Major Mysteries in Particle Physics

Spontaneous Symmetry Breaking: What is the Higgs?

What is the origin of mass for the fundamental fermions and bosons?

- Does he Higgs exist, and if so, what is its mass?
- Is the Higgs field "fundamental" or does it arise dynamically, eg, Technicolor?

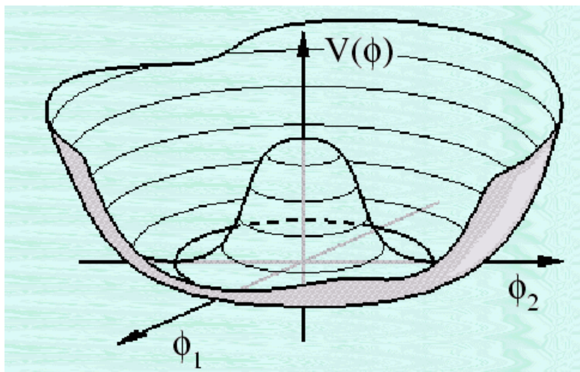
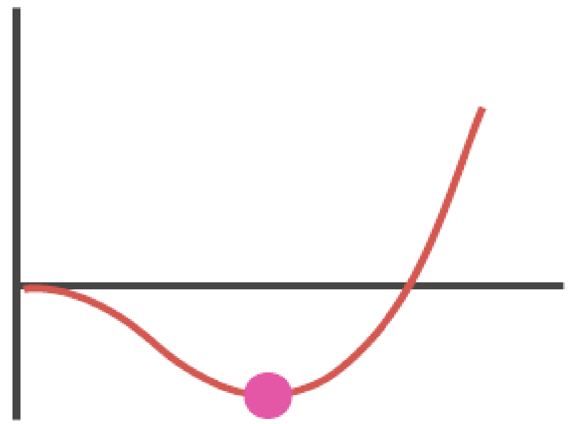
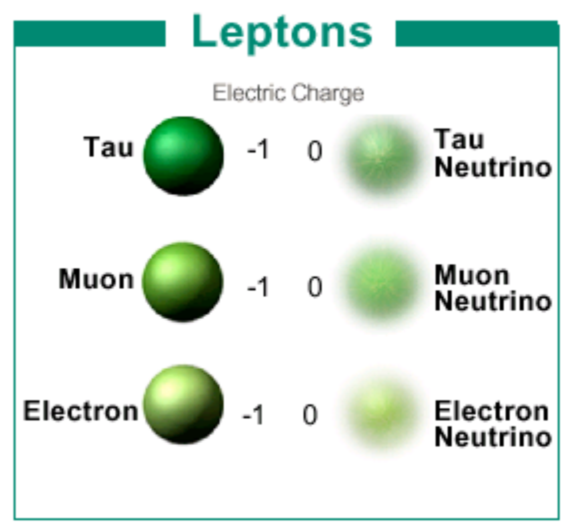


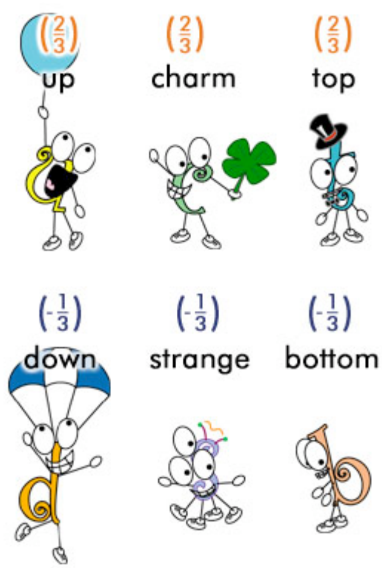
Figure 4: Shape of the ``Mexican hat'' potential in two dimensions. (Picture courtesy: E.P.S. Shellard, DAMTP, Cambridge.) From http://www.geocities.com/CapeCanaveral/2123/breaking.htm

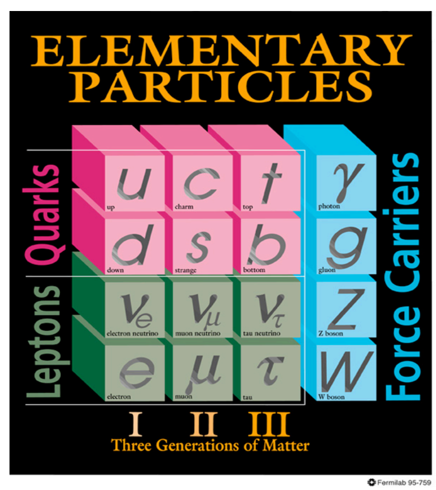


Fermion families

- What is the origin of family structure? Ie, why are quarks and leptons alike (universality of couplings) yet different?
- How many families exist? If three, why? (and does it have anything to do with CP violation?)

