RICE UNIVERSITY

Search for Top Squark via All-Hadronic Decay Channels with Heavy Object Tagging

by

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ABSTRACT

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Introduction

1.1 Motivation

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Supersymmetry and the Standard Model

The fundamental theory of particle physics, known as the Standard Model (SM) can predict precise interactions between the fundamental particles in our universe. With these predictions we are able to confirm processes, but there are some aspects of the universe that have not yet been explained. In this chapter, we will analyze the Standard model and the respective models that cannot be explained.

2.1 The Standard Model

After decades of theoretical and experimental research the SM has been developed into a theory that explains the Electromagnetic (EM), Strong, and Weak force. The SM has not yet been able to include Gravity into the theory. With the robust theoretical and experimental methods used in the SM, we have discovered new elementary particles and predicted others.

2.2 The Fundamental Particles

All the matter can be explained by three kinds of elementary particles: leptons, quarks, and gauge bosons. Each of these can be distinguished by various respective properties. The leptons and quarks are fermions which are particles that have half-integer spin. The leptons are particles that only interact with the EM force, while quarks interact with the EM and Strong force. The gauge bosons are the force carries for each respective force and have integer spin.

There are three generations of leptons and quarks which are differentiated by a charge $\pm e$, the charge of an electron. The leptons have three different charged

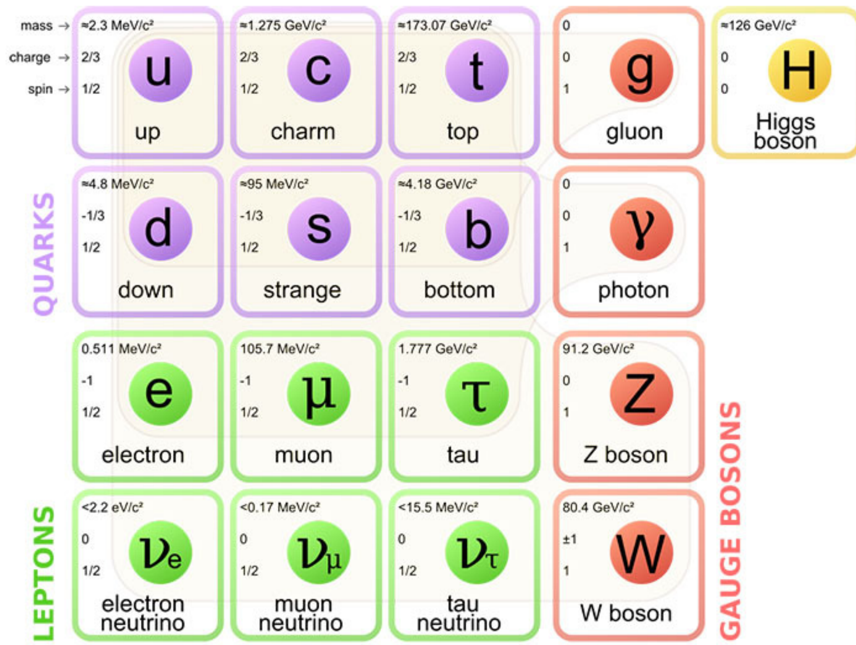

Figure 2.1 : The fundamental particles of the Standard Model. There are three generations of quarks and leptons. Along with the five bosons, where four of them relate to the interactions of the three forces included in the SM: Electromagnetism, the Weak force, and the Strong force and the final being the Higgs boson which give mass to particles.

particle: electron (e), muon (μ), and tau (τ). With each charged particle having a corresponding neutrino (ν) of the same flavour, see fig 2.1. The quarks are also separated into three generations of doublets, the down-type ($-\frac{1}{3}e$): down (d), strange (s), and bottom (b) and up-type ($\frac{2}{3}e$): up (u), charm (c), and top (t), see fig 2.1. Each of the quarks has a color associated with it with is analogous to an electric charge, except there are three colors charges: red, blue, and green.

2.3 Quantum Field Theory

The interactions of all of these particles are described by the interactions of quantized fields. These fields become operators that describe the creation and annihilation of particles. Each of the fields of the SM have a corresponding boson, see fig. 2.1.

The most well known field being the Electromagnetic (EM) field and its interactions.

