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, look at some specific shortcomings, and introduce supersymmetry as a possible solution.

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 and Weak force, while quarks interact with all of the forces of the SM. 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

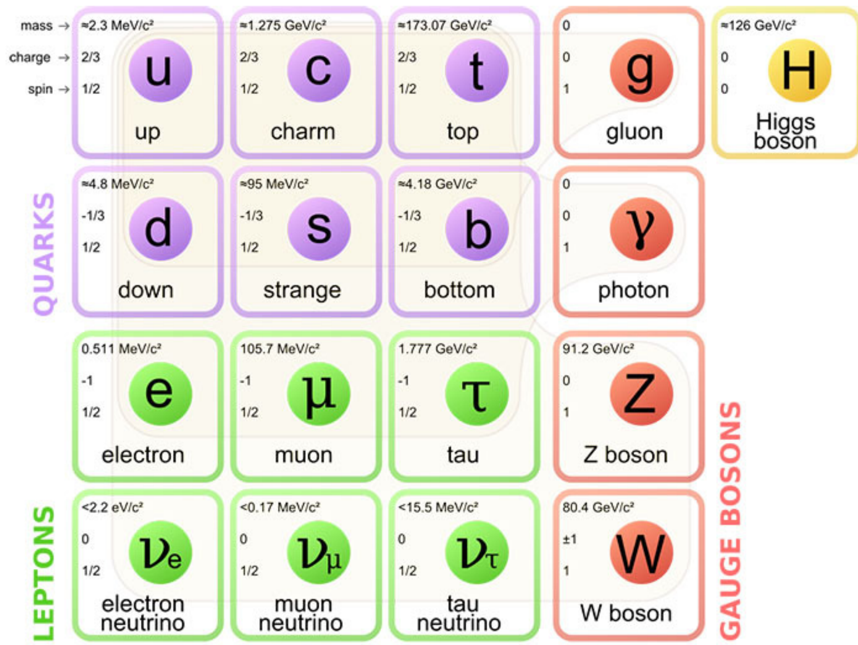

Figure 2.1 : The fundamental particles of the Standard Model. There are three generations of quarks and leptons. Along with the five bosons, where four of them relate to the interactions of the three forces included in the SM: Electromagnetism, the Weak force, and the Strong force and the final being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

a charge $\pm e$, the charge of an electron. The leptons have three different charged particles: 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 quantized fields whose operators describe the creation and annihilation of particles. Each of the fields of the

SM have a corresponding gauge boson, see fig. 2.1. The most well known being the EM field and its interactions. Now we want to be able to write down a concise theory of the particles in the SM. To do this, the symmetry and conservation laws of the SM can be derived by starting with Noether's Theorem.

2.4 Noether's Theorem

Noether's theorem states, "to each symmetry of a local Lagrangian, there corresponds a conserved current. This can be done by allowing for an infinitesimal symmetry variation. This requires the Lagrangian to be invariant under $\phi(x) \to \phi\prime(x) = \phi(x) + \alpha\Delta\phi(x)$, where α is infinitesimal real parameter and $\Delta\phi$ is a deformation to the field, up to a 4-divergance,

$$\mathcal{L}(x) \to \mathcal{L}(x) + \alpha\partial_\mu \mathcal{J}^\mu(x), \tag{2.1}$$

where $\mathcal{J}^\mu$ is a current. If we apply the Euler-Lagrange equation,

$$\partial_\mu(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)}) - \frac{\partial\mathcal{L}}{\partial\phi} = 0, \tag{2.2}$$

on Eqn. 2.1 with the addition of the fluctuation of the particle field. After some simplification we get a conserved current,

$$\begin{aligned} &\partial_\mu j^\mu(x) = 0, \text{ where} \\ &j^\mu(x) = \frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)}\Delta\phi - \mathcal{J}^\mu \end{aligned} \tag{2.3}$$

.

We see from the above equation that the current $j^\mu(x)$ of the Lagrangian is conserved. Now let's apply this to the particle fields of the SM.

2.5 QED

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

$$\psi(x) \rightarrow e^{i\alpha(x)}\psi(x), \tag{2.4}$$

where $\alpha(x)$ has an arbitrary dependence on space and time.

