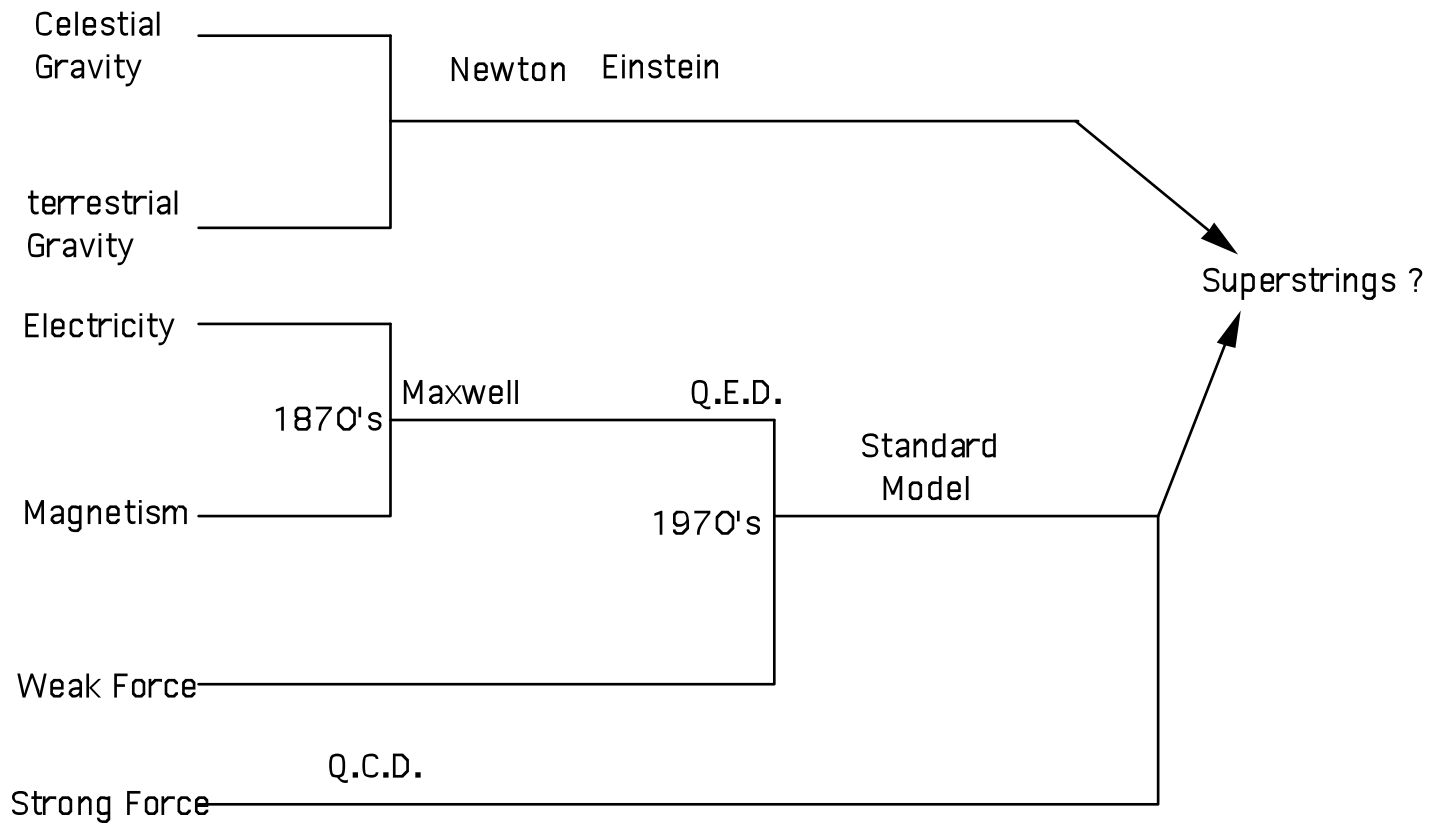


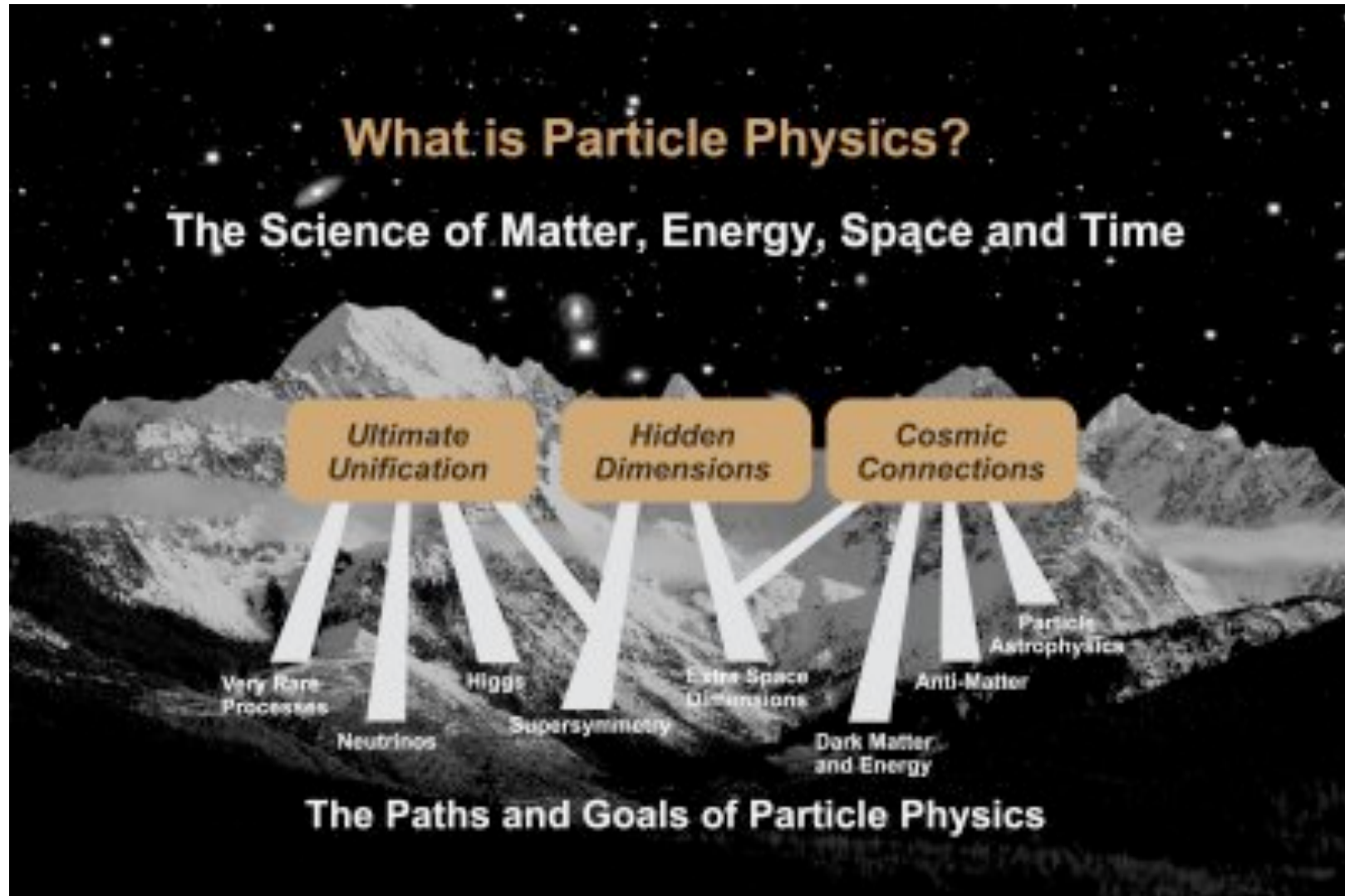
Introduction

Read:
Ch 1 of M&S

- What questions does this field address?
 - ★ Want to know the basic law of nature.
 - ★ Can we unify all the forces with one equation or one theory?



Particle Physics



Reference: Fermilab

Questions:

- Why are all elementary particles either quarks or leptons?
 - ★ Maybe lepto-quarks?
- Why do particles have such a wide range of masses?
 - ★ neutrino: almost massless
 - ★ electron: $0.511 \text{ MeV}/c^2 \sim m_p/2000$
 - ★ proton: $938 \text{ MeV}/c^2$
 - ★ Z^0 : $91,188 \text{ MeV}/c^2 \sim 90 m_p$
 - ★ top quark: $174,000 \text{ MeV}/c^2 \sim 170 m_p$
 - ★ Does the Higgs mechanism determine the mass patterns?
- Why is the electric charge of the proton identical to that of the electron?
 - ★ electron is a lepton
 - ★ proton is made up of 3 quarks
- How many generations of quarks and leptons are there?
 - ★ Quarks and leptons can be grouped into “doublets”
 - For every quark doublet there is a lepton doublet.
- Do quarks and/or leptons have structure like atoms or protons?
- What is the origin of CP violation?
 - ★ Particles and antiparticles are not symmetric in nature!
 - ★ How does CP violation fit in the Standard Model?

