Standard Model Lecture Notes

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1 Introduction

1.1 Introduction

What even is the standard model? You may have heard of this before but we'll try to start from scratch in this course.

Definition. Standard Model The Standard model is a theoretical physics construction (what we call a theory, or a model), which describes all known elementary particles and their interactions, based on relativistic quantum field theory (QFT). This is a major thing - one of the biggest achievements in the history of science so far.

What are the 'ingredients' of the Standard Model? The SM is mostly based on the principle of symmetries, which is the key word here. The most important symmetry to consider here are spacetime symmetries, and we'll list these as well as some other important ones below.

- Spacetime: 3 + 1 dimensional Minkwoski space. Symmetry: The Poincare group.
- We can list the particles of the SM.
  - spin $s = 0$: Higgs. A big part of this course will be to describe the statistics of the Higgs boson.
  - spin $s = \frac{1}{2}$: 3 families of quarks and leptons.
- How do these particles interact? The interactions are
  - $s = 1$: 3 gauge interactions
  - $s = 2$: 1 gravity

  The above gauge interactions are based on Gauge symmetry. This is a local symmetry. In QFT for example, we saw an example of a $U(1)$ gauge symmetry. For the standard model this symmetry is $SU(3)_C \times SU(2)_L \times U(1)_\gamma$. The c stands for colour, which describes the strong interaction. The L stands for left, which describes the elctroweak force, and the γ stands for hypercharge. This symmetry is spontenously broken to get

  $$SU(3)_c \times SU(2)_L \times U(1)_\gamma \to SU(3)_c \times U(1)_{EM}$$

  The Higgs particle, can take a value different from zero at the minimum. The symmetry of the vacuum is then no longer the same as the symmetry of the theory. This is called symmetry breaking.

  We have the following particle representations

  - Quarks and leptons have the representation

    $$3\left[\left(3,2;\frac{1}{6}\right)+\left(\overline{3},1;-\frac{2}{3}\right)+\left(\overline{3},1;-\frac{1}{3}\right)+\left(1,2;-\frac{1}{2}\right)+(1,1;-1)+(1,1;0)\right]$$

    In this order, we have $Q_L, U_R, d_R, L_L, e_R, \nu_R$ The factor of 3 is non-trivial (this is called flavour). So, we have three flavours of quarks, three flavours of leptons, etc.

- The Higgs representation is $\left(1, 2; -\frac{1}{2}\right)$.
- Our gauge is represented by

$$(8, 1; 0) + (1, 3; 0) + (1, 1; 0)$$

From left to right, these are gluons, $W^{\pm}, \mathbb{Z}$ bosons, and γ.

We have some comments

- Interactions given by QFT.
- Our main tool us symmetry!
- Total symmetry: spacetime and internal symmetries (gauge).
- There are also accidental (global) symmetries like lepton and baryon number.
- We also have symmetries which are approximate symmetries like flavour.
- Look at the sum of the hypercharges $\sum \gamma = \sum \gamma^3 = 0$. We also have that $3 = \overline{3}$, and 2 even. (Multiply everything in the vector to get hypercharge).
- Gluons are confined. The same way that quarks are confined. This is an open question to prove that quarks are confined.
- There is rich structure (3 phases, Coulomb charge, Higgs and confinement).

There are other symmetries like baryon number and lepton number, which are accidental and not fundamental - they just happen to be there.

1.2 Motivation

Why should we learn about the SM?

- It is fundamental!
- It is based on elegant principles of symmetry.
- It is true! The SM has been tested in many different ways, with some outstanding prediction. For example $(\left(\mathbb{Z}^0, W^{\pm}\right)$, the Higgs, and so on. There are also precision tests; but there is an anomalous magnetic dipole moment electron.

$$a = \frac{g-2}{2}$$

We also have measured the fine structure constant

$$\alpha^{-1} =$$

$\overline{h}\frac{c}{e^2}$

- The standard model is incomplete!

2 Spacetime Symmetries

3 Gauge Symmetries

4 Symmetry Breaking

5 Electroweak Unification

6 QCD

7 Phenomenology of the SM

8 EFT's and open questions

Example Sheet 1