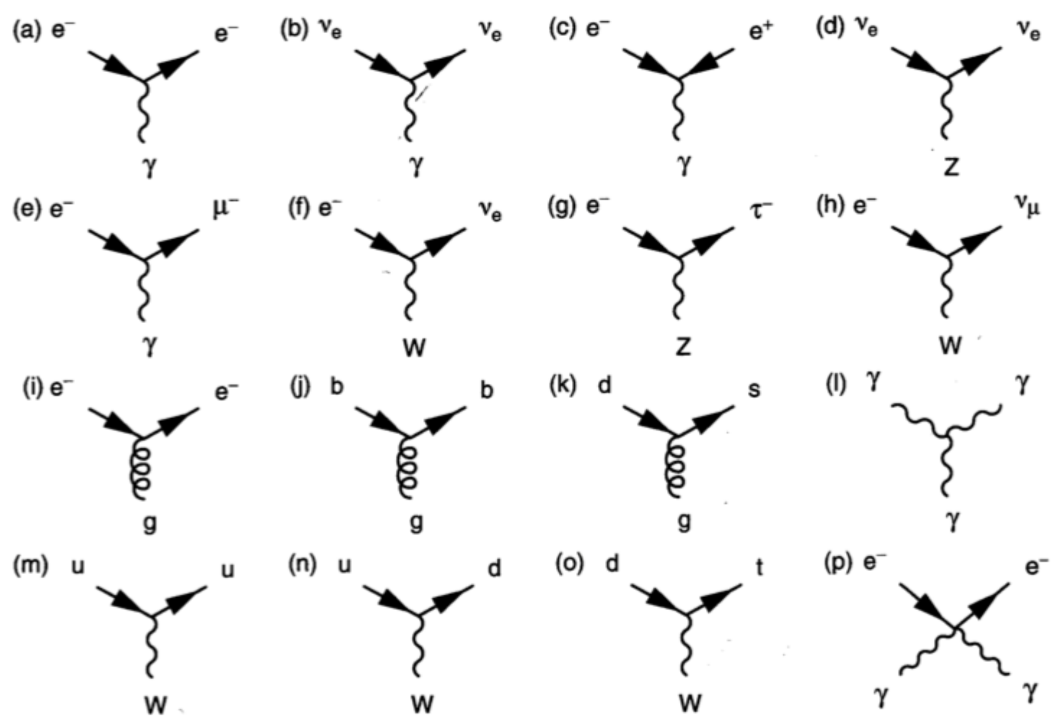
$$\alpha = \frac{e^2}{4\,\pi\epsilon_o\,\hbar c} = \frac{1}{137}$$

Strong	$\alpha_s \sim 1$
Electromagnetic	$\alpha = \frac{1}{137}$
Weak	$\alpha_W \sim \frac{1}{30}$

The intrinsic strength of the weak interaction is greater than that of QED; however, the large mass of the W boson means that at relatively low-energy scales, the weak interaction is very much weaker than QED.

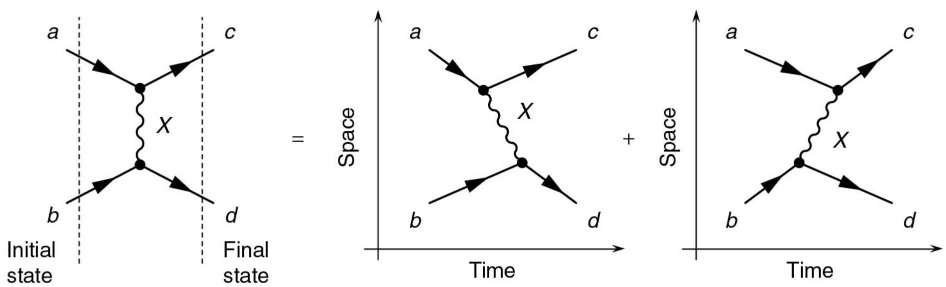
Homework 1-1

1.1 Feynman diagrams are constructed out of the Standard Model vertices shown in Figure 1.4. Only the weak charged-current ($W^{\pm}$) interaction can change the flavour of the particle at the interaction vertex. Explaining your reasoning, state whether each of the sixteen diagrams below represents a valid Standard Model vertex.