If one were to include this into the Lagrangian for a spin-1/2 particle in a vacuum,

$$\mathcal{L} = i\overline{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\overline{\psi}\psi \tag{2.5}$$

you would find that it is not invariant under such a local phase transformation. In Eqn. 2.5, the γ^{μ} are the Dirac matrices, ∂_{μ} is the partial derivative, m is the mass of the particle. To allow for the field to be invariant, we must include a derivative, D_{μ}, that is covariant under phase transformations,

$$D_{\mu} \equiv \partial_{\mu} - ieA_{\mu}. \tag{2.6}$$

The covariant derivative must include the vector field A_{μ} which must also transform as,

$$A_{\mu} \rightarrow A_{\mu} + \frac{1}{e}\partial_{\mu}\alpha. \tag{2.7}$$

So after requiring that there be a local gauge transformation, we were forced to introduce a vector field A_{μ}, called the gauge 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. 2.7 which leads us to final representation of the QED lagrangian which can be written down concisely as,

$$\mathcal{L}_{QED} = \overline{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi + e\overline{\psi}\gamma^{\mu}A_{\mu}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}, \tag{2.8}$$

where A_μ is the EM field operator, and $F^{\mu\nu}$ is the EM field tensor. This lagrangian describes the interactions between spin-1/2 charged particles and the $U(1)$ EM force. Each of the parts of this equation are lorentz invariant which allows this to be true in all reference frames.

2.6 QCD

Let's now 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,

$$\mathcal{L}_{QCD}^{vac} = \overline{q}_j(i\gamma^\mu \partial\mu - m)q_j, \tag{2.9}$$

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

$$q(x) \rightarrow Uq(x) \equiv e^{i\alpha_a(x)T_a}q(x), \tag{2.10}$$

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,

$$[T_a, T_b] = if_{abc}T_c, \tag{2.11}$$

where f_{abc} are constants.

We need to impose $SU(3)$ local gauge invariance on Eqn. 2.9, we allow for the following phase transformations,

$$\begin{aligned} &q(x) \rightarrow [1 + i\alpha_a(x)T_a]q(x), \\ &\partial_\mu q \rightarrow (1 + i\alpha_a T_a)\partial_\mu q + iT_a q \partial_\mu \alpha_a. \end{aligned} \tag{2.12}$$

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

$$D_\mu = \partial_\mu + igT_a G^a_\mu. \tag{2.13}$$

where the field G^a_μ transforms as

$$G^a_\mu \rightarrow G^a_\mu - \frac{1}{g}\partial_\mu \alpha_a. \tag{2.14}$$

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 it does not produce a gauge-invariant Lagrangian. One final transformation is required for the G^a_μ fields,

$$G^a_\mu \rightarrow G^a_\mu - \frac{1}{g}\partial_\mu \alpha_a - f_{abc}\alpha_b G^c_\mu. \tag{2.15}$$

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

$$\mathcal{L}_{QCD} = \overline{q}(i\gamma^\mu \partial_\mu - m)q - g(\overline{q}\gamma^\mu T_a q)G^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a. \tag{2.16}$$

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

2.7 Weak Force

The Weak force is responsible for nuclear decay. It is a $SU(2)$ vector-axial (V-A) interaction. As a small aside, the bilinear quantities $\overline{\psi}(4 \times 4)\psi$ have certain properties under lorentz transformations when the 4×4 matix is a γ-matrices. These are of the form,

Type	Form	Components	Space Inversion
Scalar	$\overline{\psi}\psi$	1	$+$ under P
Vector	$\overline{\psi}\gamma^{\mu}\psi$	4	Space compts.: $-$ under P
Tensor	$\overline{\psi}\sigma^{\mu\nu}\psi$	6	
Axial Vector	$\overline{\psi}\gamma^{5}\gamma^{\mu}\psi$	4	Space compts.: $+$ under P
Pseudoscalar	$\overline{\psi}\gamma^{5}\psi$	1	$-$ under P

