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Folded Supersymmetry as a candidate to solve the Hierarchy Problem of the Standard Model

Carlos Yosep Bautista Choqque

Orientador

Eduardo Pontón Bayona

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Resumo

O problema da hierarquia no Modelo Padrão surge devido à presença de divergências quadráticas provenientes de correções quânticas ao parâmetro de massa do bóson de Higgs. O presente trabalho trata sobre um recurso conhecido como Supersimetria Dobrada (*Folded Supersymmetry*), que pode ser usado para construir extensões do Modelo Padrão que estejam livres dessas divergências. Dado que a contribuição do top quark é a mais significativa, este trabalho se propõe centralizar nele demonstrando que o cancelamento é possivel mediante um parceiro do top quark de spin oposto e carga de cor diferente ao da particula top. Deve-se notar a diferencia com as teorias supersimétricas, onde o parceiro, apesar de ter spin oposto, necessariamente possui a mesma carga de cor. Finalmente, construimos uma teoria com uma dimensão espacial extra que serve como *UV Completion* para explicar a origem dos cancelamentos à energias maiores.

Palavras Chaves: Supersimetria Dobrada; Supersimetria, Modelo Padrão; Problema de hierarquia; MSSM; Dimensões extra.

Áreas do conhecimento: Além do Modelo Padrão .

Abstract

The hierarchy problem in the Standard Model arises due to the presence of quadratic divergences coming from loop corrections to the mass parameter of the Higgs boson. The present work reviews a tool known as Folded Supersymmetry that can be used to build Standard Model extensions which are free of those divergences. Since the top quark contribution is the most significant, this dissertation focuses on it showing that it is possible to cancel it out with a top quark partner with opposite spin-statistics and the same color charge as the top particle. We must note the difference with supersymmetric theories where the partner (superpartner), despite having opposite spin-statistics, necessarily has the same color charge. Finally, we construct a suitable UV completion in a 5-dimensional spacetime for the folded supersymmetric theory that explains the origin of the cancellations at higher energies.

Keywords: Folded Supersymmetry; Supersymmetry; Standard Model; Hierarchy problem; MSSM; Extra Dimensions.

Knowledge areas: Beyond the Standard Model.

Contents

Chapter 1

Introduction

There exist four known fundamental interactions in nature: electromagnetism, weak interaction, strong interaction and gravitation. In the search for unification, physicist have achieved a description of the first three of them in one theory known as the Standard Model (SM). It is, so far, the best theory to describe elementary particle interactions neglecting the effects of gravity. Its predictions have been tested with great accuracy including the discovery of the Higgs particle at the LHC in 2012. All currently known elementary particles, along with some of their properties, are listed in Table 1.1.

However, lots of phenomena are still not explained by the SM. Among them we have: the nature of dark matter, the origin of the mass of the neutrinos, the matter-antimatter asymmetry, the strong CP problem and the hierarchy problem. These suggest that the SM is, actually, an effective theory valid up to some high energy, above which new physics is expected. New physics means new particles which must have specific properties that could solve some or all those phenomena.

One of the problems that the SM faces is the Hierarchy problem, which arises when one calculates the quantum corrections to the mass parameter of the Higgs particle. It turns out that these corrections are quadratically sensitive to high energy scales, making the physical mass of the Higgs field extremely large unless an incredible fine tuning is impose, which seems to be unnatural.

Naturalness in the form of the hierarchy problem is one of the basis upon which extended realizations of the SM are constructed. In this dissertation we describe one possible way of extending the Standard Model in order to partially solve it called Folded Supersymmetry which was first introduced by Burdman, Chacko, Goh and Harnik in [1].

Particle	Mass	Electric charge	Spin
e	$0.5109989461 \pm 0000000031$ MeV	-1	1/2
ν_e	< 2 eV	0	1/2
μ	$105.6583745 \pm 0.0000024$ MeV	-1	1/2
ν_μ	< 0.19 MeV	0	1/2
τ	1776.86 ± 0.12 MeV	-1	1/2
ν_τ	< 18.2 MeV	0	1/2
u	$2.2^{+0.6}_{-0.4}$ MeV	2/3	1/2
d	$4.7^{+0.5}_{-0.4}$ MeV	$-1/3$	1/2
s	96^{+8}_{-4} MeV	$-1/3$	1/2
c	1.275 ± 0.003 GeV	2/3	1/2
b	$4.18^{+0.04}_{-0.03}$ GeV ($\overline{MS}$)	$-1/3$	1/2
t	173.21 ± 0.51 GeV	2/3	1/2
γ	$< 1 \times 10^{-18}$ eV	$< 10^{-35}$	1
$W^\pm$	80.385 ± 00151 GeV	± 1	1
Z	91.1876 ± 0.0021 GeV	0	1
g	0 (theoretically)	0	1
H^0	125.09 ± 0.11 GeV	0	0