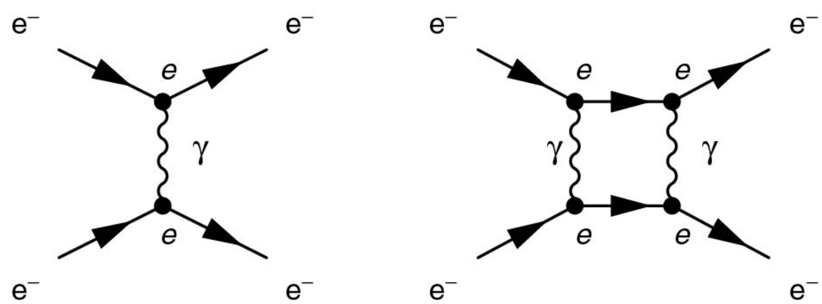


The Standard Model Interaction Vertices

The Feynman diagram for the scattering process $a + b \rightarrow c + d$

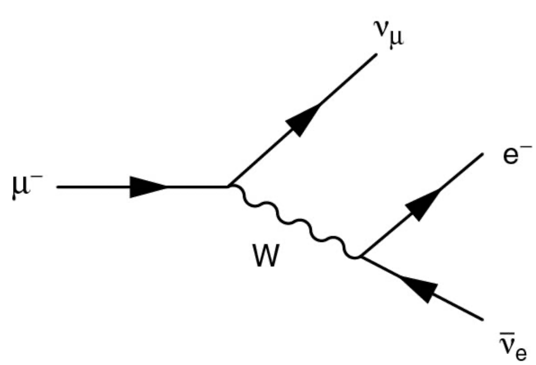


This shows two possible Feynman diagrams for an electron scattering “off of” another electron.

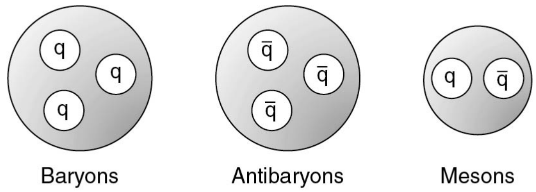


Particle Decays

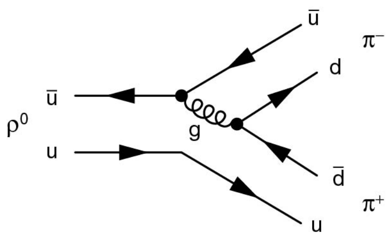
The Feynman diagram for muon decay.



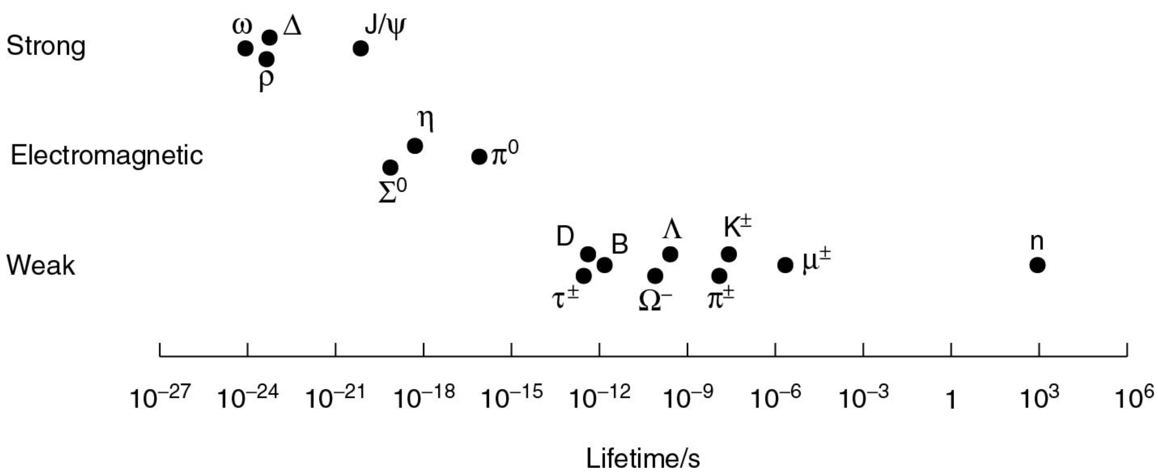
Three types of hadronic states.   (Strong Interactions)



Decay of the ρ^0



The Lifetimes of a common hadronic states grouped by the type of decay. The τ and the μ lepton are shown as examples of the weak decay.



Interactions of particles with matter

Experiments are designed to detect and identify the particles produced in high-energy collisions.

