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o júri / the jury

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Honestamente acho que isto vai ter que ser escrito antes da entrega

Honestly this will be written in english translated poorly from above :)

Resumo

Esta parte esta em pt

Abstract

The Standard Model of particle physics has been for some time now recognized as a placeholder theory. Too many problems have been propping up over the years, such as the strong CP problem, neutrino oscillations, matter–antimatter asymmetry, the nature of dark matter and dark energy and most recently the existence of gravitational waves background ?. In response many theories have been proposed to deal with each one of these problems. However, it's important to realise that these are not independent problems and as such we must search for a way to tackle all of these. Here we propose a simple model and look into some (maybe all?) of these problems.

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Introduction

The Standard Model

1 The Standard Model

It is hard to question that the Standard Model (SM) is a successful approximately framework with whom to describe the phenomenology of Particle Physics up to the largest energy scales probed by collider measurements so far. Proposed in the sixties by Glashow,Salam and Weinberg it has been extensively tested. In fact, contemporary direct searches for new physics or indirect probes via e.g. flavour anomalies and precise electroweak parameter measured in proton-electron collisions, have been showing an increasingly consistency with SM predictions. These will show themselves fundamental for our study and we'll discuss these mechanisms in greater detail over the course of this work. Given this it is fair to say that the joint description of the electromagnetic and the weak interaction by a single theory certainly is one of major achievements of the physical science in this century.

However, it is far from perfect with several open questions that are yet to be fully understood, it is these questions that modern physicists use to justify the research made in the area of high energy physics and Phenomenology. One of such weaknesses is a missing explanation of tiny neutrino masses confirmed by flavour-oscillation experiments which we will try to approach later in this dissertation .

Given it's successes researchers have long been tempted to try to complete the SM somehow rather than fundamentally alter it. In fact several mechanisms have been proposed that build upon the SM rather than replace it. We'll investigate some of these in this project (BLSM 3HDM) .

1.1 Gauge Principle

It is well known that symmetry played a very important role in the development of modern physics ever since Emmy Noether's first theorem, which derives conserved quantities from symmetries. Precisely the theorem states if an action is invariant under some group of transformations (symmetry), then there exist one or more conserved quantities (constants of motion) which are associated to these transformations.

The question that the lead to the framework of the standard model was: upon imposing to a given Lagrangian the invariance under a certain symmetry, would it be possible to determine the form of the interaction among the particles? In other words, could symmetry also imply dynamics. This train of thought led to Quantum Electrodynamics (QED) the successful first prototype of quantum field theory.

In QED the existence and some of the properties of the gauge field (which we'll later identify as the photon) follow from a principle of invariance under local gauge transformations of the $U(1)$ group.

We can quote Salam and Ward:

"Our basic postulate is that it should be possible to generate strong, weak and electromagnetic interaction terms (with all their correct symmetry properties and also with clues regarding their relative strengths) by making local gauge transformations on the kinetic energy terms in the free Lagrangian for all particles."

We are glossing over a lot of complexity here, for the SM to be truly complete Noether's theorem alone wouldn't suffice and new concepts had to be introduced. In the case of weak interactions the presence of very heavy weak gauge bosons require the new concept of spontaneous breakdown of the gauge symmetry and the Higgs mechanism. Also, the concept of asymptotic freedom played a crucial role to describe perturbatively the strong interaction at short distances, making the strong gauge bosons trapped.

1.1.1 Symmetries

A symmetry can be very broadly defined as a property of a system that is preserved or remains unchanged. However for our interests we are going to look at field transformations that leave a Lagrangian system invariant. To exemplify this consider the following generic transformation of a field ϕ:

$$\phi \longrightarrow \phi'\phi + \delta\phi \tag{1}$$

To be invariant means the langraingian will be unchanging, thus,

$$\mathcal{L}(\phi) \tag{2}$$

1.2 Higgs Mechanism

1.3 Composition of the Standard Model

The Standard Model is composed by force carriers, the weak gauge bosons W and Z, the photon, the electromagnetic interaction messenger and the strong force mediators, the gluons, as well by matter particles, the quarks and leptons. Being that the Higgs boson is responsible for the mass generation mechanism.