Table 2.1 : Some words of explanation

$$\gamma^0 = \begin{bmatrix} \boldsymbol{I} & 0 \\ 0 & -\boldsymbol{I} \end{bmatrix}, \boldsymbol{\gamma} = \begin{bmatrix} 0 & \boldsymbol{\sigma} \\ -\boldsymbol{\sigma} & 0 \end{bmatrix}, \gamma^5 = \begin{bmatrix} 0 & \boldsymbol{I} \\ \boldsymbol{I} & 0 \end{bmatrix} \tag{2.17}$$

where the $\boldsymbol{I}$ is the identity matrix and $\boldsymbol{\sigma}$ are the Dirac matrices. We can combine the first two parts of Eqn. 2.17 we can write is compactly as γ^{μ} where $\mu = 0, 1, 2, \text{and } 3$. The possible interesting quantities of the above transformations are shown in Table 2.1.

The Weak force has an interaction of the type $\frac{1}{2}\gamma^{\mu}(1-\gamma^5)$ so it is an Vertex-axial interaction. From this, we can conclude that it violates Parity. Parity is an transformation from $(x, y, z) \rightarrow (-x, -y, -z)$ or space inversion. Since it violates Parity, the next step is to consider a conservation of CP, where C is charge conjugation (particle-to-antiparticle).

The main experimental implications of this proposed conservation com from the decay of the neutral Kaon, $K^0(\overline{s}d)$ and $\overline{K}^0(s\overline{d})$. These have two CP states which are, $CP\,|K^0\rangle = -\,|\overline{K}^0\rangle$, and $CP\,|\overline{K}^0\rangle = -\,|K^0\rangle$. Once we normalize these eigenstates of CP we get the corresponding wavefunctions,

$$|K_1\rangle = \left(\frac{1}{\sqrt{2}}\right)(|K^0\rangle - |\overline{K}^0\rangle) \text{ and } |K_2\rangle = \left(\frac{1}{\sqrt{2}}\right)(|K^0\rangle + |\overline{K}^0\rangle),$$

where each has the invariance $CP\,|K_1\rangle = |K_1\rangle$ and $CP\,|K_2\rangle = -\,|K_2\rangle$. The two Kaon states are expected to decay into either two pions or three pions for $|K_1\rangle$ and

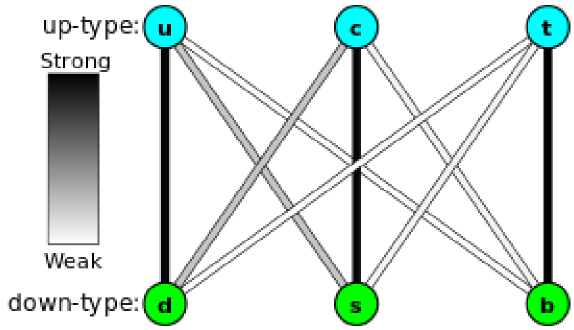

Figure 2.2 : https://en.wikipedia.org/wiki/Cabibbo%E2%80%93Kobayashi%E2%80%93Maskawa_m

$|K_2\rangle$, respectively. Since there is a greater energy release in the $|K_1\rangle$ state the lifetime of that particle is thought to be less than $|K_2\rangle$. After experimenting on the purity of Kaon decays after a long distance away from the interaction point, we have found that it is possible for the $|K_1\rangle$ to decay into three pions. This is direct evidence of Weak decays violating CP conservation.

Now the Weak force is mediated by two vector bosons, W and Z see fig. 2.1. These are unlike the other forces because these vector bosons have a large mass of $m_W = 80.379 \pm 0.012$ GeV and $m_Z = 91.1876 \pm 0.0021$ GeV. The W boson is a charged particle and interacts with many nuclear decays.

The W boson interacts very interestingly for quarks in the SM. There is a mixing of flavors of quarks for particles. They will mix between partners between up-type and down-type particles, see fig. 2.2. [Kobayashi, M. and Maskawa, K. (1973) Progress in Theoretical Physics, 49, 652]. The interactions for the generalized three generations of quarks is known as the CKM (Cabibbo-Kobayashi-Maskawa) matrix,

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}, \tag{2.18}$$

where for example, V_{ud} is the coupling of u to d which is exactly $(d \to u + W^+)$.