The discovery of the top quark

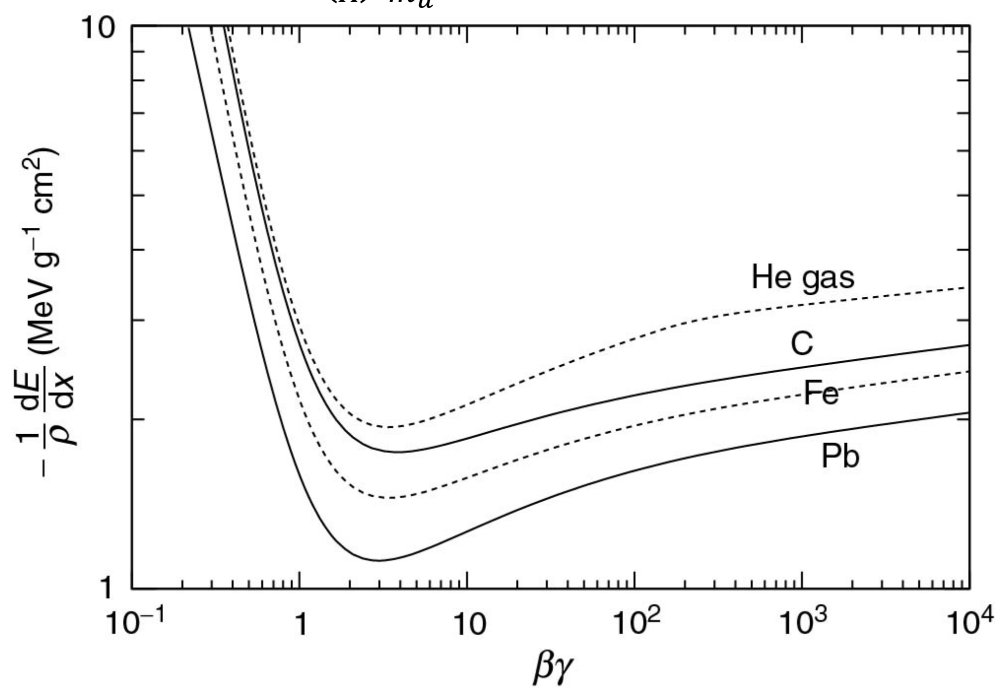
http://www-physics.lbl.gov/~spieler/physics_198_notes_1999/PDF/I-2-d-vertex.pdf

Interactions and detection of charged particles ("heavy" particles with z=# of charges on each of the beam particles).

The Bethe-Bloch equation (Wikipedia):

$$-\langle\frac{dE}{dx}\rangle = \frac{4\,\pi n z^2}{m_e c^2\,\beta^2}\left(\frac{e^2}{4\,\pi\epsilon_o}\right)^2\left\{\ell n\left[\frac{2\,\beta^2 m_e c^2}{I_e(1-\beta^2)}\right]-\beta^2\right\}$$

$$n = N_A\left(\frac{Z}{A}\right)\frac{\rho}{m_u} \qquad m_u \approx 1.00000000\; gm/mol$$



The units for $\frac{1}{\rho}\frac{dE}{dx}$ are $\left(\frac{MeV}{gm/cm^2}\right)$ sometimes called the "stopping power"

The mean excitation energy $I_e \sim 10\,Z\ \ eV$
other sources $I_e = 16\,Z^{0.9}\ \ eV$

Fig. 2.1 Energy loss by ionization for protons in silicon, based on the data available at http://www.nist.gov/pml/data/star/

Source: R. Poggiani, *High Energy Astrophysical Techniques*. © Springer International

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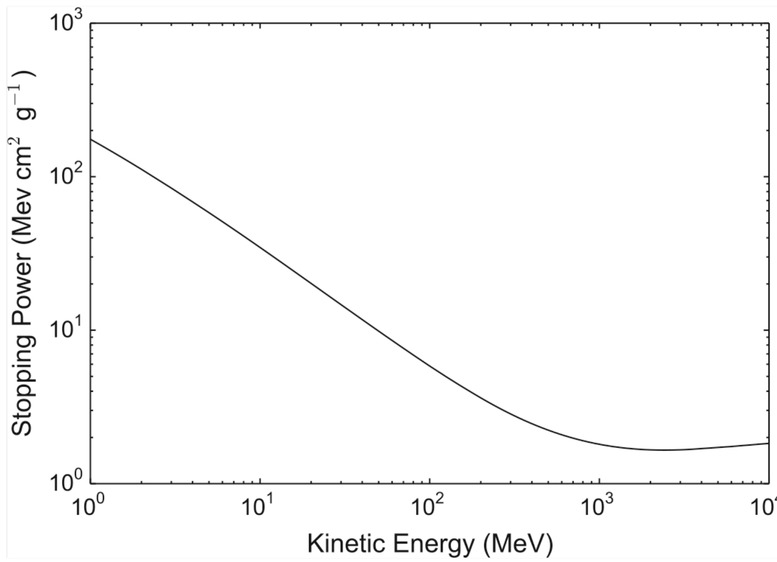


Minimum Ionizing

Minimum ionizing occurs at $\beta\gamma \sim 3$.

