CHAPTER 1

The Standard Model and Beyond

§1.1 The Standard Model

The Standard Model (SM) is a “theory of almost everything” that describes the interactions of elementary particles. The theory is the synthesis of quantum electrodynamics, the theory of weak nuclear interactions, and the strong nuclear force. There are three types of elementary particles in the SM: quarks, leptons, and gauge bosons.

Prior to the development of the SM, three different theories theories of particle physics where used to describe different phenomena, which are discussed in turn. The interaction of light and matter, is described by Quantum Electrodynamics (QED), a relativistic field extension of the theory of electromagnetism. The physics of radioactivity and nuclear decay was described by the theory of weak interactions. Finally, the forces that bind together the nuclei of atoms was described by the strong nuclear force.

The development of the complete Standard Model as it is known today was precipitated by two theoretical developments: Glashow’s discovery [**?**] of the potential to unify QED with the weak force using spontaneous symmetry breaking, and the development of the Higgs mechanism [**?**], which breaks the electroweak symmetry using the clever addition of an additional scalar particle (the Higgs boson).

§1.1.1 Quantum Electrodynamics

The theory of QED is a relativistic formulation of Maxwell’s theory of electromagnetism, describing the interaction of matter with light. The development of QED is a result of efforts to develop a quantum mechanical formulation of electromagnetism compatible with the theory of Special Relativity. QED is a *gauge* theory, which means that the physical observables are invariant under local gauge transformations. Requiring local gauge invariance gives rise to a "gauge" field, which can be interpreted as particles that are exchanged during an interaction.

In the following, we can show that requiring the relativistic Lagrangian of a free charged particle to be invariant under local gauge transformations creates an effective gauge boson field. This "gauge field" creates terms in the Lagrangian that represent interactions between the particles.

The Dirac equation **what is this** of a free spin 1/2 particle of mass m is

$$\mathcal{L} = \bar{\psi}(i\hbar c\gamma^{\mu}\partial_{\mu} - mc^2)\psi \tag{1.1}$$

where ψ is the field of the particle in question, $\hbar$ is Planck's constant, c the speed of light, and γ^{μ} are the Dirac matrices. As $\bar{\psi}$ is the Hermitian conjugate of ψ, the Lagrangian is invariant under the global gauge transformation

$$\psi' \longrightarrow e^{i\theta}\psi \tag{1.2}$$

. The Lagrangian is invariant under *local* gauge translations if θ can be defined differently at each point in space, i.e. if $\theta = \theta(x)$ in equation 1.2. However, as the derivative operator ∂_{μ} in equation 1.1 does not commute with $\theta(x)$, the Lagrangian must be modified to satisfy local gauge invariance. This modification is accomplished with the use of a "gauge covariant derivative." By making the replacement

$$\partial_{\mu} \longrightarrow D_{\mu} = \partial_{\mu} - \frac{ie}{\hbar}A^{\mu} \tag{1.3}$$

in equation 1.1, where **don't think this is right** $A^{\mu} = \partial^{\mu}\theta(x)$ the Lagrangian becomes locally gauge invariant:

$$\mathcal{L} = \bar{\psi}(i\hbar c\gamma^{\mu}D_{\mu} - mc^2)\psi \tag{1.4}$$

The difference between the locally (equation 1.4) and globally (equation 1.1) gauge invariant Lagrangians is then

$$\mathcal{L}_{int} = \frac{e}{\hbar}\bar{\psi}\gamma^{\mu}\psi A_{\mu} \tag{1.5}$$

. This term can be interpreted as the coupling between the particle and the gauge boson (force carrier) fields. The existence of this coupling is required if the Lagrangian is to satisfy local gauge invariance. The addition of a term with the gauge Field Strength Tensor yields the QED Lagrangian:

$$\mathcal{L}_{QED} = \bar{\psi}(i\hbar c\gamma^{\mu}D_{\mu} - mc^2)\psi - \frac{1}{4\mu_0}F_{\mu\nu}F^{\mu\nu} \tag{1.6}$$

§1.1.2 The Weak Interactions

§1.1.3 Quantum Chromodynamics

§1.1.4 Electroweak Unification

§1.1.5 The Higgs mechanism

§1.2 Searches for the Higgs boson

§1.2.1 Higgs boson phenomenology

§1.2.2 Searches at LEP

§1.2.3 Searches at the Tevatron

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§1.3 Beyond the Standard Model

§1.3.1 The Hierarchy Problem

§1.3.2 Supersymmetry

§1.3.3 The Minimal Supersymmetric Model and τ leptons

§1.4 τ leptons as a probe of new physics