First, we start with the assumption that the wave function $\psi(x)$ should transform as,

$$\psi(x) \rightarrow e^{i\alpha(x)}\psi(x), \tag{2.1}$$

where $\alpha(x)$ has an arbitrary dependence on space and time. If one were to include this into the Dirac equation you would find that it is not invariant under such a local phase transformation. To include an invariace of the field, we must include a derivative, D_μ, that is covariant under phase transformations,

$$D_\mu \equiv \partial_\mu - ieA_\mu. \tag{2.2}$$

The covariant derivative must include the vector field A_μ which must also transform as,

$$A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu \alpha. \tag{2.3}$$

So after requiring that there be a local gauge transformation, we were forced to introduce a vector field A_μ, called the guage field, which couples to Dirac particles in the same way as the photon field. We will think of this new field as the real photon field, which means we need to add a kinematic energy portion to the lagrangian. This kinematic term will be invariant under Eqn. 2.3 which leads us to final final representation of the QED lagrangian which can be written down concisely as,

$$\mathcal{L}_{QED} = \overline{\psi}(i\gamma^\mu \partial_\mu - m)\psi + e\overline{\psi}\gamma^\mu A_\mu \psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}, \tag{2.4}$$

where γ^μ are invariant tensors, ∂_μ is the partial derivative, m is the mass of the particle, ψ is the wave function of the particle, A_μ is the EM field operator, and $F^{\mu\nu}$ is the EM field tensor. Each of the parts of this equation are lorentz invariant which allows this to be true in all reference frames. This lagrangian describes the interactions of a particle and the EM field moving through spacetime.

After this we will transition from the description of the $U(1)$ EM field to the $SU(3)$ QCD field and the transformation of quark fields. A free moving quark is described by,

$$\mathcal{L}_{QCD}^{vac} = \overrightarrow{q}_j(i\gamma^\mu \partial\mu - m)q_j, \tag{2.5}$$

where q_1, q_2, and q_3 are the three color fields. From this we want the we want to require that the field is again invariant under another local phase transformation such as,

$$q(x) \rightarrow Uq(x) \equiv e^{i\alpha_a(x)T_a} q(x), \tag{2.6}$$

where U is a 3×3 unitary matix, T_a with $a = 1, ..., 8$ are a set of linearly independent traceless 3×3 matrices, and α_a are the group parameters. Since the generators T_a do not necessarily commute with each other, we can see that it is indeed non-Abelian and the commutator of can be represented as,

$$[T_a, T_b] = if_{abc}T_c, \tag{2.7}$$

where f_{abc} are constants.

We need to impose $SU(3)$ local gauge invariance on Eqn. 2.5, we allow for the following phase transformations,

$$\begin{aligned} q(x) &\rightarrow [1 + i\alpha_a(x)T_a]q(x), \\ \partial_\mu q &\rightarrow (1 + i\alpha_a T_a)\partial_\mu q + iT_a q \partial_\mu \alpha_a. \end{aligned} \tag{2.8}$$

From this is seems straight forward that we can proceed in exactly the same manner as QED, which is to add

$$G_\mu^a \rightarrow G_\mu^a - \frac{1}{g}\partial_\mu \alpha_a, \tag{2.9}$$

and a covariant derivative

$$D_\mu = \partial_\mu + igT_a G^a_\mu. \tag{2.10}$$

This will give us a similar lagrangian to the QED one derived above, but this is not sufficient for a non-Abelian gauge transformation and is does not produce a gauge-invariant Lagrangian. One final transformation is required for the G^a_μ fields to achieve gauge invariance,

$$G^a_\mu \to G^a_\mu - \frac{1}{g}\partial_\mu \alpha_a - f_{abc}\alpha_b G^c_\mu, \tag{2.11}$$

This finally give us a gauge invariant kinetic energy term for all of the G^a_μ fields and thus we can write the QCD interactions as,

$$\mathcal{L}_{QCD} = \overline{q}(i\gamma^\mu \partial_\mu - m)q - g(\overline{q}\gamma^\mu T_a q)G^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a. \tag{2.12}$$

From all of this we seem to be missing a vital part of the SM, specifically a theory for the Weakly interacting processes which are mediated by the massive bosons, W and Z from fig. 2.1. This requires the Higgs Mechanism.