Fermions are organized in three generations. Furthermore, there are 6 different types of quarks, up and down for the first generation, charm and strange for the second as well as top and bottom for the third one. Similarly, there are 6 types of leptons, the charged ones, electron, muon and tau, and the associated neutrinos, respectively represented by (u, d, c, s, t, b) while leptons as $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$

So far we have described the physical states that are often denoted as the building blocks of nature. However we have not yet explained how such states have acquired their masses and gauge quantum numbers, such as colour and electric charge. To see this, we start by noting the the SM is a gauge theory based on the group.

$$SU(3)_c \times SU(2)_L \times U(1)_Y \quad . \tag{3}$$

Fermions are half integer spin particles most of which have electrical charge (except the neutrinos). While quarks interact via the weak, electromagnetic and strong forces, the charged leptons only feel the electromagnetic and weak forces and the neutrinos are solely weakly interacting.

A physical fermion is composed of a left-handed and a right-handed part. While the former transform as $SU(2)_L$ doublets and can be written as,

$$L^i = \begin{pmatrix} \nu_{e_L} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu_L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau_L} \\ \tau_L \end{pmatrix} \quad \text{and} \quad Q^i = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad , \tag{4}$$

1.4 Anomaly cancellation

BLSM

2 Introduction and motivation for the Model 1

Now having discussed the Standard Model. We can introduce the minimal $U(1)_{B-L}$ extension of the Standard Model (B-L-SM). This is a model trough which we can explain neutrino mass generation via through a see-saw mechanism as well as model that contains two new physical particle states, specifically a new Higgs like boson and a Z′gauge Boson. Both these bosons are given mass trough the spontaneous breaking of the $U(1)_{B-L}$ symmetry. This origin for the mass of the referenced bosons means model is already very heavily constricted due to direct searches in the Large Hadron Collide (LHC).

One of the goals of this project was to investigate precisely the phenomenological status of the B-L-SM by confronting the new physics predictions with the LHC and electroweak precision data.

The name of B-L-SM stem from the addition of a unitary symmetry $U(1)_{B-L}$, as mentioned, originating from the promotion of a accidental symmetry present in the SM. Thus the Baryon number (B) minus the Lepton number (L) become a fundamental Abelian symmetry group. As a note this model is easily embedded into higher order symmetry groups like for example the SO(10) group meaning this model can be used for the study of Grand Unified Theories.

The cosmological consequences of the B-L-SM formulation are also worth mentioning. First, the presence of an extended neutrino sector implies the existence of a sterile state that can play a role of Dark Matter candidate

2.1 Neutrino masses

As mentioned briefly during the course of this dissertation the SM suffers from lacking a way to explain the observed neutrino masses by default. The minimal way of addressing this problem is by adding heavy Majorana type neutrinos in order to realise a seesaw mechanism. In this chapter we hope to explain how by perform the addition we could generate light neutrino states and how this addition is justified as part of a larger theory.

2.2 Electro-Weak searches

2.2.1 Oblique parameter analysis

2.2.2 The $(g-2)_\mu$ anomaly

3HDM

Conclusions

Appendix

3 Appendix

3.1 Gamma Matrices

The γ matrices are defined as,

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu} I \tag{5}$$

where,

$$g^{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \tag{6}$$

and if $\gamma_\mu = (\gamma^0, \gamma)$ then it is usual to require for the hermitian conjugate matrices,

$$\gamma^{0\dagger} = \gamma^0 \quad \text{and} \quad \gamma^\dagger = -\gamma \tag{7}$$

3.2 Lagrangian Dynamics

In Lagrangian dynamics we define the action S has,

$$\mathcal{S} = \int L\, dt = \int \mathcal{L}(\phi, \partial\phi)\, d^4x \tag{8}$$

where L is the Lagrangian, and the $\mathcal{L}$ is designated as the *Lagrangian density*, note these terms are usually used interchangeable. Here $\mathcal{L}$ is a function of the field ϕ and it's spatial derivatives.

The action S is constrained by the principle of least action, this requires the "path" taken by a field between an initial and final set of coordinates to leave the action invariant, this can be expressed by,

$$\partial\mathcal{S} = 0 \tag{9}$$

from here one can deduce the *Euler-Lagrange* equations,

$$\partial_\mu \left(\frac{\partial\mathcal{L}(\phi, \partial\phi)}{\partial(\partial_\mu)} \right) - \frac{\partial\mathcal{L}(\phi, \partial\phi)}{\partial\phi} = 0 \tag{10}$$