This matrix can be reduced to a form which has three generalized Cabibbo angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and a phase factor ($\delta$). The coupling between the third generation does not mix with the other two generations. From that we can recover the Cabibbo-GIM matrix[cite here]. For the moment, we can only experimentally determine the values from experiment.

The Z boson is whats known as the neutral current. This boson mediates forces between particles and its respective antiparticles. This is mainly seen in the form of neutrino-nucleon scattering, which has to be a neutral interaction such as,

$$\begin{aligned} \overline{\nu}_\mu + N \rightarrow \overline{\nu}_\mu + X \\ \nu_\mu + N \rightarrow \nu_\mu + X \end{aligned} \tag{2.19}$$

This requires the Higgs Mechanism.

2.8 The Higgs Mechanism

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

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2, \tag{2.20}$$

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

$$\phi = \frac{1}{2} \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{bmatrix} \tag{2.21}$$

and is invariant under global $SU(2)$ phase transformations $\phi \rightarrow e^{i\alpha_a \tau_a/2}\phi$. To allow for local invariance, we first allow for a covariant derivative

$$D_\mu = \partial_\mu + ig\frac{\tau_a}{2} W_\mu^a, \tag{2.22}$$

where we now have three gauge fields, W_μ^a with $a = 1, 2, 3$. If we assume an infanitesimal gauge transformation for the $SU(2)$ doublet $\phi(x) \to \phi'(x) = (1 + i\boldsymbol{\alpha}(x) \cdot \boldsymbol{\tau}/2)\phi(x)$, then the gauge fields will transform as

$$\boldsymbol{W}_\mu \to \boldsymbol{W}_\mu - \frac{1}{g}\partial_\mu \boldsymbol{\alpha} - \boldsymbol{\alpha} \times \boldsymbol{W}_\mu. \tag{2.23}$$

You can see that Eqn. 2.23 is just the compact vector transform of Eqn. 2.15 where we have replaced the QCD gauge field with the three gauge fields W_μ^a. If we include these locally invariant transformations into the above $SU(2)$ Lagrangian we get

$$\mathcal{L} = (\partial_\mu \phi + ig\frac{1}{2}\boldsymbol{\tau} \cdot \boldsymbol{W}_\mu \phi)^\dagger (\partial^\mu \phi + ig\frac{1}{2}\boldsymbol{\tau} \cdot \boldsymbol{W}^\mu \phi) - \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 - \frac{1}{4}\boldsymbol{W}_{\mu\nu} \cdot \boldsymbol{W}^{\mu\nu}, \tag{2.24}$$

where the inclusion of the gauge field kinetic term has been included at the end. The most interesting regions of this lagrangian is when $\mu^2 < 0$ and $\lambda > 0$, where the potential has a minimum at $\phi^\dagger \phi = -\frac{\mu^2}{2\lambda}$. With this we will expand the potential around the minimum and require that

$$\phi_1 = \phi_2 = \phi_4 = 0, \phi_3^2 = -\frac{\mu^2}{2\lambda} \equiv v^2. \tag{2.25}$$

This is the spontaneous symmetry breaking of the $SU(2)$ symmetry, because of this we are able to substitute an expansion for the field

$$\phi = \sqrt{\frac{1}{2}} \begin{bmatrix} 0 \\ v + h(x) \end{bmatrix} \tag{2.26}$$

With this specific transformation of the $SU(2)$ doublet and the simplification of Eqn. 2.24, the only remaining field is $h(x)$ which is refered to as the Higgs field. This is what is known as the Higgs Mechanism for a $SU(2)$ symmetry.