$$\begin{aligned} 1 \text{ MeV} &= 10^6 \text{ eV} \\ 1 \text{ GeV} &= 10^9 \text{ eV} \\ 1 \text{ TeV} &= 10^{12} \text{ eV} \end{aligned}$$

$$\begin{pmatrix} q = \frac{2}{3} \\ q = -\frac{1}{3} \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} q = -1 \\ q = 0 \end{pmatrix} \begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

History 1870's-1919

1873 Maxwell's theory of E&M describes the propagation of light waves in a vacuum.

1874 George Stoney develops a theory of the electron and estimates its mass.

1895 **Röntgen** discovers x rays.

Nobel Prize
winners in red

1898 Marie and Pierre **Curie** separate radioactive elements.

Thompson measures the electron, and puts forth his “plum pudding” model of the atom
-- the atom is a slightly positive sphere with small, raisin-like negative electrons inside.

1900 **Planck** suggests that radiation is quantized.

1905 **Einstein** proposes a quantum of light (the photon) which behaves like a particle. Einstein's other theories explained the equivalence of mass and energy, the particle-wave duality of photons, the equivalence principle, and special relativity.

1909 Geiger and Marsden, under the supervision of Rutherford, scatter alpha particles off a gold foil and observe large angles of scattering, suggesting that atoms have a small, dense, positively charged nucleus.

1911 **Rutherford** infers the nucleus as the result of the alpha-scattering experiment performed by Geiger and Marsden.

1913 **Bohr** constructs a theory of atomic structure based on quantum ideas.

1919 **Rutherford** finds the first evidence for a proton.

<http://particleadventure.org/other/history/index.html>

History 1920's

1921 **Chadwick** and Bieler conclude that some strong force holds the nucleus together.

1923 **Compton** discovers the quantum (particle) nature of x rays, thus confirming photons as particles.

1924 **de Broglie** proposes that matter has wave properties.

1925 **Pauli** formulates the exclusion principle for electrons in an atom.

Bothe and Geiger demonstrate that energy and mass are conserved in atomic processes.

1926 **Schroedinger** develops wave mechanics, which describes the behavior of quantum systems for bosons.

Born gives a probability interpretation of quantum mechanics.

G.N. Lewis proposes the name "photon" for a light quantum.

1927 Certain materials had been observed to emit electrons (beta decay). Since both the atom and the nucleus have discrete energy levels, it is hard to see how electrons produced in transition could have a continuous spectrum (see 1930 for an answer).

1927 **Heisenberg** formulates the uncertainty principle.

1928 **Dirac** combines quantum mechanics and special relativity to describe the electron.

History 1930's

- 1930 There are just three fundamental particles: protons, electrons, and photons. Born, after learning of the Dirac equation, said, “Physics as we know it will be over in six months.”
- 1930 **Pauli** suggests the neutrino to explain the continuous electron spectrum for β decay.
- 1931 **Dirac** realizes that the positively-charged particles required by his equation are new objects (he calls them “positrons”). This is the first example of antiparticles.
- 1931 **Chadwick** discovers the neutron. Nuclear binding and decay become primary problems.
- 1933 **Anderson** discovers the positron.
- 1934 **Fermi** puts forth a theory of β decay that introduces the weak interaction. This is the first theory to explicitly use neutrinos and particle flavor changes.
- 1935 **Yukawa** combines relativity and quantum theory to describe nuclear interactions by an exchange of new particles (mesons called “pions”) between protons and neutrons. From the size of the nucleus, **Yukawa** concludes that the mass of the conjectured particles (mesons) is about 200 electron masses. Beginning of the meson theory of nuclear forces.
- 1937 A particle of 200 electron masses is discovered in cosmic rays. While at first physicists thought it was **Yukawa's** pion, it was later discovered to be the muon.
- 1938 Stuckelberg observes that protons and neutrons do not decay into electrons, neutrinos, muons, or their antiparticles. The stability of the proton cannot be explained in terms of energy or charge conservation; he proposes that heavy particles are independently conserved.

