Physics G8069
Final projects

Here are some suggested topics for final projects. If some other topic interests you more just let me know.

General guidelines:
You should work together in groups of three; each group chooses a topic and gives a 1 to $1\frac{1}{2}$ hour presentation.

Scheduling talks:
I'm hoping to finish lecturing on Dec. 6. I'd like to have student talks the following week, on

- Monday 12/11
- Tuesday 12/12
- Wednesday 12/13

We'll have a final exam on Monday Dec. 18.

1. **Calculations in electroweak theory:** $e^+e^- \to W^+W^-$

   This is an interesting process because some rather intricate cancellations between different diagrams are required in order to get a well-behaved tree-level cross-section. The cancellations can be traced back to the underlying spontaneously broken gauge structure of the standard model. This process has been used to measure the $ZWW$ and $\gamma WW$ couplings at LEP.

   References: Peskin & Schroeder p. 750 do the calculation for vanishing electron mass. Things get more interesting when you keep the electron mass non-zero: then the Higgs particle becomes necessary, as discussed by Quigg on p. 130. For the LEP experiments see hep-ex/0402036; for a nice picture see p. 5 in hep-ph/0502252.

2. **Partial-wave unitarity and bounds on the Higgs mass**

   Another interesting process to study is high-energy scattering of longitudinally-polarized gauge bosons $W_L^+ W_L^- \to W_L^+ W_L^-$. The amplitude for this process violates tree-level unitarity if the Higgs mass is too large. This can be used to put a theoretical upper bound on the Higgs mass, assuming the standard model remains weakly coupled: $m_H < 870\,\mathrm{GeV}$. What's more, it leads to a "no – loose" theorem for the LHC: new physics must be present at an energy scale below $\sim 1.7\,\mathrm{TeV}$. Either the Higgs boson will be found, or some other particles will be discovered, or at the very least strong coupling effects will set in.

   References: S. Dawson, *Introduction to electroweak symmetry breaking* (hep-ph/9901280), pp. 47 – 51. It's hard to compute longitudinal $W$ scattering directly; it's similar to the process $e^+e^- \to W^+W^-$ studied above. But if you're only interested in the high energy behavior you can use the "equivalence theorem" mentioned in Dawson and developed more fully in Peskin & Schroeder section 21.2. If you require that the standard model satisfy tree-level unitarity to arbitrarily large energies you can derive the bound $m_H < 870\,\mathrm{GeV}$. On the other hand if you send $m_H \to \infty$ you find that tree-level unitarity is violated at $\sqrt{s} \sim 1.7\,\mathrm{TeV}$. See Dawson for details.

3. **Anomaly cancellation**

   We constructed the standard model by gauging certain global symmetries. This only makes sense if we have valid global symmetries to begin with. At the classical level there's no difficulty – the Lagrangian is invariant under the symmetry transformations – however quantum effects can violate classical symmetries. Rather remarkably the standard model fermion content is set up so that all potential "gauge anomalies" cancel.

   References: This is discussed in Quigg p. 137. For a detailed treatment of anomalies in 1+1 and 3+1 dimensions see Peskin & Schroeder sections 19.1 and 19.2. Anomaly cancellation is discussed in section 19.4 and applied to the standard model on p. 705.

4. **Higher dimension operators, lepton and baryon number conservation and neutrino masses**

   We constructed the standard model as a renormalizable gauge theory. This has a remarkable consequence: due to an accidental symmetry, baryon and lepton number conservation is automatic.[1] However there's no reason to think there aren't higher-dimension operators present, suppressed by powers of some large energy scale. It's likely that these operators violate conservation of lepton and baryon number. It's also likely that these operators induce (lepton-number-violating) Majorana mass terms for the neutrinos. A concrete way of generating such operators from an underlying renormalizable theory is known as the see-saw mechanism. In any case, these days the evidence for neutrino flavor oscillations ($\Leftrightarrow$ non-zero neutrino masses) has become overwhelming.

   References: you might start with the review article by Gonzalez-Garcia and Nir, *Neutrino masses and mixings: evidence and implications*, hep-ph/0202058. A discussion of higher-dimension electroweak operators can be found in Ramond section 6.3.

5. **FCNC and the GIM mechanism:** $K^0 \to \mu^+\mu^-$

   In the standard model "flavor changing neutral currents" are absent at tree level, and the process $K^0 \to \mu^+\mu^-$ proceeds via a loop diagram (Peskin & Schroeder p. 725). The loop diagram turns out to be surprisingly small due to the "GIM mechanism." This phenomenologically desirable cancellation led Glashow, Iliopoulos and Maiani to postulate the existence of the $c$ quark four years before the $J/\psi$ was discovered. Some other GIM-suppressed processes are the decay $K \to \pi\nu\bar{\nu}$ (Ramond p. 209) and the $K_L - K_S$ mass splitting (Ramond p. 212 and Cheng & Li p. 379).

   References: Halzen & Martin p. 282 has a nice discussion, also see Quigg p. 150. For more detailed calculations see the article by Gaillard and Lee, *Phys. Rev.* **D10**, 897 (1974). The particle data book p. 72 has the current measurements.

[1] Strictly speaking this classical symmetry is anomalous.

6. **3-generation CKM matrix and CP violation**

   With three generations of quarks and leptons the CKM matrix turns out to be complex, with a single CP-violating phase. This phase is the origin of CP violation by the weak interaction. CP violation in neutral kaons has a long history; these days the experimental focus has shifted to CP violation by B mesons.

   References: Cheng & Li covers the CKM matrix in section 11.3 and kaon physics in section 12.2. B physics is covered in the review articles hep-ph/0411138 and hep-ph/0410351.

7. $SU(5)$ **grand unification**

   The standard model gauge group has three separate factors corresponding to three independent gauge couplings. Also the fermion content of the standard model is more complicated than one would like. This makes it appealing to consider theories based on a simple gauge group $G$ that can be spontaneously broken to give the standard model. There are two good phenomenological candidates: $G = SU(5)$ and $G = SO(10)$. In this framework you can predict the weak mixing angle!

   References: The $SU(5)$ case is discussed in Quigg chapter 9. Gauge coupling unification works even better with supersymmetry: S. Weinberg, *Quantum theory of fields*, vol. III sect. 28.2.