2.9 Electroweak

We want to include the methods of the Higgs Mechanism into the weak isospin and weak hypercharge,$SU(2)_L \times U(1)_Y$, transformations of electoweak interactions. First, we need to include the coupling of the weak current $\boldsymbol{J}_\mu$ and the gauge field $\boldsymbol{W}^\mu$ such that,

$$-ig\boldsymbol{J}_\mu \cdot \boldsymbol{W}^\mu = -ig\overline{\chi}_L \gamma_\mu \boldsymbol{T} \cdot \boldsymbol{W}^\mu \chi_L \tag{2.27}$$

which is the basic interaction for the $SU(2)_L$ symmetry. Then, we also need to include the weak hypercharge current with the fourth vector boson B^μ,

$$-i\frac{g'}{2} j_\mu^Y B^\mu = -ig'\overline{\psi}\gamma_\mu \frac{Y}{2}\psi B^\mu, \tag{2.28}$$

here the operators $\boldsymbol{T}$ and Y are generators for the $SU(2)_L$ and $U(1)_Y$ gauge transformations, respectively. Now we combine the two symmetries with the transformations of the left and right hand components of ψ as

$$\begin{aligned} \chi_L \rightarrow \chi_L' &= e^{i\boldsymbol{\alpha}(\boldsymbol{x})\cdot \boldsymbol{T} + i\boldsymbol{\beta}(\boldsymbol{x})\boldsymbol{Y}} \chi_L, \\ \psi_R \rightarrow \psi_R' &= e^{i\beta(x)Y}\psi_R \end{aligned} \tag{2.29}$$

from this we can write down the contributions of the two gauge fields W_μ^3 and B_μ and the mising angle θ_W to find the interactions of the two neutral currents. The physical fields are thus,

$$-igJ_\mu^3 W^{3\mu} - i\frac{g'}{2} j_\mu^Y B^\mu = -iej_\mu^{em}\boldsymbol{A}^\mu - \frac{ie}{sin\theta_W cos\theta_W}[J_\mu^3 - sin^2\theta_W j_\mu^{em}]Z^\mu. \tag{2.30}$$

From this we can write down the Electroweak Lagrangian, for any fermion that interacts with the field. Moreover, we can formulate the Higgs mechanism, such that we can calculate the theoretical masses of the gauge bosons and fermions as,

$$
\begin{aligned}
M_W &= \frac{1}{2} v g \\
M_Z &= \frac{1}{2} v \sqrt{g^2 + g'^2},
\end{aligned}
\tag{2.31}
$$

but these masses cannot be predicted since they depend on the values from the chosen Higgs field.

2.9.1 The Standard Model Lagrangian

With the inclusion of the Higgs mechanism and the formulation of a local gauge invariant Lagrangian for the Electroweak and QCD fields, we have the complete SM Lagrangian as,

$$
\begin{aligned}
\mathcal{L} = &- \frac{1}{4} \boldsymbol{W}_{\mu\nu} \boldsymbol{W}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
&+ \overline{L} \gamma^{\mu} (i\partial_{\mu} - g \frac{1}{2} \boldsymbol{\tau} \cdot \boldsymbol{W}_{\mu} - g' \frac{Y}{2} B_{\mu}) L \\
&+ \overline{R} \gamma^{\mu} (i\partial_{\mu} - g' \frac{Y}{2} B_{\mu}) R \\
&+ |(i\partial_{\mu} - g \frac{1}{2} \boldsymbol{\tau} \cdot \boldsymbol{W}_{\mu} - g' \frac{Y}{2} B_{\mu}) \phi|^2 - V(\phi) \\
&- (G_1 \overline{L} \phi R + G_2 \overline{L} \phi_c R + \text{hermitian conjugate}),
\end{aligned}
\tag{2.32}
$$

where the first terms are the kinetic energies and self-interations of the $W^{\pm}, Z,$ andγ bosons, the second and third terms are the kinetic energies and interactions of the leptons and quarks with the $W^{\pm}, Z,$ andγ bosons where L is a left-handed fermion doublet and R is a right-handed fermion singlet. The fourth term is the $W^{\pm}, Z, \gamma$ and Higgs masses and couplings. The final term is the lepton and quark masses and couplings to the Higgs field.

2.10 Fundamental Problems in the Standard Model

The SM is 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

$g-2$ for 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, and a possible grand unified theory. Let's look into each of these further.

2.10.1 Dark Matter

The main motivation for Dark Matter is the difference between the visible matter and the measureable matter in the universe. This has most notibly been seen in the radial velocities of stars in galaxies. In a galaxy which is solely made up of visible matter, matter that interacts with light, the radial velocity of stars should decrease as $1/\sqrt{r}$ the further away it is from the galactic nuclei. Though measurements show the velocity becoming constant as a function of radius.