History 1940's

- 1941 Moller and Pais introduce the term “nucleon” as a generic term for protons and neutrons.
- 1946-47 Physicists realize that the cosmic ray particle thought to be **Yukawa's** meson is instead a “muon,” the first particle of the second generation of matter particles to be found. This discovery was completely unexpected -- **Rabi** comments “who ordered that?” The term “lepton” is introduced to describe objects that do not interact too strongly (electrons and muons are both leptons).
- 1947 A meson that interact strongly is found in cosmic rays, and is determined to be the pion.
- 1947 Physicists develop procedures to calculate electromagnetic properties of electrons, positrons, and photons. Introduction of Feynman diagrams.
- 1948 The Berkeley synchro-cyclotron produces the first artificial pions.
- 1949 **Fermi** and **Yang** suggest that a pion is a composite structure of a nucleon and an anti-nucleon. This idea of composite particles is quite radical.
- 1949 Discovery of K^+ via its decay.
-- Era of “Strange” Particles

History 1950's

- 1950 The neutral pion (π^0) is discovered.
- 1951 “V”-particles are discovered in cosmic rays. The particles were named the Λ^0 and the K^0 .
- 1952 Discovery of particle called delta: there were four similar particles (Δ^{++} , Δ^+ , Δ^0 , and Δ^-).
- 1952 **Glaser** invents the bubble chamber (looking at beer). The Brookhaven Cosmotron, a 1.3 GeV accelerator, starts operation.
- 1953 The beginning of a “particle explosion” -- a proliferation of particles.
- 1956 Scattering of electrons off nuclei reveals a charge density distribution inside protons, and even neutrons. Description of this electromagnetic structure of protons and neutron suggests some kind of internal structure to these objects, though they are still regarded as fundamental particles.
- 1954 **Yang** and Mills develop a new class of theories called “gauge theories.” Although not realized at the time, this type of theory now forms the basis of the Standard Model.
- 1955 **Chamberlain** and **Segre** discover the antiproton.
- 1957 **Schwinger** writes a paper proposing unification of weak and electromagnetic interactions.
- 1957-59 **Schwinger**, Bludman, and **Glashow**, in separate papers, suggest that all weak interactions are mediated by charged heavy bosons, later called W^+ and W^- . Note: **Yukawa** first discussed boson exchange 20 years earlier, but he proposed the pion as the mediator of the weak force.

History 1960's

- 1961 As the number of known particles keep increasing, a mathematical classification scheme to organize the particles (the group $SU(3)$) helps physicists recognize patterns of particle types.
- 1962 Experiments verify that there are two distinct types of neutrinos (e and μ neutrinos). Also inferred from theoretical considerations (Lederman, Schwartz, Steinberger).
- 1964 Gell-Mann and Zweig tentatively put forth the idea of quarks.
Glashow and Bjorken coin the term “charm” (c) for the fourth quark.
Observation of CP violation in Kaon decay by Cronin and Fitch.
- 1965 Greenberg, Han, and Nambu introduce the quark property of color charge (another DOF).
Greenberg, PRL 13, 598 (1964), M. Han and Y. Nambu, Phys. Rev. 139B, 1006 (1965)
- 1967 Weinberg and Salam separately propose a theory that unifies electromagnetic and weak interactions into the electroweak interaction. Their theory requires the existence of a neutral, weakly interacting boson Z^0 .
- 1968-9 Bjorken and Feynman analyze electron scattering data collected at SLAC in terms of a model of constituent particles inside the proton. They use the word “parton” not quark.

By mid-1960's > 50 “elementary” particles! -- periodic table
3 quarks introduced to “explain” the periodic table.
BUT quarks were not considered to be “real” particles.