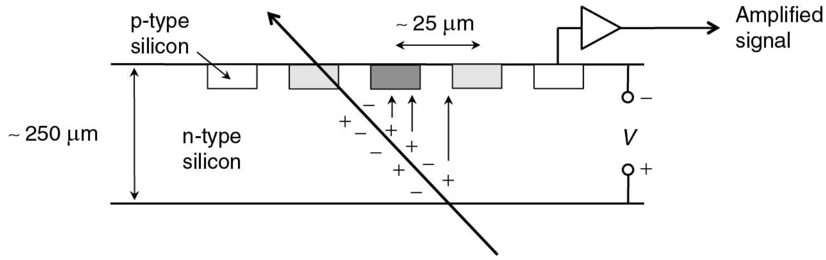
$$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)_{min} \sim 2\ MeV\ g^{-1}cm^2$$

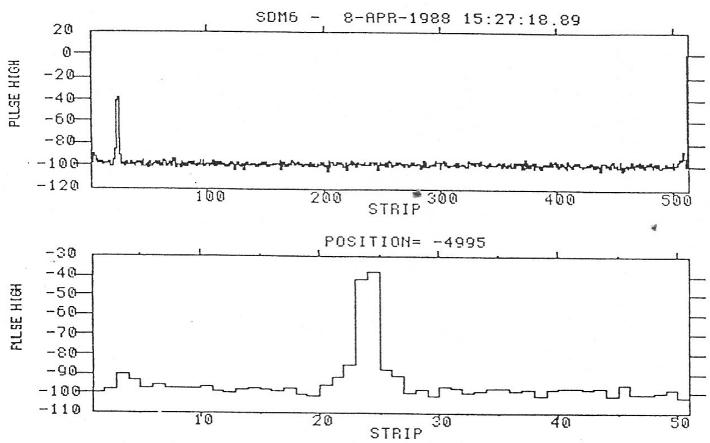
The stopping power of plastic scintillator ($\rho \sim 1\ g/cm^3$) with respect to a minimum-ionizing particle (e.g., high energy cosmic rays) is $\sim 2\ MeV/cm$.

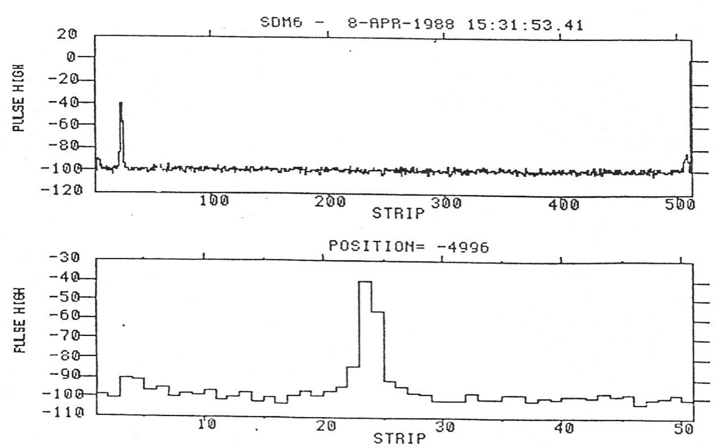
Silicon Vertex Detectors

Early work by me using Silicon Strip detectors:

CERN—North Area π^+, p (positively charged particles ~ 1 GeV) April, 1988



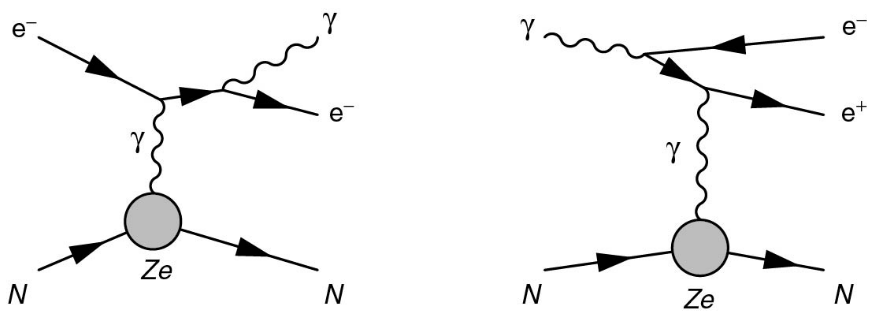




Detection of electrons and photons

Electrons

- At low energies, energy loss of electrons is dominated by ionization.
- Above a “critical energy” E_c, the main energy loss is due to bremsstrahlung
$$E_c \sim \frac{800}{Z}\ MeV$$
- The rate of bremsstrahlung is inversely proportional to the square of the mass. For example: muon bremsstrahlung is suppressed by $\left(\frac{m_e}{m_\mu}\right)^2$
- Muon energy loss is predominantly through ionization until $E_\mu > 100\ GeV$. Then bremsstrahlung “kicks in.”



The bremsstrahlung and e⁺e⁻ pair-production processes. *N* is a nucleus of charge *+Ze*. Yes, . . . they mislabeled the e⁻ e⁺ particles in the second figure. Switch $e^+ \leftrightarrow e^-$

Radiation Length

- The e.m. interactions of “high energy” electrons and photons in matter are characterized by the *radiation length* X_0.
- The radiation length is the average distance over which the energy of an electron is reduced due to bremsstrahlung by a factor of $1/e$.

$$X_o \approx \frac{1}{4\alpha n\, Z^2 r_e^2\, \ell n\left(287/Z^{1/2}\right)} \quad \text{(for electrons--Bremsstrahlung)}$$

n = # of nuclei / cm^2 $\quad r_e = 2.8\ \times 10^{-15}$ m (classical radius of the e$^-$)

- X_o for $\gamma \rightarrow e^+e^-$ is $\sim 7/9\ X_o^{electron}$

Photons

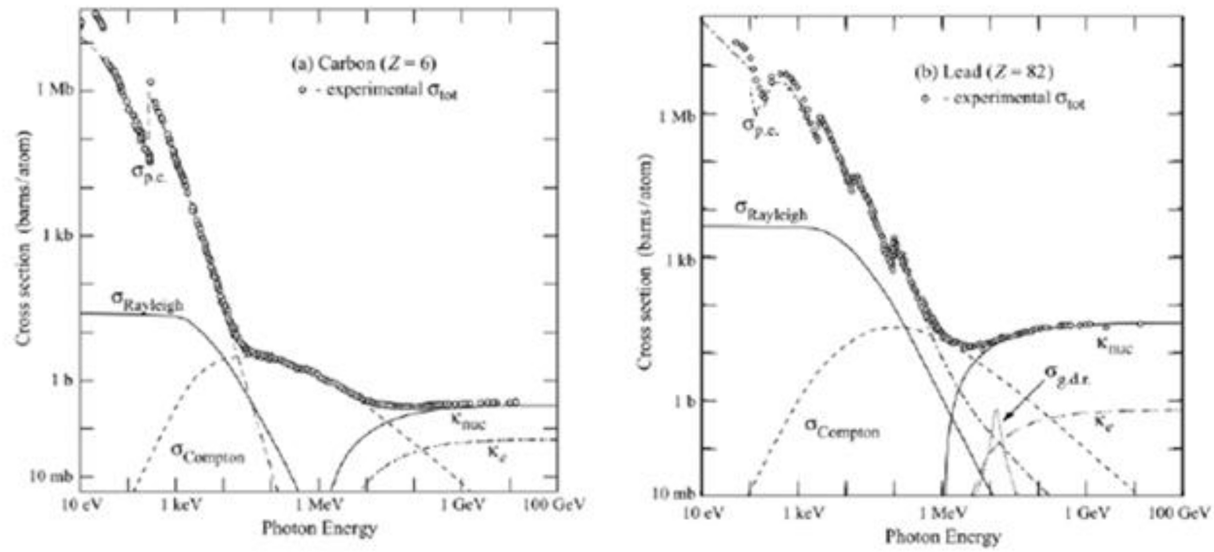
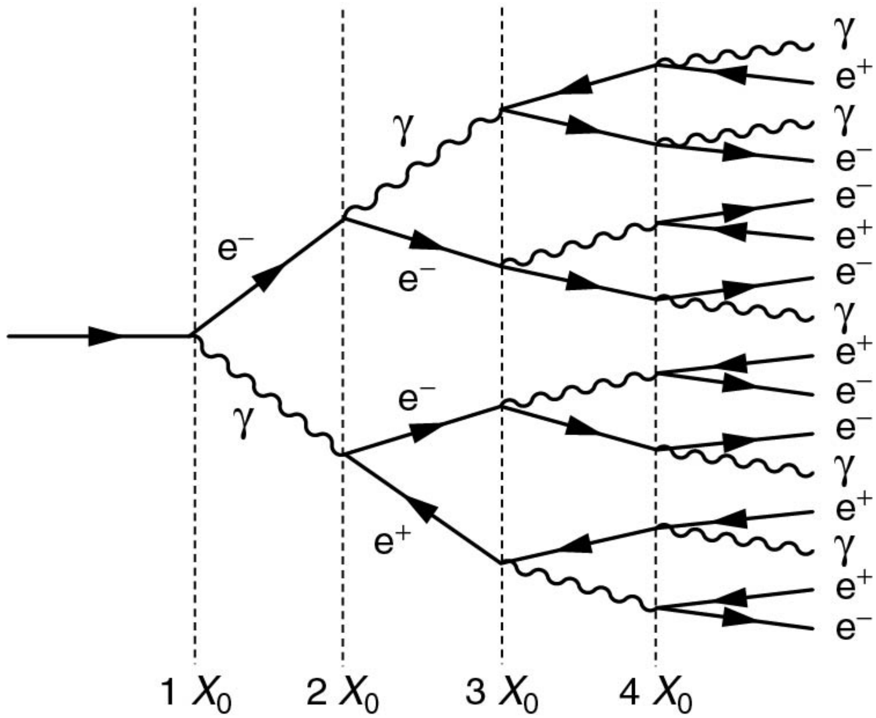