2.4 The Higgs Mechanism

We are interested in the spontaneous symmetry breaking of a local $SU(2)$ gauge symmetry. We are interested in the following $SU(2)$ Lagrangian,

$$\mathcal{L} = (\partial_\mu \phi)^\dagger(\partial^\mu \phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2, \tag{2.13}$$

with ϕ being a $SU(2)$ doublet of complex scalar fields

$$\phi = \frac{1}{2}\begin{bmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{bmatrix} \tag{2.14}$$

and is invariant under global $SU(2)$ phase transformations $\phi \to e^{i\alpha_a \tau_a/2}\phi$

2.5 Fundamental Problems in the Standard Model

The SM has been able to accurately and precisely describe many facits of the universe. Whether is comes to predicting the existance of a sixth quark or the confirmation of the $g-2$ of the muon to 9 orders of magnitude. Unfortunately, there is some evidence of matter or interactions that cannot be described such as dark matter, the Hierarch problem, or a possible grand unified theory. Let's look into each of these further.

2.5.1 Dark Matter

The amount of visible matter in the universe does not explain all of the measurable matter. This has most notibly been seen in the radial velocity of galaxies. In a universe which is solely made up of visible matter, matter that interacts with light, the radial velocity of stars should decrease the further away it is from the galactic nuclei. Though measurements show the velocity becoming constant as a function of radius. To reproduce these features in models, the mass of the galaxy must be significantly more that what is seen. This implies some unseen dark matter, that still interacts with the gravitational field but not with the EM field.There is currently no such particle that has these properties in the SM.

2.5.2 Hierarchy Problem

The higgs boson is a beautiful solution to electroweak symmetry breaking and gives a method for particles to aqcuire mass and was discovery to have a measured mass, $m_H = 125.15$ GeV. This value though is not predictable with the SM and leads to some inconsistencies when you include loop corrections. Since the higgs is strongly coupled to particles with large masses, the dominant loop correction will be due to interactions with t. These higher order loop corrections to the higgs mass, m_H^2, caused by the fermionic t loop, see fig 2.2, is

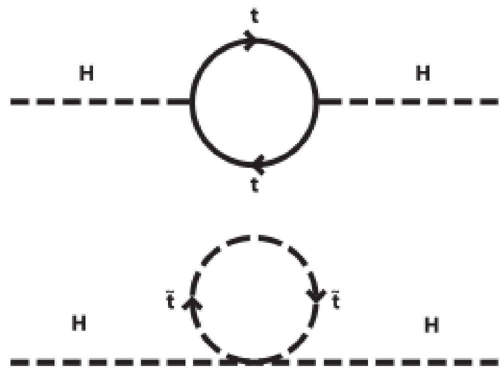

Figure 2.2 : The loop corrections to the Higgs boson interacting with a top quark and its superpartner the top squark. This is only the NLO corrections to the Higgs boson mass.

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots, \tag{2.15}$$

where λ_f is the vertex factor for the respective fermion and Λ_{UV} is the ultraviolet momentum cutoff. The higgs boson loop corrections are highly dependent on all virtual and real particles that couple to the higgs field. From this, we can see the corrections from Eqn. 2.15 for each fermion in the SM will cause a large divergence. The quadratic divergence of the higgs mass is only renormalizable with a fine tuning of the parameters λ_f and Λ_{UV}. This means the only way for the SM to reconcile this unfortunate fact is to have a relatively luck cancellation of very large numbers of order 10^{32} with equally small numbers. If we look at the contribution with the addition a scalar partner to the fermion the higgs loop corrections reduce to,

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda_{UV}^2 - 2m_S^2 ln(\Lambda_{UV}/m_S) + \cdots]. \tag{2.16}$$

With the introduction of a scalar partner to the t, there is a logarithmic divergence to the higgs boson mass and can be renormalized through the normal methods.

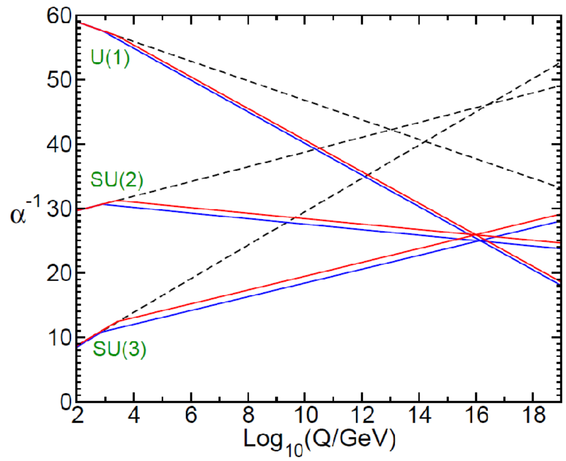

Figure 2.3 : The energy dependence of the inverse gauge couple of each force in the SM (dashed line) and the MSSM (solid lines). The MSSM gives two thresholds for the sparticle mass 750 GeV and 2.5 TeV.