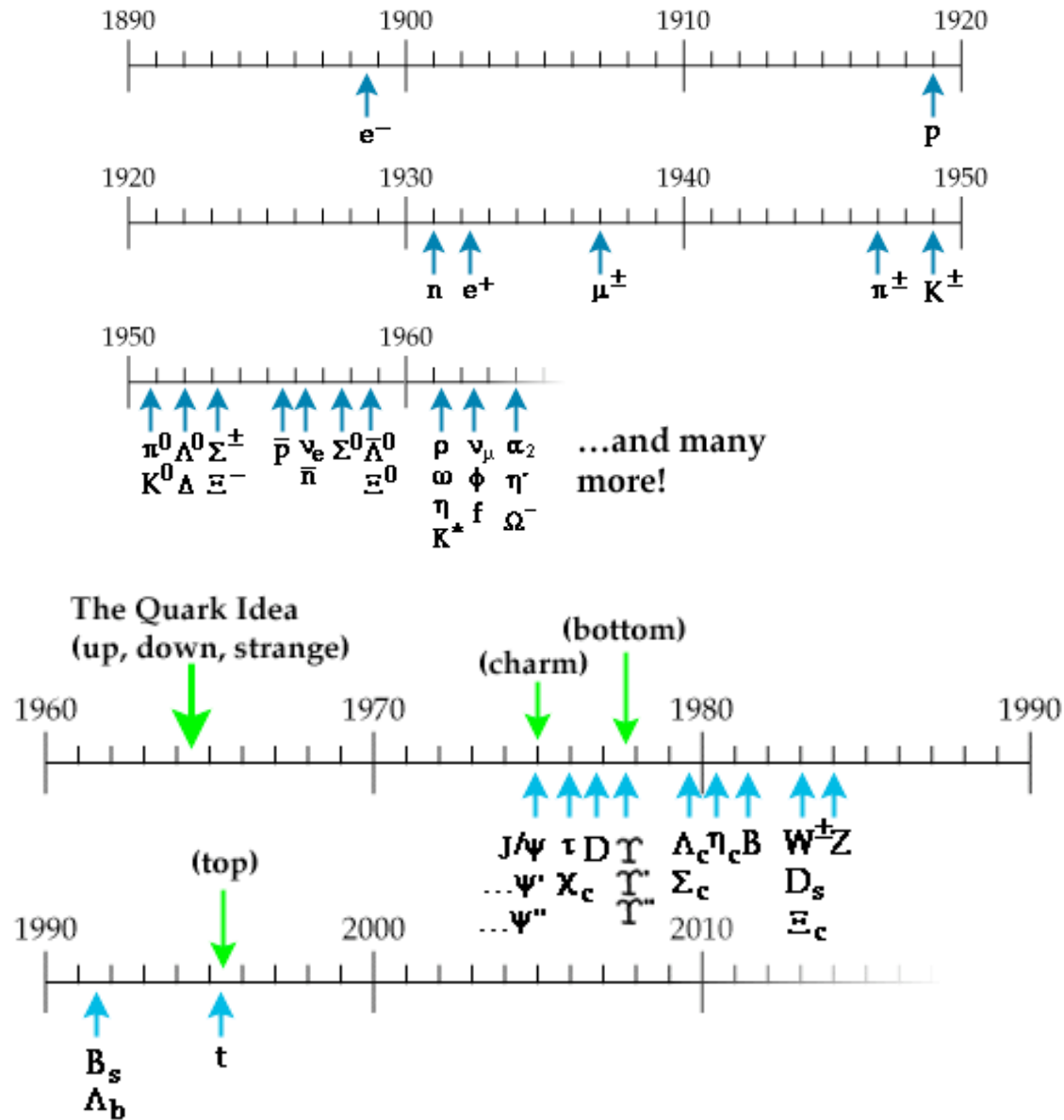
History 1970's

- 1970 **Glashow**, Iliopoulos, and Maiani (GIM) recognize the critical importance of a fourth type of quark in the context of the Standard Model.
- 1973 First indications of weak interactions with no charge exchange (due to Z^0 exchange.)
A quantum field theory of strong interaction is formulated (QCD)
Politzer, **Gross**, and **Wilczek** discover that the color theory of the strong interaction has a special property, now called “asymptotic freedom.”
- 1974 **Richter** and **Ting**, leading independent experiments, announce on the same day that they discovered the same new particle J/Ψ , bound state of charm anti-charm.
- 1976 Goldhaber and Pierre find the D^0 meson (anti-up and charm quarks).
- 1976 The tau lepton is discovered by **Perl** and collaborators at SLAC. Since this lepton is the first recorded particle of the third generation, it is completely unexpected.
- 1977 **Lederman** and collaborators at Fermilab discover the b-quark.
- 1978 Prescott and **Taylor** observe Z^0 mediated weak interaction in the scattering of polarized electrons from deuterium which shows a violation of parity conservation, as predicted by the Standard Model, confirming the theory's prediction.
- 1979 Evidence for a gluon radiated by the initial quark or antiquark at PETRA, DESY, Germany.

History 1980's-Now

- 1983 Discovery of the W^\pm and Z^0 at the CERN synchrotron using techniques developed by Rubbia and Van der Meer to collide protons and antiprotons.
- 1989 Measurement of the width (line shape) of Z^0 at SLAC and CERN strongly suggest that there are three and only three generations of fundamental particles.
- 1995 Discovery of the top quark at Fermilab by the CDF and D0 experiments.
- 1998 Observation of neutrino oscillations by SuperK collaboration. Neutrinos have mass!
- 2000-1 Observation of CP violation in B -mesons by BABAR, BELLE experiments.
- 2002 Solar Neutrino problem “solved”.