Figure 1 Cross sections of photons in Carbon (a) and Lead (b) in barns/atom; 1barn=10^{-24} cm^2. (source: CERN)

- Low energy photons (<1 MeV) lose energy primarily through the photoelectric effect.
- Medium energy photons (~1 MeV) lose energy primarily through Compton scattering.
- High energy photons (>10 MeV) lose energy primarily through pair-production.

Electromagnetic Showers

When high-energy electrons interact in a medium, they radiate a bremsstrahlung photon, which in turn produces an e^+e^- pair.



The development of an electromagnetic shower where the number of particles roughly double after each radiation length.

- The average energy of particles of *x* radiation lengths: $\langle E \rangle = \frac{E}{2^x}$

- Afterwards, the shower continues to develop until the average energy of the particles falls below the critical energy E_c.

- At energies < E_c, the *electrons* and *positrons* lose their energy primarily through ionization.

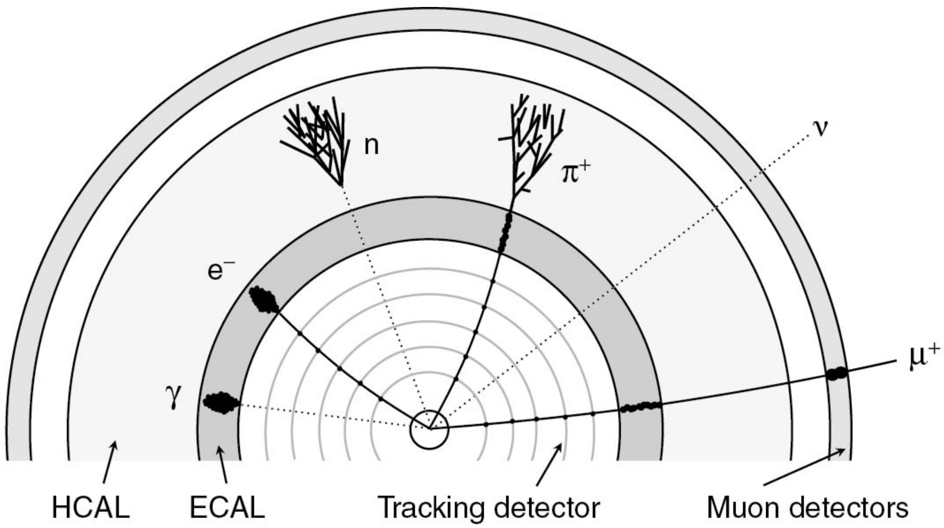
- The maximum number of particles in the shower occurs at x_{max} radiation lengths. Where $\langle E \rangle \approx E_c$