The original sutdy of this was from the galaxy NGC 1560, where the measured galactic velocity curve provided a result that was 400 times large than the visible matter in the cluster (A. H. Broeils Astron. and Astrophys. 256 19 (1992)). 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 in the SM that has these properties.

2.10.2 Hierarchy Problem

The higgs boson is a beautiful solution to electroweak symmetry breaking and gives a method for particles to aqcuire mass, see Eqn. 2.20, and was discovery to have a measured mass of $m_H = 125.18 \pm 0.16$ 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 is due to interactions with the t quark. These higher order loop corrections to the higgs mass, m_H^2, caused by the fermionic t loop, see fig 2.3, are

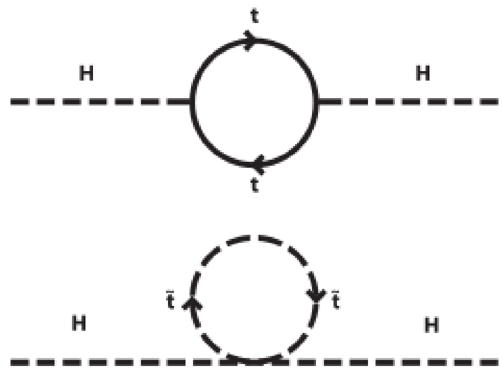

Figure 2.3 : The loop corrections to the Higgs boson interacting with a top quark and its superpartner the top squark. This is only the NLO corrections to the Higgs boson mass.

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots, \tag{2.33}$$

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. 2.33 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 lucky cancellation of very large numbers of order 10^{32} with equally small numbers. Fortunately, if we add the contribution of a bosonic partner of the fermion the higgs loop corrections reduce to,

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda_{UV}^2 - 2m_S^2 ln(\Lambda_{UV}/m_S) + \cdots]. \tag{2.34}$$

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.

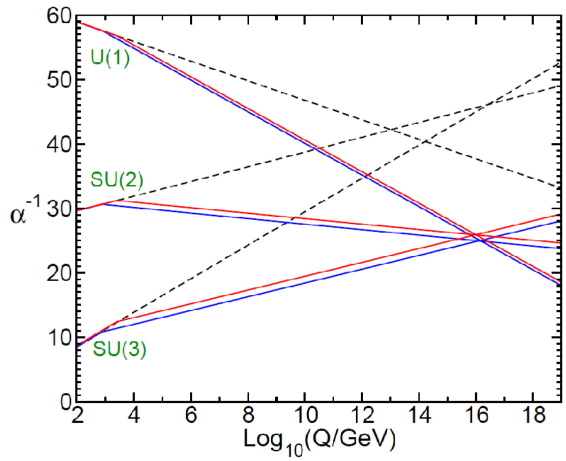

Figure 2.4 : The energy dependence of the inverse gauge couple of each force in the SM (dashed line) and the MSSM (solid lines). The MSSM gives two thresholds for the sparticle mass 750 GeV and 2.5 TeV.

2.10.3 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.

At standard energy for particle physics experiments the difference in the strength of each force is quite noticeable. But it has been shown that in the SM the strengths of each force is dependent on the energy scale and it would be ideal that they converge to a single force at large energies, such as 10^{16} GeV. In fig. 2.4, we see the extrapolated energy scales of the forces in the SM shown as the dotten line. These unfortunately, do not meet at a single point to become one force, but if we include supersymmetry into the model we get a nice convergence between the forces.

2.11 Supersymmetry

We have seen from the above three problems that there is still more to learn. Some of the unexpainable features of the universe, such as; dark matter, the hierarchy problem, and a grand unified theory have not been explained. We saw from the Hierarchy problem that the addition of a bosonic partner to a fermion will allow for the loop corrections to be renormalizable without fine tuning. Forturnately, some theories have allowed for such problem to be solved. Namely the theory of supersymmetry (SUSY) which essentially states that each particle in the SM has a superpartner that has only the spin changed, that every fermion has a bosonic partner that has all the same parameters except the spin differ by 1/2, and vice-versa.

