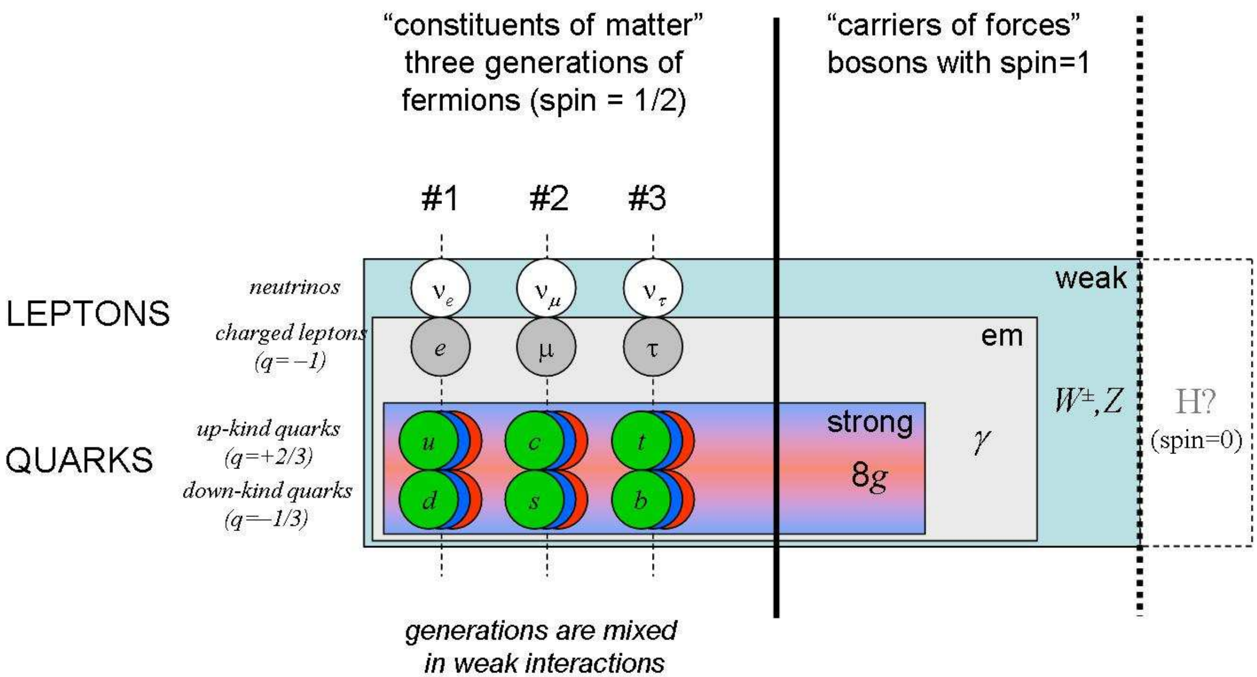
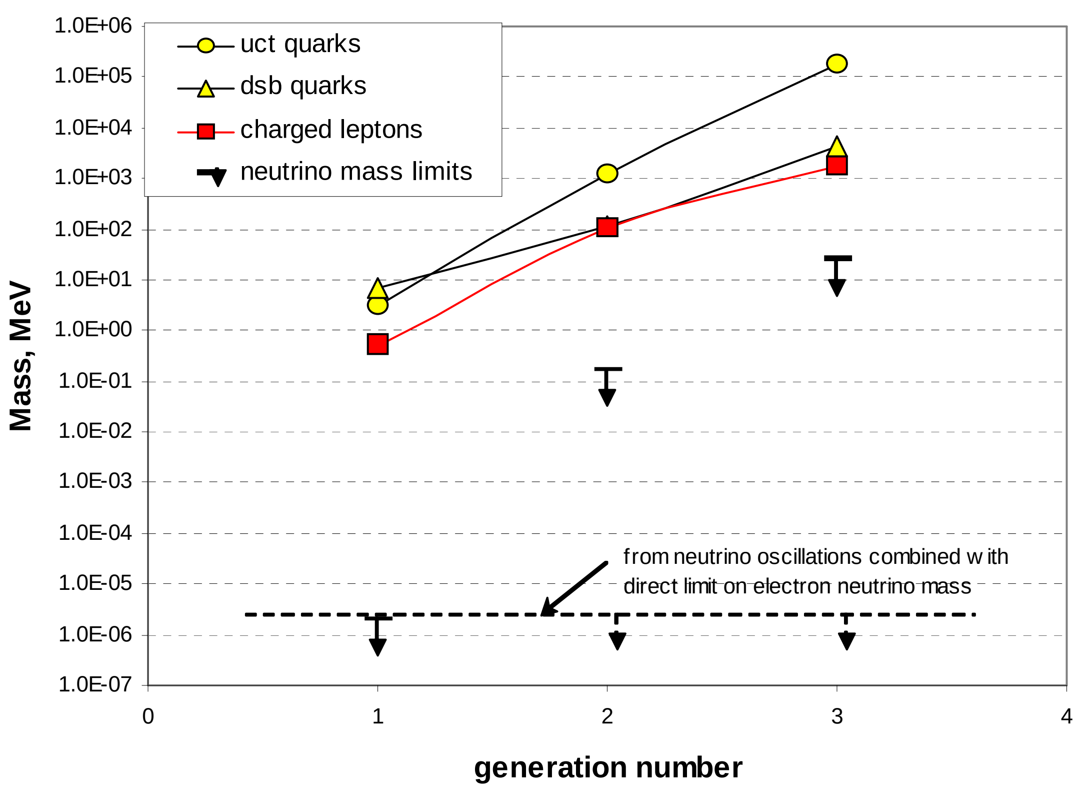