Table 1.1: Masses, electric charges and spin of the elementary known particles.[13]

1.1 Outline of the dissertation

The present work is structured as follows.

- In Chapter 2, we present the notation and conventions used in the dissertation. We also review some concepts such as Dirac, Weyl and Majorana spinors and Grassmann numbers.

- In Chapter 3, we review the Standard Model. We show how the Higgs mechanism works in order to give mass to fermions and gauge bosons and finally we list some problems within the SM that serve as motivation for looking for extended theories.

- In Chapter 4, we review basic concepts of supersymmetry in 4 dimensions. We study the chiral and the vector supermultiplet and construct supersymmetric

Lagrangians out of them. Then we treat the minimal extension of the SM with supersymmetry, namely, the Minimal Supersymmetric Standard Model (MSSM).

- Chapter 5 deals with the topic of Extra dimensions. We study the particular case of a 5-dimensional spacetime. We introduce the concepts of orbifold and Scherk-Schwarz compactifications as well as the Kaluza-Klein decomposition.
- In Chapter 6, Folded supersymmetry is introduced. We begin by studying two examples of orbifolded theories in order to understand how they overcome the hierarchy problem and elaborate a prescription to build folded supersymmetric theories. We also note the need for a UV completion which is constructed in a 5-dimensional spacetime framework.

Appendix A and Appendix B contain derivations that are useful to understand some implications of folded supersymmetric theories and their UV completions.

Chapter 7

Conclusions

The Standard Model of particle physics is a well tested theory that predicts experimental data with great accuracy up to the range of energies currently reached. Nevertheless, we saw in Chapter 3 that experimental and theoretical issues make evident that it is incomplete and there must be new physics waiting to be understood at higher energies. One of the main problems Standard Model faces is known as Hierarchy problem and arises when we consider that the theory is valid up to a certain high energy Λ usually took as the Planck scale. Within this assumption, the Higgs mass receives large quantum corrections that are quadratically sensitive to Λ, requiring a delicate fine tuning between the bare Higgs mass parameter and the quantum corrections in order to obtain a fix value of the physical Higgs mass (measured to be 125 GeV).

One of the possible solutions to hierarchy problem is based on supersymmetry which was studied in Chapter 4. It accomplishes to avoid the large quadratic contributions by adding a new field known as superpartner for every field in the SM. The superpartners have the same properties as ordinary fields except for the spin which differ by 1/2. They generate new quadratically sensitive contributions that have the same value as that of the SM but with opposite sign making the cancellation possible and solving the hierarchy problem. However, no experimental evidence of supersymmetry has been found so far.

In Chapter 6, we studied two examples of orbifolded theories where quadratic divergences due to one loop corrections to the mass of a scalar are canceled out. One for a theory with gauge interactions and the other for a theory with Yukawa coupling. We understood that cancellations take place because in the parent theory the scalar mass enjoys bifold protection. It served us to write down a prescription for constructing a folded supersymmetric theory. Then, we used that prescription to build a folded supersymmetric toy model out of the Yukawa interaction in Standard Model. We focused in the top Yukawa interaction because it is what contributes most to quadratic divergences in the SM. By doing so, we noticed that the orbifolded theory possesses an unexplained relation between coupling parameters of different interaction terms. So, we required to build a UV completion that account for that relation. The outlined UV completion was constructed in a 5-dimensional spacetime (whose basic concepts were reviewed in Chapter 5) with $\mathcal{N} = 1$ supersymmetry and made use of appropriate Scherk-Schwarz and orbifold boundary conditions to break supersymmetry and obtain the correct effective folded supersymmetric theory at low energies.

As future perspectives we intend to analyze realistic model where folded supersymmetry is realized not only for the Yukawa sector but also for the gauge sector.

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