The partners to the fermions are donoted with a 's' in front of the name to notify that it is the scalar form of the particle and the partners to the bosons have a 'ino' attached at the end, such as photino, gluino, wino, and higgsino. So for the partners to the fermionic particles in the standard model we have: sup ($\widetilde{u}$), sdown ($\widetilde{d}$), scharm ($\widetilde{c}$), sstrange ($\widetilde{s}$), stop ($\widetilde{t}$), and sbottom ($\widetilde{b}$) for the squarks and selectron ($\widetilde{e}$), smuon ($\widetilde{\mu}$), and stau ($\widetilde{\tau}$) for the charged sleptons. The partners to the neutrinos, which are always left-handed if you neglect the minimal masses, are sneutrinos ($\widetilde{\nu}_e, \widetilde{\nu}_\mu, \widetilde{\nu}_\tau$), where whe have one for each flavor of lepton.

If the SUSY was unbroken the superpartners would have exactly the same properties as the SM pairs except their spin. This would cause a massless photino or a $m_{\widetilde{e}} = 0.511$ keV selectron. These particles would certainly have been detected at this point, which leads us to think that SUSY is a broken symmetry where all the superpartners have a mass that is significantly higher than their SM partners.

2.11.1 Supermultiplets and Chirality

A supermultiplets is any symmetry where the number of bosonic degrees of freedom and fermionic degrees of freedom are equal, $n_B = n_F$. The simplest way to achieve this is to have a combination of a single Weyl fermion, which has two spin helicity states, $n_F = 2$, and two real scalars with each having $n_B = 1$. It becomes convenient for the mathematics to combine the two real scalars into one complex scalar field. Now the combination of a complex scalar field and a Weyl fermion is known as a chiral supermultiplet.

2.12 Minimal Supersymetric Standard Model

We have discussed how the fermions transform under the rules of SUSY, but how do the scalar field mediators translate into this new framework. First, lets look at the Higgs boson. We know that there is not only one chiral supermultiplets. If there was only one in the electroweak gauge symmetry, with a Higgsino of spin-1/2, would not have the anomaly cancellation of the traces, $Tr[T_3^2 Y] \neq 0$ and $Tr[Y^3] \neq 0$, where T_3 is the third component of weak isospin and Y is the weak hypercharge. In the SM, the traces of these for the fermions are already satified. We must include two chiral supermultiplets of the Higgsino, with $Y = \pm\frac{1}{2}$, see table 2.2.

It turns out that this is also necessary for the Higgsino to give mass to different particles in the SM. A Higgs with $Y = 1/2$ has the Yukawa couplings that allow it to interact with the up-type quarks (u, c, t). Only a Higgs with $Y = -1/2$ has the correct Yukawa couplings to interact with the down-type quarks (d, s, b) and the charged leptons (e, μ, τ).

The SM vector boson will also have a corresponding supermultiplet. They have fermionic superpartners that are referred to as gauginos. For the $SU(3)_C$ color gauge interactions of QCD, which are a spin-1/2 color-octet, has a partner called a gluino ($\widetilde{g}$). The electroweak gauge theory $SU(2)_L \times U(1)_Y$ has the superpartners $\widetilde{W}^+, \widetilde{W}^0, \widetilde{W}^-$, and $\widetilde{B}^0$ each with spin-1/2, called winos and bino, see table 2.3. The gaugino mixtures of $\widetilde{W}^0$ and $\widetilde{B}^0$ give the corresponding zino ($\widetilde{Z}^0$) and photino ($\widetilde{\gamma}$). The chiral supermultiplets shown in table 2.2 and 2.3 give the particles of the Minimal Supersymmetric Standard Model (MSSM).