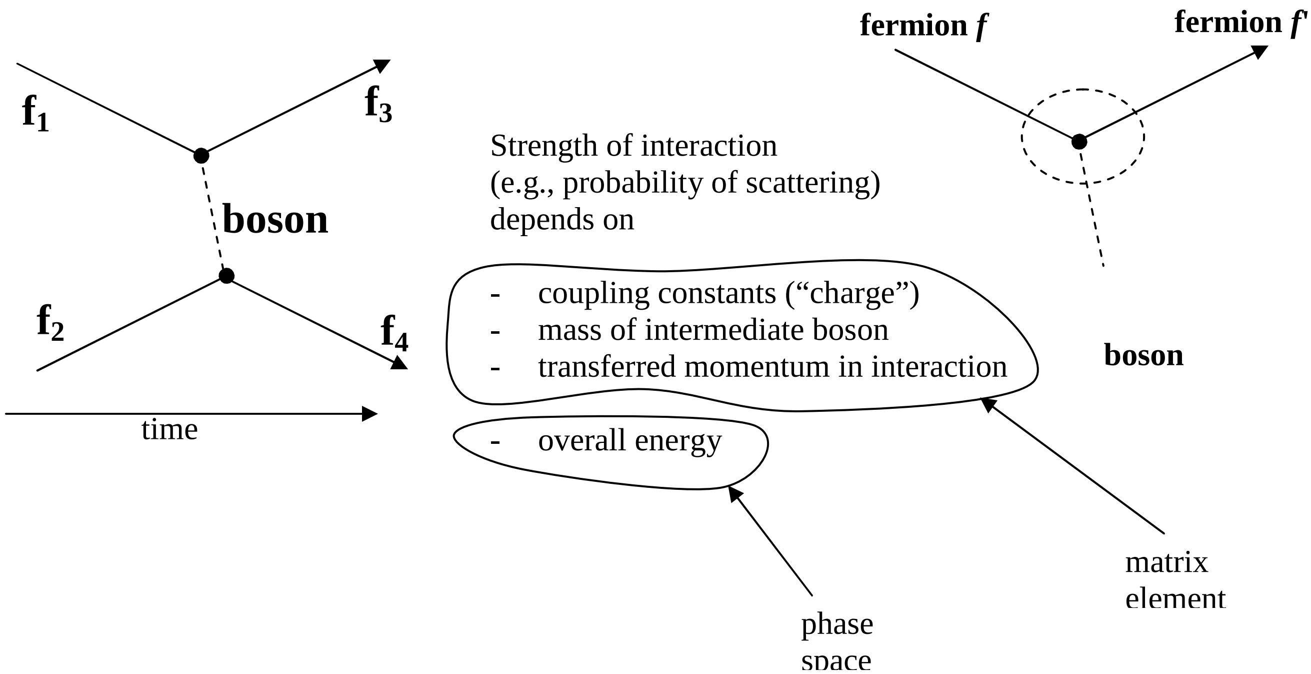
Periodic Table of Particles/Forces in the Standard Model



