# Excluding SUSY parameter space: The effects of incorporating stop branching ratios

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April, 2013

**Abstract**

Past and current stop squark searches at ATLAS and CMS focus on considering simplified models, where stops are assumed to decay 100% of the time via a certain decay channel. In this report, we lift the assumption that stop squark decay modes have a 100% branching ratio. In the context of excluding stop masses, allowing branching ratios to vary between 0 and 100% is shown to weaken quoted mass exclusion zones; at the same time, the methods used here allow for the study of larger regions of SUSY's parameter space.

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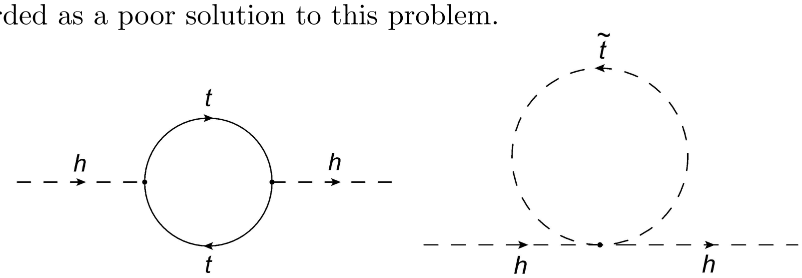
# I. Introduction

## I.A. Motivation for Supersymmetry

The Standard Model (SM) of particle physics, as it stands, is believed to be an incomplete theory when it comes to explaining the matter content of our universe. When studied in detail, the SM gives multiple results and predictions that put the theory on unstable footing. A canonical example is the issue of choosing a suitable momentum cutoff for renormalization. Consider for example the Feynman diagram shown in Figure 1(a). This virtual top quark loop diagram is associated to the mass of the Higgs boson, with a contribution given by[1]

$$\Delta m_H^2 = -3\frac{|\lambda_t|^2}{8\pi^2}\Lambda_{UV}^2. \tag{1}$$

Here, $\lambda_t$ is the coupling strength of the top quark to the Higgs, and $\Lambda_{UV}$ is the chosen ultraviolet momentum cutoff. Clearly it would be desirable to choose a value for $\Lambda_{UV}$ that is relatively small, in order to keep the Higgs in the mass range of 125 GeV. The problem is that our current understanding of the Standard Model works only for energies below this momentum cutoff, so $\Lambda_{UV}$ must be large. The Standard Model solution to this problem is aptly called fine tuning: if other SM contributions to the Higgs mass conspire to precisely cancel this top loop contribution, a Higgs mass of 125 GeV may be preserved. Coincidences, however, rarely occur in nature without good cause, so fine tuning is generally regarded as a poor solution to this problem.




(a) Top quark loop (b) Stop squark loop

Figure 1: Feynman loop diagrams for contributions to the mass of the Higgs

Supersymmetry (SUSY) resolves this particular issue by directly *constructing* these necessary cancellations. SUSY proposes that for each fermion there exists a bosonic superpartner with the same charge, and similarly for each Standard Model boson there exists a fermionic superpartner. For example, the top quark will have a scalar superpartner called the stop squark (denoted $\tilde{t}$), with its single loop diagram shown in Figure 1(b). The contribution of this diagram to the mass of the

Higgs is dominated by[1]

$$\Delta m_H^2 = 3\frac{\lambda_{\tilde{t}}}{16\pi^2}\Lambda_{UV}^2. \tag{2}$$

where $\lambda_{\tilde{t}}$ is the coupling strength of the stop squark to the Higgs. If each fermion has two scalar superpartners, each with $\lambda_{\tilde{f}} = |\lambda_f|^2$, then this provides an exact cancellation to the mass contribution of the fermion, obviating the need for a low energy renormalization scale. SUSY's framework constructs these scalars to be the partners of the left- and right-handed chiral components of the SM particle. As an example, the superpartners of the top quark would then be denoted by $\tilde{t}_L$ and $\tilde{t}_R$.

Were supersymmetry perfect, the mass of each Standard Model particle would be equal to that of its superpartner, and the cancellation would be perfect. However, since no superparticle has ever been observed, this implies that $m_{\tilde{f}} \neq m_f$, and hence supersymmetry is a broken symmetry. As the disparity between $m_{\tilde{f}}$ and $m_f$ increases, the usefulness of supersymmetry decreases, rendering supersymmetry less "natural". This naturalness is the main motivation for the various mass spectra that will be considered in this paper.