Names		spin 0	spin 1/2	$SU(3)_C,\, SU(2)_L,\, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\,\mathbf{3},\, \mathbf{2}\,,\, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\, \mathbf{1},\, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\, \mathbf{1},\, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\;\, \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\,\mathbf{1},\, \mathbf{2}\,,\, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\, \mathbf{1},\, 1)$
Higgs, higgsinos	H_u	$(H^+_u \;\; H^0_u)$	$(\widetilde{H}^+_u \;\; \widetilde{H}^0_u)$	$(\,\mathbf{1},\, \mathbf{2}\,,\, +\frac{1}{2})$
	H_d	$(H^0_d \;\; H^-_d)$	$(\widetilde{H}^0_d \;\; \widetilde{H}^-_d)$	$(\,\mathbf{1},\, \mathbf{2}\,,\, -\frac{1}{2})$

Table 2.2 : The chiral supermultiplets of the Minimal Supersymmetric Standard Model. Spin-0 fields are comples scalars and spin-1/2 fields are left-handed two component Weyl fermions. CITE SUSY PRIMER

Names	spin 1/2	spin 1	$SU(3)_C,\, SU(2)_L,\, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\, \mathbf{1}\,,\, 0)$
winos, W bosons	$\widetilde{W}^\pm \;\; \widetilde{W}^0$	$W^\pm \;\; W^0$	$(\,\mathbf{1},\, \mathbf{3}\,,\, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\, \mathbf{1}\,,\, 0)$

Table 2.3 : The chiral supermultiplets of the Minimal Supersymmetric Standard Model. CITE SUSY PRIMER

2.12.1 R Parity

R-parity or matter parity is the multiplicatively conserved quantum number defined as,

$$P_R = (-1)^{3(B-L)+2s}, \tag{2.35}$$

where B is the baryon number, L is the lepton number, and s is the spin of the particle. From this we can find the R-parity of all of the particles in the SM and MSSM. The definition of R-parity is quite useful because all of the particle of the SM have an R-partity of $P_R = +1$, while all of the squarks, sleptons, gauginos, and higgsinos have $P_R = -1$.

R-parity is thought to be exactly conserved in SUSY, where there is no mixing between particles ($P_R = +1$) and sparticles ($P_R = -1$). This leads to three important consequences:

- The lightest sparticle that has $P_R = -1$ is called the "lightest supersymmetric particle" or LSP, which must be absolutely stable. If it is electrically neutral, it is an possible candidate for a non-baryonic dark matter candidate.
- Every sparticle, other than the LSP, must eventually decay into an odd number of LSPs.
- For collider experiments, sparticles will only be produced in even numbers.

We are going to be investigating a MSSM that conserves R-parity. This is quite well motivated by the possiblilty of a dark matter candidate and putting constraints on the proton decay.

2.13 Mass Spectrums

The third family of squarks and sleptons should have quite different masses compared to their first- and second-family counterparts, which is cause by the large

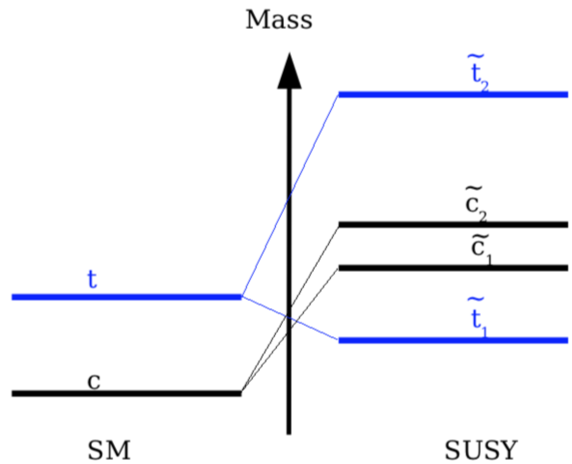

Figure 2.5 : On the right we have the arbitrary masses of the top and charm quarks.

Yukawa (y_t, y_b, y_τ) and soft (a_t, a_b, a_τ) couplings. This causes significant mixing between the chiral superpartners $(\widetilde{t}_L, \widetilde{t}_R), (\widetilde{b}_L.\widetilde{b}_R)$, and $(\widetilde{\tau}_L, \widetilde{\tau}_R)$.

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

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

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,

$$N_{pred}^{LL} = TF_{LL} \cdot N_{data}(1l). \tag{4.1}$$

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,

$$TF_{LL} = \frac{N_{MC}(0l)}{N_{MC}(1l)}, \tag{4.2}$$

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 cust 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.