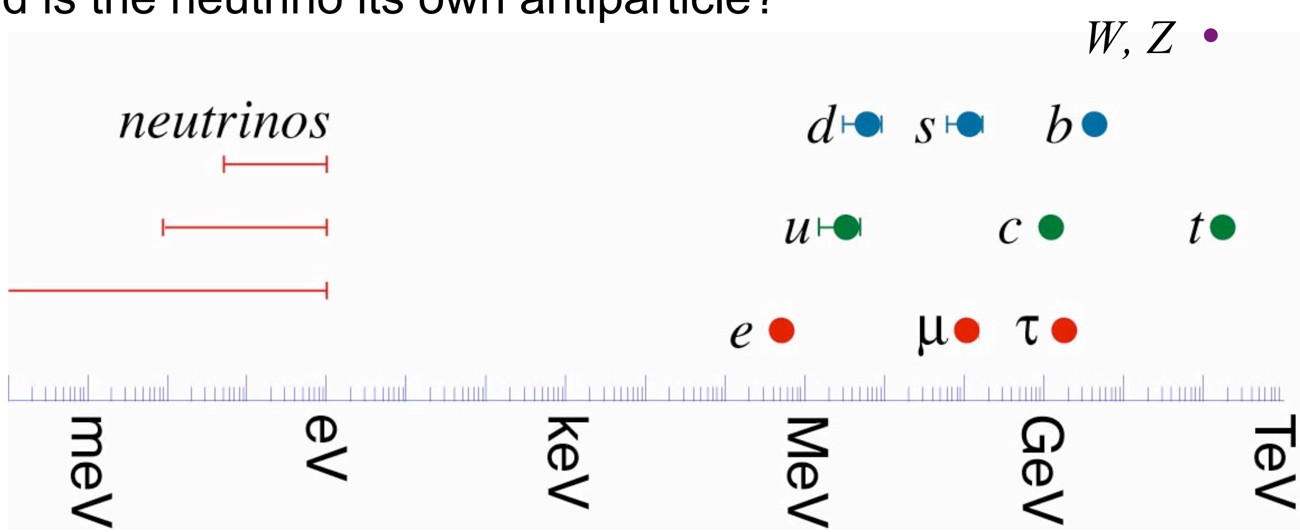






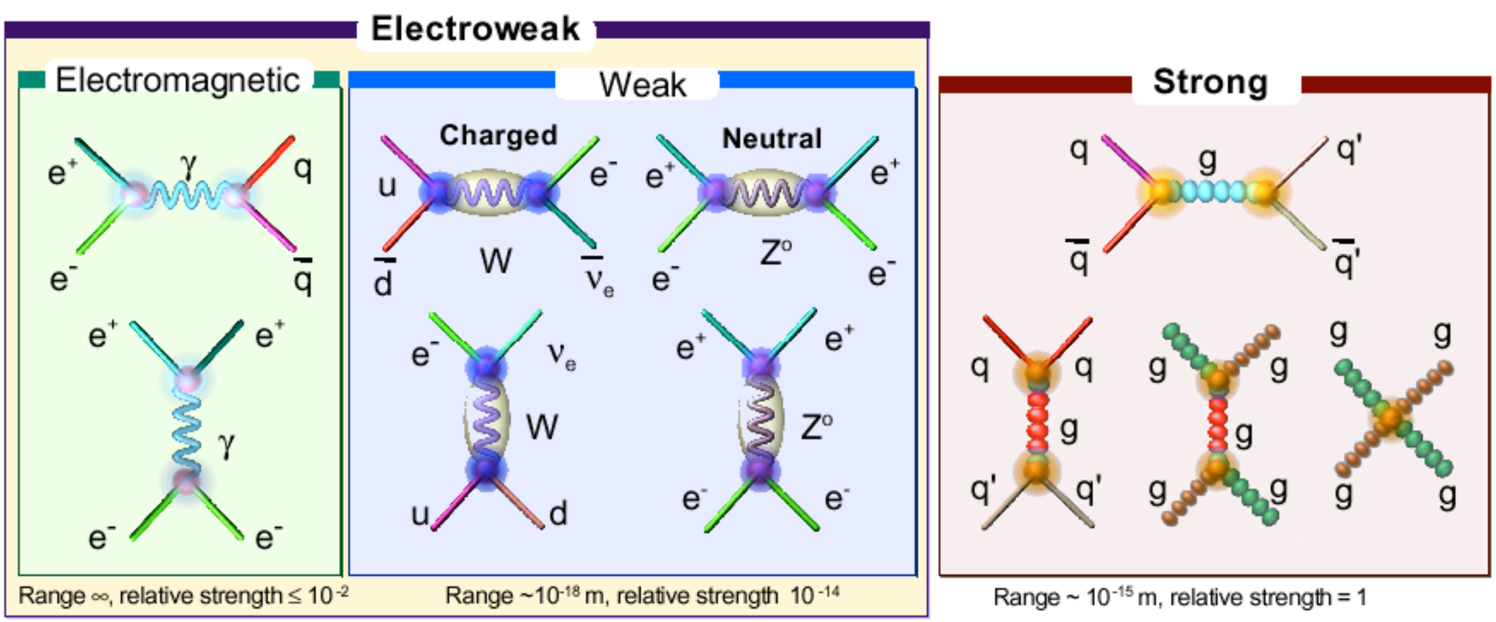
Fermion masses

- What does the very strange fermionic mass spectrum come from?
  - could it be that there is substructure, so that the quarks and leptons that appear to be fundamental (pointlike) are composite objects that can be excited or even broken apart?
  - If so, what is the nature of the "preons" and of the very strong force that holds them together so tightly?
  - Why is the top quark so heavy?
  - Why are the neutrinos so light?
- Just what are the masses of the neutrinos anyway?
  - And is the neutrino its own antiparticle?



Why the known forces?

- Why are there three known forces (interactions) that govern the micro-world? Why do they respect gauge symmetry?
- Why do they have the strengths (couplings) that they have?
- Why do they manifest such different properties?
- Are they all manifestations of one Grand Unified force?
- Why is parity (P), and charge-conjugation (C), violated in the Weak interaction? Is it a "spontaneously broken" symmetry?



Gravity

- The gravitational force is the odd guy out
- It's exceedingly weak:
  - Grav force between 2 protons is $G_N M_p^2 / r^2$
  - EM force between 2 protons is e^2/r^2
  - Dimensionless coupling $G_N M_p^2 / \hbar c = 5.3\times10^{-40}$
  - To be compared with EM: $\alpha_{EM} = e^2 / \hbar c = 1/137.036$