## I.B. The Mass Spectrum of Natural Supersymmetry

The most massive SM particles are the top quark, the W boson, the Z boson, and the Higgs itself. As such, the strength of their coupling to the Higgs is the most significant, making their cancellations the most urgent. Phenomenologically speaking this means that their respective superpartners, the stop squark, the wino, the bino, and the higgsino, must be at the bottom of any "natural" supersymmetric mass spectrum. Just as the bottom quark shares a doublet with the top quark, the sbottom squark occupies the same doublet as the stop squark. Consequently, the mass of the sbottom is linked to the mass of the stop, forcing the inclusion of the sbottom into any natural supersymmetry (NSUSY) mass spectrum. The other superparticle that must be included is the gluino, the gluon's fermionic superpartner, due to high energy unification considerations.[1]

In order to generate a mass spectrum from SUSY's theoretical framework, many free parameters need to be put in by hand. The parameter $|\mu|^2$ determines the squared mass of the supersymmetric Higgs particles $H_u^0$, $H_u^+$, $H_d^0$, and $H_d^-$. The angle $\beta$ is defined as the ratio between vacuum expectation values for $H_u^0$ and $H_d^0$. Three trilinear couplings, $A_t$, $A_b$, and $A_\tau$, are used to characterize the degree to which supersymmetry is broken. The SUSY breaking soft mass parameters $M_1$, $M_2$, $M_3$, $m_{Q_3}$, and $m_{U_3}$ respectively give mass to the bino, the wino, the gluino, the third generation left-handed squarks, and the right handed stop squark.

These free parameters are then used to characterize the mass terms of the supersymmetric Lagrangian. We may now write the stop mass terms of the supersymmetric Lagrangian as[1,2]

$$\mathcal{L}_{stop\ mass} = -\left[\begin{array}{cc} \tilde{t_L}^* & \tilde{t_R}^* \end{array}\right]\left[\begin{array}{cc} m_{Q_3}^2 + m_t^2 + m_Z^2 T_L & m_t X_t \\ m_t X_t & m_{U_3}^2 + m_t^2 + m_Z^2 T_R \end{array}\right]\left[\begin{array}{c} \tilde{t_L} \\ \tilde{t_R} \end{array}\right], \tag{3}$$

where $m_t$ is the mass of the top quark. For notational brevity, the variables $X_T$ and $T_{L,R}$ have been introduced. Their definitions are as follows: $X_t \equiv A_t - \frac{\mu}{\tan\beta}$, $T_L \equiv [\frac{1}{2} - \frac{2}{3}\sin^2\theta_W]\cos 2\beta$, and $T_R \equiv \frac{2}{3}\sin^2\theta_W \cos 2\beta$. Here $\theta_W$ is the weak mixing angle, representing the breaking of the electroweak symmetry.

This matrix can be diagonalized in terms of the mass eigenstates $t_1$ and $t_2$, giving

$$\mathcal{L}_{stopmass} = \left[\begin{array}{cc} \tilde{t}_1^* & \tilde{t}_2^* \end{array}\right]\left[\begin{array}{cc} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{array}\right]\left[\begin{array}{c} \tilde{t}_1 \\ \tilde{t}_2 \end{array}\right] \tag{4}$$

or, paramaterizing this relationship using the stop mixing angle $\theta_{\tilde{t}}$:

$$\left[\begin{array}{c} m_{\tilde{t_1}} \\ m_{\tilde{t_2}} \end{array}\right] = \left[\begin{array}{cc} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}} \\ -\sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{array}\right]\left[\begin{array}{c} m_{\tilde{t_L}} \\ m_{\tilde{t_R}} \end{array}\right]. \tag{5}$$

Looking at equation (3), the off-diagonal elements are proportional to the mass of the top quark. The amount of mixing between left and right superpartners is proportional to the mass of the Standard Model particle, so depending on $X_t$, there may be significant splitting between the $\tilde{t_1}$ and $\tilde{t_2}$ mass eigenstates.

The sbottom mass term of the supersymmetric Lagrangian is similarly given by[1,2]

$$\mathcal{L}_{sbottom\ mass} = -\left[\begin{array}{cc} \tilde{b_L}^* & \tilde{b_R}^* \end{array}\right]\left[\begin{array}{cc} m_{Q_3}^2 + m_b^2 + m_Z^2 B_L & m_b X_b \\ m_b X_b & m_{D_3}^2 + m_b^2 + m_Z^2 B_R \end{array}\right]\left[\begin{array}{c} \tilde{b_L} \\ \tilde{b_R} \end{array}\right]. \tag{6}$$

Here, $X_b \equiv \frac{A_b}{\tan\beta} - \mu$, $B_L \equiv [-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W]\cos 2\beta$, and $B_R \equiv -\frac{1}{3}\sin^2\theta_W \cos 2\beta$. The factor $m_{D_3}$ is the soft mass of the right-handed sbottom squark, which is not required by naturalness to be light. Since the mass of the bottom quark is relatively light, the off diagonal terms in equation

(6) can be neglected, ensuring that there is no significant mixing between the left and right sbottom squarks.