Three Generations of Fermions: Pattern of Masses



Interactions via exchange with particles
(Feynman diagrams)



Intermediate bosons	gluons	photons	Z/W	H
Relative strength of quarks interactions at transferred momenta of ~1 GeV	1	$\sim 10^{-2}$	$\sim 10^{-7}$	mass-dependent

Side Note: Boson Self-Coupling Vertices allowed in SM:

- **gluons:** ggg; gggg
- **γ, Z, W:** γWW, ZWW; γγWW, γZWW, ZZWW
- **H, Z, W:** HZZ, HWW, HHH; HHHH, ZZHH, WWHH

Particles and anti-particles: For each particle, there is anti-particle with the same mass/spin and opposite quantum numbers like charge (electric, color, etc.), magnetic moment, etc. For photon , Z, and H, an anti-particle is the same as a particle. Same can be true for neutrinos, but we do not yet know this…

In general, fermions—particles with half-integral spin: ½ , 3/2, …. Bosons—particles with integral spin: 0, 1, 2, … In quantum mechanics, they obey different statistics of indistinguishable particles: same-kind fermions may exist only in anti-symmetric states, bosons—otherwise. We will discuss it later.

Fermions, leptons and quarks with spin=½, are conventionally called matter. Three columns represent 3 nearly identical generations; the masses being the only difference between them. This three-generation structure allows for not yet understood phenomena of mixing.

Each generation consists of:

- two leptons (charged lepton and an associated neutrino) and
- three pairs of quarks (colored blocks representing quarks with three different color charges)
- all fermions have masses

All particles have their own names:

- electron neutrino and electron, up- and down-quarks;
- muon neutrino and muon, charm- and strange-quarks;
- tau neutrino and tau-lepton, top- and bottom-quarks (*bottom* is also known as *beauty*);

Quarks have three kinds of strong force "charges", which we call red, green, blue

Quarks form particles (**hadrons**), which must be color-neutral, or colorless

- 3 quarks of blue, green, red color
- quark-antiquark pairs in color-anticolor combinations (e.g., red-antired)
- Experimentally most important hadrons (long-lived hadrons): uud (proton), udd (neutron), $u\bar{d}$ (pion), $s\bar{d}$ (Kaon)

Bosons: There are 3 distinct kinds of bosons with spin=1 (mediators of forces):

- 8 gluons (spin=1) of different color-anticolor charges—responsible for the **<u>strong force</u>** (coupled to color charge, i.e. only quarks participate in interaction via exchange of gluons)
- 1 photon (spin=1)—responsible for **<u>electromagnetic force</u>** (coupled to electric charge, i.e. only charged particles participate in interaction via exchange of photons)
- Z- and $W^{\pm}$-bosons (spin=1)— responsible for **<u>weak force</u>** (coupled to weak hypercharge and weak isospin; all fermions participate in interaction via exchange of Z and W). Unlike gluons and photons, Z and W are massive particles (91 and 80 GeV)

Higgs boson (spin=0)—*the only not yet discovered force/particle* (its mass >114 GeV), <u>invented</u> to allow for Z, W, and fermion masses in the *weak sector of SM*. Its coupling to particles is related to their masses: the larger the mass, the larger the force.

W-boson is the only force via which particles can transform:

- e.g., $n \rightarrow p\ e\ \bar{\nu}$ (or at the more fundamental level: $d \rightarrow u\ e\ \bar{\nu}$)

***Gravity** is ignored (it is VERY weak and there is NOT a coherent quantum theory of gravity). Graviton should have zero mass and spin=2. The strength of gravitational interactions between elementary particles is imperishably smaller than even the weak force.*

Questions within Standard Model:

- **Origin of masses:** Is there a Higgs boson, after all? (Note that alternatives are possible…)

- **Neutrinos:** Are neutrinos Majorana- or Dirac-kind particles, i.e. are neutrino and anti-neutrino the same particle?

- **Neutrinos:** What are neutrino masses, mixing angles and a CP-violating phase?
  This is a question of a measurement

- **Quark-Gluon Plasma:** What are the properties of this state of matter?
  This is sort of condensed matter physics for quarks and gluons…

- **Perturbative theory limitations:** Can we deal with non-perturbative phenomena? This is more a technical question ("calculus") rather than fundamental physics

What Standard Model does NOT explain:

- **Higgs:**
  i. **Hierarchy problem:** Even if we find the Higgs boson in its simplest form, the Standard Model is likely to require new physics to avoid very bad divergences and/or fine tuning of parameters. Is it Supersymmetry (SUSY), Extra Dimensions?
  ii. **Why does the Higgs boson, if discovered, couple so differently to various particles?**
  iii. **Higgs filed vacuum energy density is huge—problems for cosmology or extreme-fine tuning?**

- **Why are there three generations of fermions?**
  There appears to be a pattern in their masses…
  What stands behind mixing of generations? There appears to be a pattern in the quark mixing matrix...
  What connects leptons to quarks?