- Quantum effects only important at very, very short distances / high energies:
  - Two pointlike particles, each having the Planck mass M_{Pl} and separated by the Planck Length $L_{Pl} = \hbar / M_{Pl}\, c$, will have a graviatational potential energy equal to their rest mass:

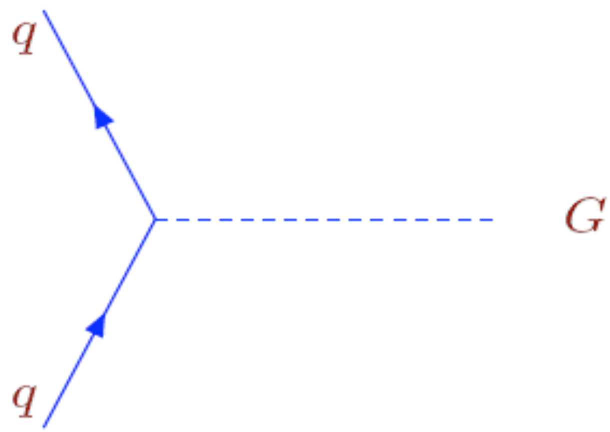
$$G_N M_{Pl}^2 / L_{Pl} = M_{Pl}\, c^2 \quad \Rightarrow$$

$$M_{Pl}\, c^2 = \hbar c / G_N = 1.2 \times 10^{19}\,\text{GeV} = 2 \times 10^{-8}\,\text{kg};\ L_{Pl} = 1.6 \times 10^{-35}\,\text{m}$$

- Gravitational effects are negligible in most particle physics experiments
- A mathematically consistent quantum theory of gravity does not exist
  - But it presumably involves a massless, spin-2 graviton
  - String theory is a good candidate
- Still, at large distances, when all forms of matter are neutral w.r.t. EM, strong, weak forces, gravity dominates; it cannot be screened

Natural to neglect gravity in particle physics

$$G_{\text{Newton}}\ \textit{small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19}\ \text{GeV}\ \textit{large}$$



$$\sim \frac{E}{M_{\text{Planck}}}$$

$$\text{Estimate } B(K \to \pi G) \sim \left(\frac{M_K}{M_{\text{Planck}}}\right)^2 \sim 10^{-38}$$

Why are the known mass scales so different?

(Λ_{QCD} ~ 0.2 GeV) << (EW ~ 246 GeV) << (M_{GUT} ~ 10^{16} GeV) << (M_{PL} ~ 10^{19} GeV)