2.5.3 Grand Unified Theory

The SM is able to accurately describe three of the fundamental sources at typical energy scales, 1 to 10^4 GeV, but idealy the forces would be able to merge into a single force at high energies. This has not been directly observed, but many theories, such as SUSY, predict its existance

2.6 Superpartners

With no additional information to hint at physics at scale about the TeV range, it seems that we need a new framework for physics at the reduced Planck scale $M_P = (8\pi G_{Newton})^{-1/2} = 2.4 \times 10^{18}$ GeV, which is the scale at which quantum gravitational effects become important. The ratio of M_p/M_W is a strong hint that there is more physics at scales beyond the SM. The Higgs field will become extremely important at these higher energy scales

Supersymmetry is broken into Chiral supermultiplets, which are fields that contain equal numbers of fermions and bosons. Each of these supermultiplets can transform and interact with each other.

2.6.1 Chirality

Equal numbers of fermions and bosons. How does the spin change?

2.7 Minimal Supersymetric Standard Model

Soft supersymetry breaking.

2.7.1 R Parity

New conserved parameter known as R parity. With this is allows for a stable particle that is a dark matter candidate. Other consequences.

2.8 Mass Spectrums

Higgs boson corrections. spectrum of squarks.

Chapter 3

Compact Muon Solenoid

3.1 Introduction

Located near Geneva, switzerland as part of the CERN collaboration. LHC provides proton beams

General CMS facts. What kind of particles is it meant to detect? What are the subdetectors? Tracker, ECAL, HCAL, superconducting solenoid, muon chambers

3.2 Silicon Tracker

3.2.1 Pixel Detector

What is it? Newly installed pixel detector. Larger particle flux and data rate. What is the design of the modules? How do they work? Increased efficiency for B tagging.

3.2.2 Silicon Strips

How is it different from the pixels?

3.3 Electromagnetic Calorimeter

What kinds of particles does this detect? Mechanism?

3.4 Hadronic Calorimeter

What kinds of particles does this detect? Mechanism?

3.5 Superconducting solenoid

Iron yoke? how strong? Purpose?

3.6 Muon Chambers

What kinds of particles does this detect? Mechanism?

Chapter 4

Stop quark Production and Backgrounds

In SUSY, spedifically the Minimally Supersymmetric Model (MSSM), the top squark $(\widetilde{t})$ is a bosonic superpartner to the top quark and should have a mass on the same scale as t. This is due to the strong mising between left and right superpartners to form eigenstates,

$$M_{\tilde{q}}^2 = \begin{bmatrix} \widetilde{M}_Q^2 + M_Q^2 + M_Z^2(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\cos 2\beta & M_Q(A_T + \frac{\mu}{\tan\beta}) \\ M_Q(A_T + \frac{\mu}{\tan\beta}) & \widetilde{M}_U^2 + M_Q^2 + \frac{2}{3}M_Z^2\sin^2\theta_W\cos 2\beta \end{bmatrix} \quad (4.1)$$

This causes one of the $\widetilde{t}$to have one eigenstate that is the smallest for the quarks, see fig.

4.1 Production and Decay Modes

Gluon fusion.

Main decay mode mode $\tilde{t} \to t + \tilde{\chi}_1^0$, $\tilde{t} \to b + \tilde{\chi}^+$. The top quark most likely decays into a b quark and W boson.

4.2 Standard Model Background

Signal events can be mimicked by SM events that have a large number of jets and missing energy.

Broken up into four major backgrounds, Lost Lepton (LL), Znunu, QCD, Rare decays

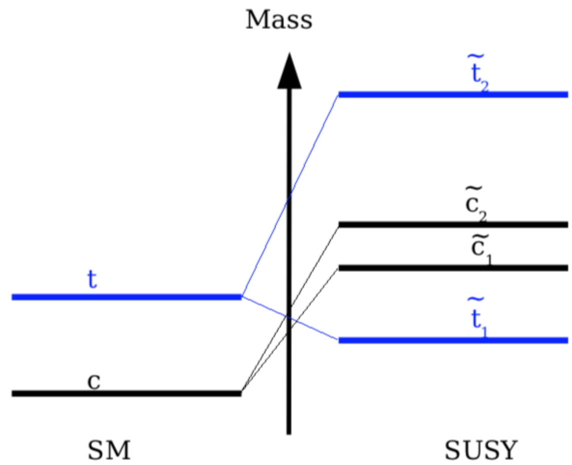

Figure 4.1 : On the right we have the arbitrary masses of the top and charm quarks.