$$x_{max} = \frac{\ell n(E/E_c)}{\ell n\, 2}$$

Electromagnetic Calorimeters

Hadronic Calorimeters

Collider Experiments



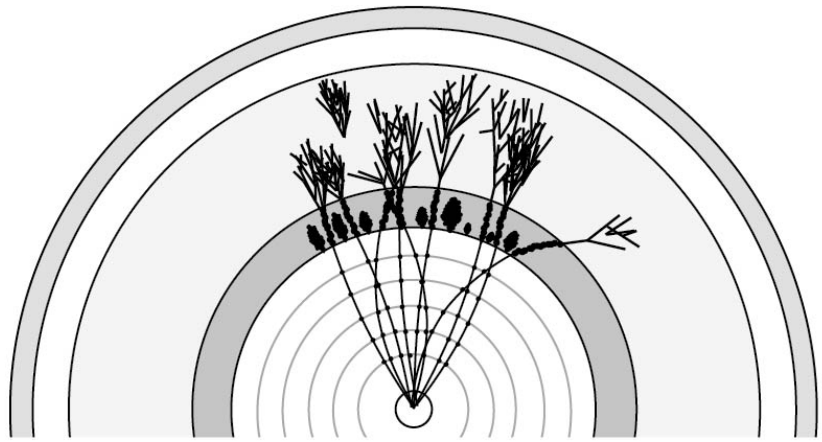
The typical layout of a large particle physics detector.

- The only charged particle to make its way through the em calorimeter (ECAL) and the hadronic calorimeter (HCAL) is the high-energy muon ($\mu^{\pm}$).
- The energy due to high energy γ-rays and electrons (including positrons) is completely absorbed in the em calorimeter (ECAL).
- The energy due high energy hadrons (particles composed of quarks and/or antiquarks) (i.e., mesons ($q\bar{q}$) and baryons (qqq or $\bar{q}\bar{q}\bar{q}$)) is complete absorbed in the hadronic calorimeter (HCAL).

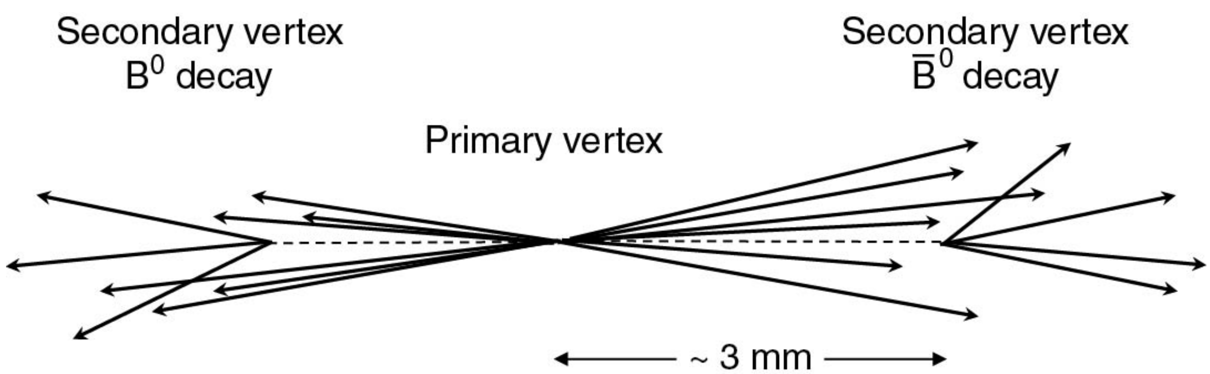
Detection of Quarks

The appearance of a jet

A single quark emerges and hadronizes into visible particles leaving tracks in the silicon detectors and depositing energy in the calorimeters (ECAL and HCAL).

