6/7/17 Lecture 18 outline / summary

• Last time: running couplings in QED vs QCD. Asymptotic freedom. Confinement. Motivate grand unification. Find (details require a full course in quantum field theory) that QED has $96\pi^2 g_1^{-2} = C\ln(\Lambda_1/\mu)$ for $\mu < \Lambda_1$ (the Landau pole scale) with $C > 0$. QCD has $96\pi^2 g_3^{-2} = B\ln(\mu/\Lambda_3)$ for $\mu > \Lambda_3$ (the strong coupling or confinement scale), and $B = 11N_c - 2N_f$, with $N_c = 3$ and $N_f = 6$ for the known Standard Model quarks. Classically QED and QCD have dimensionless couplings α_1 and α_3. In the quantum theory, there are running couplings with associated scales Λ_1 and Λ_3. Find Λ_1 is ridiculously huge, while $\Lambda_3 \sim 230MeV$ the scale where the strong interactions become very strong. The running coupling α_s is often quoted in terms of the value at M_z, with $M_z \approx 91.1884GeV$ the mass of one of the weak force carriers and it is found that $\alpha_3(M_s) \approx 0.121$.

Draw grand unification picture of running couplings. It is not yet known if the forces in fact unify. The structure of the SM suggests $SU(5)$ with $10 + \bar{5}$ as the quark and lepton generations, as the simplest possibility. Unification predicts protons can decay, e.g. via $p^+ \to e^+ + \pi^0$. The super K detector, which found neutrino oscillations, was originally designed to look for proton decay. The non-observance of events allows experimenters to put a lower bound on the lifetime of the proton, which constrains GUT theories into a tighter corner of theory space.

• On to the weak force! Two differences from other forces: it is chiral (hence parity violating), and the force carriers (Ws and Zs) are massive, which is why it is weak. "How can a force carrier be massive?" given that forces are related to gauge symmetries, and gauge invariance forbids mass terms (e.g. for the photon). Answer: the gauge invariance is *spontaneously broken* by the Higgs field. This is roughly similar to the Bose condensate in a superconductor. Sombrero picture of $V(\phi)$. Higgs particle = radial fluctuation. The angular directions yield the longitudinal components of $W^\pm$ and Z^0.

• Weak interactions at low-energies involve 4 Fermion interactions. Fermi's theory. But parity is violated. Wu (1957): ${}^{60}Co \to {}^{60}Ni^* + e^- + \overline{\nu_e}$, electrons are preferentially emitted in the direction opposite to $\vec{B}$, so not parity invariant. The 4-Fermi interaction involves $j^\mu_{V-A} \sim \bar{\psi} P_L \psi$, where recall $P_L = \frac{1}{2}(1-\gamma_5)$. The 4-Fermi theory predicted its own demise, since it breaks down for energies $\sim 100GeV$. It is replaced with $SU(2)_W$ gauge fields, with $m_W = 80.358 \pm 0.015GeV$. Also $m_Z = 91.1975 \pm 0.0021GeV$. Only the left-handed Fermions couple to the $SU(2)_W$ force; this is P violating. This forbids mass terms for any of the SM Fermions. The Higgs field is needed to get Fermion masses, via the Yukawa couplings. (These couplings also contain CP violating phases.)

- Again, recall the structure of the Standard Model, and various ideas and evidence for BSM physics.