# Tutorial 6

December 9, 2015

## 1 Morning lecture (8-10am)

You will be able to check the marked copy of your first test and ask questions about it. Then I will correct the test in detail on the board.

This will be a good opportunity for you to ask questions about things you haven't understood since the start of the semester. It is important you are comfortable with all the material for the remaining of the course, so take some time to think about things you might have questions on.

## 2 Afternoon tutorial

### 2.1 Anomalies (in the Standard Model Lagrangian)

In the lectures, you have showed that the anomaly $A(3,3,1)$ vanishes (I am using the notation of *The Standard Model: A Primer*).

Review this calculation, and use the same reasoning to show the other two non-trivial relations that guarantee there are no anomalies associated with the (local) gauge symmetry of the Standard Model:

$$A(2,2,1) = A(1,1,1) = 0\,. \tag{1}$$

To this end first give the representation of the symmetry generators

$$T_a = \sum_{\oplus\, ferm.\ reps.} t_a$$

in block-diagonal matrix form. All the independent left-handed components of all fermion fields have to be considered.

### 2.2 Problem 2.3 of *The Standard Model: A Primer*

We will use this exercise as a way to review some important aspects of the course up to now. The idea of the problem is to try to add right-handed neutrinos to the Standard Model, one for each generation. Clearly this exercise fits well to this years Nobel Prize in physics (see special lecture by G. Herten 8.12.2015 17:00, Grosser Hörsaal).

**Question 1:** Start by defining $N_m$ as the Majorana spinor whose right handed component is the right handed neutrino. Assume this field to be neutral under all gauge transformations. Then show that the only new renormalisable terms that can appear in the Lagrangian are

$$-\frac{1}{2}\bar{N}_m \not{\partial} N_m - \frac{1}{2} M_m \bar{N}_m N_m - \Big( k_{mn} \bar{L}_m \mathrm{P}_R N_n \tilde{\phi} + \text{h.c.} \Big) \ . \tag{2}$$

In this expression, $M_m$ is a real mass, $k_{mn}$ the Yukawa couplings. The fields $\tilde{\phi} = \varepsilon \phi^*$ and $L_m$ are the usual $SU_L(2)$ Higgs and lepton doublets, respectively.

**Question 2:** We specialise to the case of one generation for simplicity. Compute the mass matrix for the leptons after sponaneous symmetry breaking. Show that the new terms induce a mass for the neutrino. Identify the basis of field in terms of which the matrix is diagonal and give the eigenvalues (masses).

**Question 3:** Express the lepton-Higgs and lepton-gauge boson interactions in terms of the leptonic mass eigenstates (keep using Majorana spinors).