- **Why are neutrinos so light?**

- **Why we do not see a CP-violation in strong force?**

- **Is there new physics at the GUT scale?** Assuming existence of SUSY particles at ~1 TeV scale, all three coupling constants of the electromagnetic, weak and strong forces seem to converge to one value at 10^{16} GeV scale (well below Plank scale where we must incorporate quantum gravity). Is it a coincidence? Are their more gauge symmetries and corresponding forces?

- **Why is there matter-antimatter asymmetry in the universe?** Baryon number conservation needs to be violated and we would need more CP-violating processes than we find with the SM.

- **What is non-baryonic dark matter?**
  i. WIMPs? (SUSY could be an answer)
  ii. Axions?

- **Gravity remains an untamed beast…**
  i. Quantum filed theory of gravity is missing… Is a string theory an answer?
  ii. Why gravity is so weak?
  iii. What is the dark energy, after all?

Natural Units

There are 4 primary SI units:
three kinematical (**meter**, **second**, **kilogram**) and one electrical (**Ampere**[1])

It is common in the realm of the elementary particle physics to redefine units so that speed of light and Plank's constant become equal to one: c=1 and $\hbar$=1. This imposes two constraints on the three kinematical units and, therefore, leaves us a free choice for one of the three kinematical units. The units of electrical charge, also, can be and are redefined (see below). Such system of units is often referred to as Natural Units (natural for the elementary particle physics, that is).

The kinematical unit of the choice is energy, E, and it is usually measured in eV (keV, MeV, GeV, TeV). Once we fixed c=1 and $\hbar$=1, all other kinematical units can now be expressed in terms of units of energy. E.g., one can easily see:

$E^2 = p^2c^2 + m^2c^4$ with c=1, units of **mass** and **momentum** are E

$\Psi = Ce^{-i\left(\frac{Et-px}{\hbar}\right)}$ with $\hbar$=1, units of **time** and **length** are 1/E
(this can be also seen from $E = h\nu$ and uncertainty principle $\Delta x \Delta p \geq 1$)

$L_z = \hbar n$ with $\hbar$=1, **angular momentum** is dimensionless

$F = ma$ **force** units are E^2

In SI system, units of current and charge can be *effectively* defined by choosing the value of ε_0 in the Coulomb's Law:

$$F = \frac{qq}{r^2}\frac{1}{4\pi\varepsilon_0}, \text{ where } \varepsilon_0 = 8.8\times10^{-12}\ \mathrm{C^2m^{-3}kg^{-1}c^2}.$$

In the Natural Units, the units of charge are defined by choosing ε_0=1. This automatically sets μ_0=1, since $c^2=1/(\varepsilon_0\mu_0)$. Since the units of force and distance in Natural Units are E^2 and 1/E, the electric charge turns out to be dimensionless in these units.

The value of the fine structure constant, being dimensionless, is the same in all units. In SI units it has the following form: $\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = \frac{1}{137}$, where *e* is the elementary charge $e=1.6\times10^{-19}$ C. In Natural Units, the fine structure constant becomes $\alpha = \frac{e^2}{4\pi} = \frac{1}{137}$. This clearly shows that an electric charge *e* has no dimensions in the Natural Units and now equals to 0.303.

Table. Units for major physical quantities in SI and Natural Units with conversion factors.

Quantity	**Dimensions**		**Conversions**
	SI Units	**Natural Units**	
mass	kg	E	1 GeV = 1.8×10^{-27} kg
length	m	1/E	1 $\mathrm{GeV^{-1}}$ = 0.197×10^{-15} m
time	s	1/E	1 $\mathrm{GeV^{-1}}$= 6.58×10^{-25} s
energy	$kg\cdot m^2/s^2$	E	1 GeV = 1.6×10^{-10} Joules
momentum	kg·m/s	E	1 GeV = 5.39×10^{-19} kg·m/s
velocity	m/s	-	1 = 2.998×10^{8} m/s (=c)
angular momentum	$kg\cdot m^2/s$	-	1 = 1.06×10^{-34} J·s (=ħ)
cross-section	m^2	$1/E^2$	1 $\mathrm{GeV^{-2}}$ = 0.389 mb = 0.389×10^{-31} m^2
force	$kg\cdot m/s^2$	E^2	1 $\mathrm{GeV^{2}}$ = 8.19×10^{5} Newton
charge	C=A·s	-	1 = 5.28×10^{-19} Coulomb; *e*=0.303 or =1.6×10^{-19} C

[1] Unit of charge, Coulomb, is Ampere · second.

