Midterm 2

1) List or draw a diagram of the particles in the Standard model. *(6 points)*
What is the spin of each particle ?

Fermions:, All spin 1/2

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}\ \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}\ \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix} \qquad\qquad \begin{pmatrix}u\\ d\end{pmatrix}\ \begin{pmatrix}c\\ s\end{pmatrix}\ \begin{pmatrix}t\\ b\end{pmatrix}\times 3 \text{ colors}$$

Gauge Bosons: All spin-1

$$g\times 8 \text{ colors} \quad W^{\pm} \quad Z \quad \gamma$$

Higgs Boson: spin-0

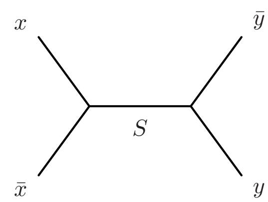
$$H$$

2) Why is the weak interaction so much weaker than then electromagnetic interactions at low energies? *(2 points)*

Weak force has massive force carriers.

3) Feynman Diagrams *(12 points)*

Fermions of type x scatter into fermions of type y through the diagram shown below, where S is a massive scalar. At low energies ($P_x P_y << m_S$) the cross section for this process is given by σ_0. Assume m_x and m_y are both negligible.



a) How does this cross section change if the "S-charge" of the x particle is doubled ? (S-charge being the $x\bar{x} \to S$ coupling)

$$\sigma \sim |M|^2 \qquad M \sim q_s$$

$$q_s \to 2q_s \Rightarrow M \to 2M \Rightarrow \sigma \to 4\sigma$$

b) How does the cross section change if the mass of the S-particle is doubled ?

$$\sigma \sim |M|^2 \qquad M \sim \frac{1}{M_S^2}$$

$$M_S \to 2M_S \Rightarrow M \to \frac{1}{4}M \Rightarrow \sigma \to \frac{1}{16}\sigma$$

c) At low energies, how does the cross section depend on the center of mass energy of the scattering E_{CM} ? *(Hint: At low energies you can think of the $xx \to yy$ scattering as described by an effective 4-point xxyy interaction, as Fermi did for neutrino scattering.)*

At low energies the scattering is described by an effective 4-point *xxyyy* interaction. The xxyy vertex has 4 fermions which each have mass dimension $\frac{3}{2}$. So the diagram has mass dimension $[g_{xxyy}]4 \times \frac{3}{2} = [g_{xxyy}] \times 6$. In order to have overall mass dimension four, the mass dimension of the coupling $[g_{xxyy}]$ must be GeV^{-2}.

$$M \sim \mathrm{GeV}^{-2} \Rightarrow |M|^2 \sim \mathrm{GeV}^{-4}$$

Dimensions of σ have to work out to be GeV^{-2}.

The only other energy scale in the problem is E_{CM} so.

$$\sigma \sim \frac{E_{CM}^2}{\mathrm{GeV}^4}$$

4) Di-boson physics: *(6 points)*

Processes in which pairs of gauge bosons are produced are a sensitive probe of the electro-weak theory. These are typically studied at the LHC by looking for signatures involving electrons or muons. Estimate how often a WZ event decays into an electron or muon and three neutrinos.
ie: $e\nu\nu\nu$ or $\mu\nu\nu\nu$

$$W \to \ell\nu \text{ (where } \ell \text{ is } \mu \text{ or } e\text{) is } \tfrac{2}{3+3\times2} = \tfrac{2}{9}$$
$$Z \to \nu\nu \text{ is } \tfrac{3}{3+3+3\times5} = \tfrac{3}{21}$$
$$\text{So, } WZ \to \ell\nu\nu\nu \text{ (where } \ell \text{ is } \mu \text{ or } e\text{) is } \tfrac{2}{9} \times \tfrac{3}{21} = \tfrac{2}{63} \sim 3\%$$

5) Collider Detectors *(4 points)*

a) In what ways do the detector signatures of electrons and muons look a-like, in what ways are they different ?

- Both have tracks in the inner tracking detector.
- Electrons shower in the EM calorimeter and stop, μs make it through the calorimeter to the muon detector.

b) In what ways do the detector signatures of electrons and photons look a-like, in what ways are they different ?

- Both shower in the EM calorimeter and stop.
- Electrons have a track in the inner tracking detector, photons do not.

6) Calorimeters *(4 points)*

Which are more challenging to accurately measure and why : Hadronic showers or electro-magnetic showers?

Hadronic showers

- More complicated: Multiple lengths scales interaction and radiation lengths important
- Less particles: hadrons are heavier so you get less per unit input energy
- Longer: require more material to contain.

7) For a new particle X with mass ~ 2 TeV, would you expect to measure the X mass more precisely from $X \to ee$ or $X \to \mu\mu$? Justify your answer. *(4 points)*

X→ ee

- Electrons energies are measured in the calorimeter, which gets more accurate at high energies
- Muons energies are measured in the trackers (inner and muon), which gets less accurate at high energies

8) How are νs detected at the LHC ? *(2 points)*

By looking for momentum imbalance in the transverse plane.

9) The God Particle *(4 points)*

Critique the statement: "The Higgs Boson (or god particle) is responsible for all the mass in the Universe"

- The Higgs Field is responsible for mass not the Higgs boson
- The Higgs Boson has nothing to do with God
- It is responsible for some mass in the univierse (the fundamental particles) not the proton or neutron mass (which are most of the observed (baryonic) mass in the universe)

10) Higgs Boson Production : *(4 points)*

Why is Higgs boson production so much rarer then W or Z production despite the fact that their masses are similar?

- It couples very weakly to light particles
- Production is from higher-order diagrams

11) Higgs-Lepton interactions *(4 points)*

The coupling of the Higgs field to leptons can be studied by looking for detector signals where the Higgs boson decays to pairs leptons. Which of the possible decay modes would be the best way to do this. Justify your answer.

Higgs to $\tau\tau$ as it has the largest mass and the Higgs coupling scales with mass. Will also give credit for Higgs to $\mu\mu$ if you comment that τ are hard to detector/measure

12) Interaction Symmetries *(9 points)*

In the first part of the course we learned that the interactions of mass-less spin-1 particles must be described by group symmetries.

a) How is the group symmetry of an underlying interaction related to the particle content ?

There is a gauge boson associated to each generator of the underlying symmetry.

b) What are the symmetry groups of the electro-weak interaction in the SM ?

$$SU(2)_L \times U(1)$$

c) How does the observed physical particle content reflect this ? (Qualitatively, no formulas required.)

The $W^{\pm}$ are two of the three generators of $SU(2)_L$.
The Z and γ are mixtures of the last $SU(2)_L$ generator and the U(1) generator