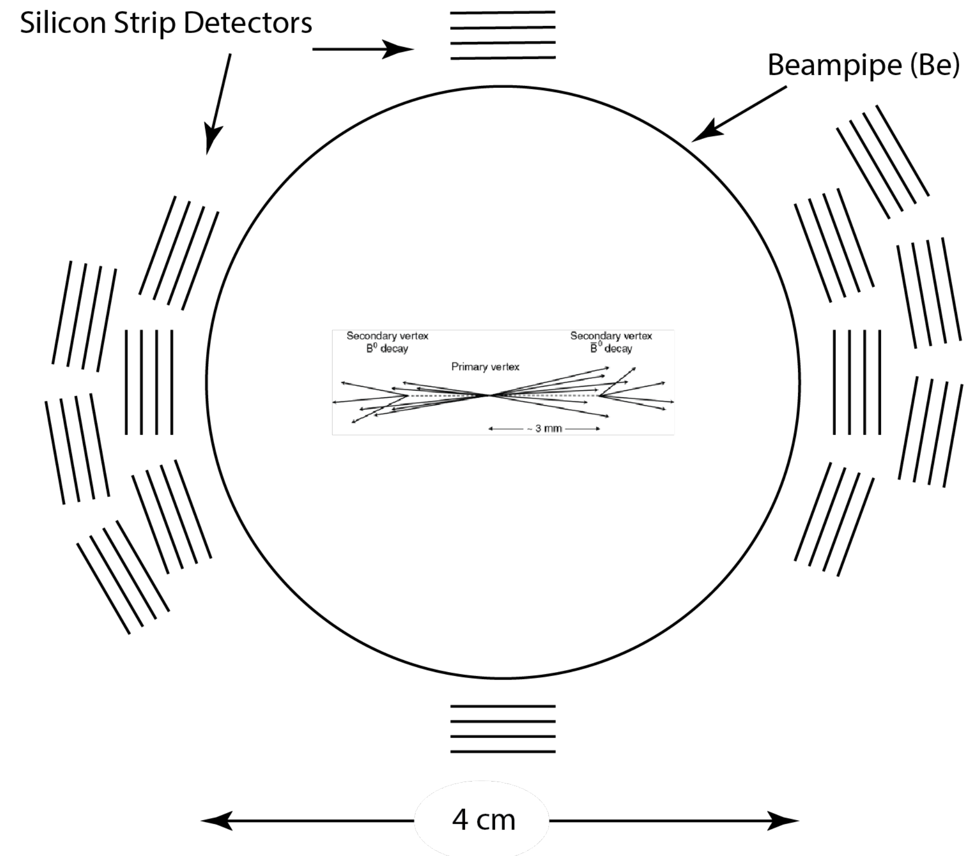


Appearance of a b-quark in an $e^+e^- \to Z^o \to b\overline{b}$ event.



We don't observe "free" quarks, in this case b or $\bar{b}$ quarks. We observe the B^0 $(b\bar{d})$ and $\bar{B}^0$ $(\bar{b}d)$ mesons instead, and their decay products. The B^0 and $\bar{B}^0$ mesons are neutral so they are not detected in charge-particle detectors such as silicon strip detectors. The bath of the B mesons are shown as dashed (undetected) lines in the figure above. However, their decay products are easily reconstructed using the silicon detectors.

N.B. As you can see from the scale up above, all these tracks occur inside a 4-cm diameter vacuum beampipe. However, the silicon strips reconstructing these displaced vertices are outside the beampipe.



Measurements at particle accelerators

Center-of-mass energy $\sqrt{s}$

The cm-energy squared is the sum of the initial 4-vectors squared.

$$s = \left(\sum_{i=1}^{2} E_i\right)^2 - \left(\sum_{i=1}^{2} \vec{p}_i\right)^2$$

Fixed Target vs. Collider

Fixed Target	7.0 TeV proton and proton “at rest.”	$\sqrt{s}$ = 115 GeV
Collider	7.0 TeV proton and 7.0 TeV proton	$\sqrt{s}$ = 14.0 TeV

The Instantaneous Luminosity $\boldsymbol{\mathcal{L}(t)}$

The instantaneous luminosity describes the number of particles/area/sec at the point where the beams collide. It can be calculated using the following equation:

$$\mathcal{L} = f \frac{n_1 n_2}{4\,\pi\,\sigma_x \sigma_y}$$

Where n_1 and n_2 are the number of particles in the two colliding bunches, σ_x and σ_y are the standard deviations of the beams (assuming a Gaussian profile) in the plane transverse to the beam direction, and *f* is the collision frequency (40 MHz for the LHC).

If a process with a known cross section (σ_{ref}) is observed in the same experiment, and N_{ref} of these events are observed, then the cross section for the "interesting events" (σ) can be calculated using the following:

$$\sigma = \sigma_{ref}\,\frac{N}{N_{ref}}$$

Integrated Luminosity $L = \int \mathcal{L}(t)\,dt$ [fb^{-1}] *inverse femtobarns* (e.g., $100\,fb^{-1}$).

The integrated luminosity is defined as the instantaneous luminosity integrated over the "live time" of the experiment. If the cross section for scattering *or* production of new particles (i.e., particles of interest) is predicted to be σ*, let's say 2.0 fb*, then the number of events you would expect to "observe" during the course of the experiment would be:

$$N = \sigma\,\int \mathcal{L}(t) dt = \text{ 200 events}$$