Scales in Natural and SI units to remember

- mass of a proton/neutron ~ 1 GeV
- mass of an electron ~ 0.5 MeV

- proton/neutron radius ~ 1 fm = 10^{-15} m = 1 **fermi** ~ 1/(200 MeV)
- time for light to cross a proton ~ 10^{-23} s

- highest energy collider (Tevatron) ~ 2 TeV center-of-mass energy
- distance scale probed at Tevatron ~ 1/(2 TeV) ~ 10^{-19} m,
  (this comes from the uncertainty principle $\delta x \cdot \delta p \sim 1$)

Side note:
If you are still a little perplexed how it is possible to measure everything in terms of just one unit, think of astronomy, where the distance is basically measured in units of time:

- distance between the Earth and the Moon is about 1.3 s
- distance between the Earth and the Sun is about 8 min
- distance between the Sun and the nearest star is about 4 years, or light years.

20th Century Elementary Particle Physics Timeline

Theoretical Breakthroughs

- 1900 Black body radiation spectrum (Planck)
- 1905 Light quanta (Einstein)
- 1905 Theory of special relativity (Einstein)
- 1913 Bohr's model of atom, momentum quantum (Bohr)
- 1925 Hypothesis of "no two fermions in identical states" (Pauli)
- 1925-26 Quantum Mechanics (Heisenberg, Schrodinger)
- 1928 Electron relativistic QM equation; antimatter (Dirac)
- 1930 Neutrino hypothesis (Pauli)
- 1934 Weak Force (Fermi)
- 1935 Nuclear Force and Yukawa particles (Yukawa)
- 1948 Quantum ElectroDynamics (Feynman; Schwinger; Tomonaga)
- 1964 Three quarks (Gell-Mann, Zweig)
- 1965 Color (Greenberg)
- 1968 ElectroWeak Unification (Weinberg, Salam, Glashow)
- 1970 Charm quarks (Glashow, Iliopoulos, Maiani)
- 1973 Quantum ChromoDynamics (Gross, Fritzsch, Gell-Mann, Politzer, Weinberg, Wilczek)

Discoveries of Building Blocks

- 1897-1899 Discovery of electron (Thompson)
- 1911 Discovery of nucleus (Rutherford)
- 1919 Discovery of proton (Rutherford)
- 1923 "Discovery" of photon (Compton)
- 1932 Discovery of neutron (Chadwick)
- 1933 Discovery of antimatter, positron (Anderson)
- 1937 Discovery of muon (Anderson, Neddermeyer)
- 1946 Discovery of charged pion (Perkins)
- 1947 Discovery of strange particles (Butler, Rochester)
- 1956 Discovery of electron neutrino (Reines, Cowan)
- 1962 Discovery of muon neutrino (Lederman, Schwartz , Steinberger)
- 1974 Discovery of charm quark (Ting, Richter)
- 1975 Discovery of τ-lepton (Mark I, Perl)
- 1977 Discovery of bottom quark (Lederman)
- Late 1970s Observation quark and gluon jets (TASSO, JADE)
- 1983 Discovery of $W^{\pm}$, Z^0 (UA1, UA2, Rubbia)
- 1995 Discovery of top quark (CDF, D0)
- 2000 Discovery of tau-neutrino (DONUT, Lundberg)
- ???? Discovery of Higgs, SUSY, compositness, leptoquarks. extra dimensions, mini black holes, ….

Not shown on the time line, but still very important:

Experiment:
- Discovery of electron spin (1925)
- Discovery of Δ-resonance (1952)
- Discovery of P-violation (1957)
- Discovery of CP-violation (1964)
- Counting of light neutrino species (1989)
- Discovery of neutrino oscillations (2000±2)

Theory:
- General Relativistic Theory (1915)
- Introduction of SUSY, extra-dimensions, strings (early 1970s)