Time line of particle discoveries



Where are We Today?

- All elementary particles are made up of quarks or leptons.
 - ◆ both are spin $\frac{1}{2}$ fermions
- Carriers of the forces are bosons.
 - ◆ spin 1: gluon, photon, W , Z
 - ◆ spin 2: graviton

Interaction	Carrier	Mass	Strength	Range	Source
Strong	gluons	0	1	< fm	“color”
E.M.	γ	0	1/137	∞	electric charge
Weak	W/Z	80-90 GeV	10^{-13}	10^{-18} m	weak charge
Gravity	Graviton	0	10^{-38}	∞	mass

- Quarks and leptons appear to be fundamental.
 - ◆ no evidence for “sub quarks” or “sub leptons”
- The particle zoo can be classified into hadrons and leptons.
 - ◆ hadrons feel the strong, weak, EM, and gravity
 - hadrons can be classified into mesons and baryons
 - ★ meson: quark-anti quark bound state (e.g. K , π)
 - ★ baryon: 3 quark bound state (e.g. proton, neutron)
 - ◆ leptons feel the weak, EM, and gravity
 - electron, muon (μ), tau (τ), neutrinos

Why do We Need *High* Energy?

- To see an object the wavelength of light (λ) must be comparable or smaller in size than that of the object.

- ☞ To view a small object you need a small wavelength.

- ◆ How SMALL a wavelength do we need ?

- ◆ de Broglie relationship:

$$\lambda = h/p$$

$$h = \text{Planck's constant} = 6.63 \times 10^{-34} \text{ J-s} = 4.14 \times 10^{-24} \text{ GeV-s}$$

p = momentum of object

- What momentum do we need to “see” a nucleus?

- ◆ Assume size of nucleus $\sim 1 \text{ fm} = 10^{-15} \text{ m}$

$$p = h/\lambda$$

$$= (4.14 \times 10^{-24} \text{ GeV-s}) / (10^{-15} \text{ m})$$

$$= 4.14 \times 10^{-9} \text{ GeV-s/m}$$

$$= 1.2 \text{ GeV/c (c = speed of light)}$$

- ☞ need an electron with energy of $\sim 1 \text{ GeV}$!

- ☞ need a big battery!

Units for High Energy Physics

M&S p.22

- The most convenient energy unit for HEP is electron volts not Joules.
 - ◆ Typical nuclear binding energies are MeV (10^6 eV).
 - ◆ The most convenient mass unit for HEP is MeV/c² not kg:
 - mass of electron = $0.511 \text{ MeV}/c^2 = 9.1 \times 10^{-31} \text{ kg}$
 - mass of proton = $938 \text{ MeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$
 - ◆ The most convenient system of units for HEP are NATURAL Units:
Planck's constant $\hbar = h/2\pi = 1$, speed of light = 1, Energy in eV (or MeV)
 - ◆ Easy to write equations
 - Relativistic relationship between energy, momentum and mass:
$$E^2 = (pc)^2 + (mc^2)^2$$
$$\rightarrow E^2 = p^2 + m^2$$

Conversion between MKS and Natural Unit

- Converting between systems is “easy”:

- ◆ MKS units:

$$Energy = M^1 L^2 T^{-2}$$

$$c = M^0 L^1 T^{-1}$$

$$\hbar = M^1 L^2 T^{-1}$$

- ◆ Example: cross section for the reaction $e^+ e^- \rightarrow \mu^+ \mu^-$

$$\sigma = \frac{A}{E^2}$$

where A is a constant.

- To put this formula back into MKS units, use the fact that a cross section has units L^2 :

$$\begin{aligned} L^2 &= \frac{\hbar^a c^b}{E^2} \\ &= \frac{(M^1 L^2 T^{-1})^a (M^0 L^1 T^{-1})^b}{(M^1 L^2 T^{-2})^2} \\ &= M^{a-2} L^{2a+b-4} T^{-a-b+4} \end{aligned}$$

$$\Rightarrow \begin{cases} a-2=0 \\ 2a+b-4=2 \\ -a-b+4=0 \end{cases}$$

$$a = b = 2$$

$$K.K. \text{ Gan} \quad \sigma = A \frac{\hbar^2 c^2}{E^2}$$