4.2.1 Lost Lepton

$t\bar{t}$ production of ttbar via the same mechanism as stop-antistop which can be gluon fusion. They then decay the same why as explained above.

W+jets: Production of W bosons plus jets. Jets can be tagged as b jets. W boson decay hadronically or leptonically (where the lepton is missed)

tW and ttW: Missed lepton

4.2.1.1 Transfer Factors

We want to suppress signal contamination by requiring $M_T(l, \not{E}_T) < 100$ GeV. This requirement confirms that it is orthogonal to the search reagions that are used in the search for direct top squark production in the single-lepton final state. Letting the two anaysis statistically combine the results in the future.

We are looking at the event count of data in each corresponding CR for the single-lepton sample. The prediction is allowed by means of a transfer factor (TF) which is obtained from simulation,

$$N_{pred}^{LL} = TF_{LL} \cdot N_{data}(1l). \tag{4.2}$$

This allows us to have the same selection for the single-lepton control sample and the zero-lepton sample. The only exception is the number of top and W-tagged candidates? what is the difference betweeen a candidate and a particle?

The LL estimation is dependent on the yield of data in the corresponding CR and the TF calculated by the single-lepton sample. The transfer factor is defined as,

$$TF_{LL} = \frac{N_{MC}(0l)}{N_{MC}(1l)}, \tag{4.3}$$

where $N_{MC}(1l)$ is the event count observed in the corresponding CR and $N_{MC}(0l)$ use the event count in the corresponding SR.

4.2.2 Z Boson Decay to Neutrinos

Znunu: production of a Z boson that decays into two nuetrinos which are then missed by the detector. Can have jets from other quarks/gluons in the interaction

4.2.3 Quantum Chromodynamic Events

QCD: Events that of jets produced by QCD processes. The missing energy from from a mismeasurement of the jets in the event causing missing energy

4.2.4 Rare Interactions

ttZ, ttH, WW, WZ, ZZ, tZq, tWZ: rare processed that can have jets plus MET. Expand upon these later

Chapter 5

Search Region Design

Using MC simulations that model the SM background for this process we want to reduce the number of events in our Search region. This is an all hadronic search so we are looking at event with zero tagged leptons. Unfortunately, some can get in by not passing the kinematic cuts or just by the non 100 % of the detector. There is a small nonzero inefficiency of mistagging a lepton as something else.

5.1 Minimizing the ttZ background

For the ttZ interactions, we produce two top quarks that can then decay to two b quarks and two W bosons. A possible way to mimick our search region is two have multiple jets, i.e. b quarks that hadronize and W bosons that decay hadronically, but we also need missing energy. This will be in addition to the Z boson decaying into two neutrinos and thus creating a large amount of missing energy.

We now try to look at the differing kinematic structure of the background, ttZ, and the signal region, stop quarks decaying. Under the assumption that the Z boson is created by radiated from the top quark the resulting decay to neutrinos should be close, small $\Delta\phi$, between the resulting jets. For the signal, the missing energy is produced by the neutralino. When the stop quark decays into top quark and neutralino the top quark should recoil off of neutralino to essentially be back-to-back. This will cause a large angle, $\Delta\phi$, between them. We then want to use the kinematic variable, $\Delta\phi(t_{1,2}, \not\!\!E_T)$, where

5.2 Lost Lepton Application

Can we apply this to other backgrounds. For boosted tops the the missing energy caused by missing the lepton in the W boson decay. The variable $\Delta\phi(t_{1,2}, \not{E}_T)$should also apply. Should work for wjts, tW, ttW.

5.3 Search Regions

The HM and LM Search regions should be defined and explained. Why are they defined the way they are?

5.4 Search Region Optimization

Look for an optimized custs for $\Delta\phi(t_{1,2}, \not{E}_T)$to maximize $\frac{S}{\sqrt{B}}$ in each SR. Could have a different cut for each region, but a combination to make it all the same would be nice. Since the signal can decay in multiple ways we need to optimize for all possible scenarios. Explain why we are maximizing $\frac{S}{\sqrt{B}}$

5.5 Limits

Looking at the significance and limits for the mass regions of the stop quark decay. Using the Higgs Combined tool, which includes statistics with a "maximal likelihood" fit? The cut, $\Delta\phi(t_{1,2}, \not{E}_T)$, would hopefully improve the values, but an optimized cut has not been chosen yet.