The neutral higgsinos and neutral gauginos can mix to form mass eigenstates called neutralinos, denoted by $\chi_i^0$, with i ranging from 1 to 4. The neutralino mass term of the supersymmetric Lagrangian is given by[1]

$$\mathcal{L}_{neutralino\ mass} = -\frac{1}{2} \begin{bmatrix} \tilde{B} & \tilde{W}^0 & \tilde{H}_d^0 & \tilde{H}_u^0 \end{bmatrix} \mathbf{M_{\tilde{N}}} \begin{bmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{bmatrix} \tag{7}$$

where the neutralino mass matrix $\mathbf{M_{\tilde{N}}}$ is, explicitly:

$$\mathbf{M_{\tilde{N}}} = \begin{bmatrix} M_1 & 0 & -m_Z \cos\beta \sin\theta_W & m_Z \sin\beta \sin\theta_W \\ 0 & M_2 & m_Z \cos\beta \cos\theta_W & -m_Z \sin\beta \cos\theta_W \\ -m_Z \cos\beta \sin\theta_W & m_Z \cos\beta \cos\theta_W & 0 & -\mu \\ m_Z \sin\beta \sin\theta_W & -m_Z \sin\beta \cos\theta_W & -\mu & 0 \end{bmatrix}. \tag{8}$$

This matrix can, of course, be diagonalized to give the squared masses of the neutralino mass eigenstates.

Winos and charged higgsinos mix to form mass eigenstates called the charginos, denoted by $\chi_j^{\pm}$, with j equal to 1 or 2. The chargino mass term of the supersymmetric Lagrangian is[1]

$$\mathcal{L}_{chargino\ mass} = -\frac{1}{2} \begin{bmatrix} \tilde{W}^+ & \tilde{H}_u^+ & \tilde{W}^- & \tilde{H}_d^- \end{bmatrix} \mathbf{M_{\tilde{C}}} \begin{bmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \\ \tilde{W}^- \\ \tilde{H}_d^- \end{bmatrix} \tag{9}$$

where the chargino mass matrix $\mathbf{M_{\tilde{C}}}$ is

$$\mathbf{M_{\tilde{C}}} = \sqrt{\mathbf{2}} \begin{bmatrix} 0 & 0 & M_2 & m_W \cos\beta \\ 0 & 0 & m_W \sin\beta & \mu \\ M_2 & m_W \sin\beta & 0 & 0 \\ m_W \cos\beta & \mu & 0 & 0 \end{bmatrix}. \tag{10}$$

The remaining mass term of the Lagrangian that we wish to exhibit is that of the gluino, denoted $\tilde{g}$. It does not mix with any particles, so its contribution is simply

$$\mathcal{L}_{gluino\ mass} \approx M_3 |\tilde{g}|^2 \tag{11}$$

where (important) terms due to the running coupling of the strong force have been neglected.

A few remaining points about the NSUSY spectrum need to be exhibited. There exists a supersymmetric conservation law is called R-parity that was constructed for the purpose of keeping the Standard Model's baryon and lepton conseveration laws intact. R-parity is defined as

$$P_R \equiv (-1)^{L+2s+3B} \tag{12}$$

where L is the lepton number, s is the spin and B is the baryon number. The implications of this conservation law are highly relevant to phenomenological studies: it implies that supersymmetric particles can only be produced in pairs, and that sparticle decay chains always end at the lightest supersymmetric particle (LSP).

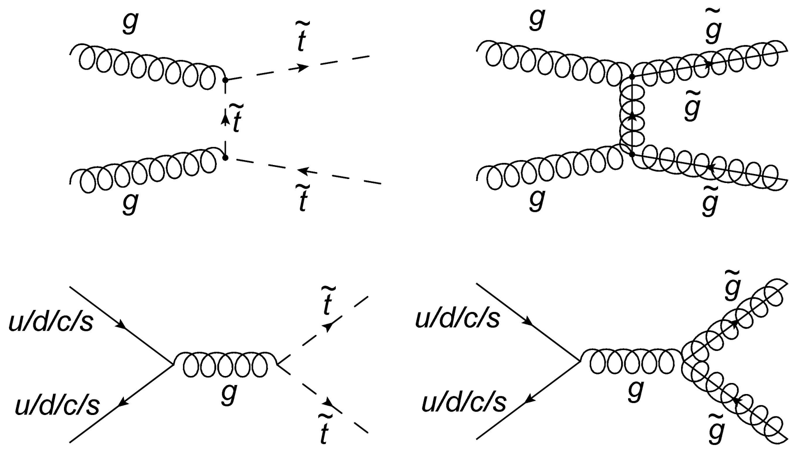
Should this LSP be electrically neutral, it would not directly interact with any SM particles; this makes a neutral LSP an ideal dark matter candidate, and is the main reason that the neutralino is often chosen to be the lighest particle in the SUSY spectrum. Futhermore, a neutral LSP would be invisible to any detector, making missing momentum extremely important when looking for signals of supersymmetry.

The fact that all sparticles should decay to the LSP is also a good way to set lower limits on various other sparticle masses. For example, the chargino can decay to a neutralino and a W boson. Depending on the mass of the chargino, the W boson may be created on or off its mass shell, but since the neutralino is stable this gives the lower limit $m_{\tilde{\chi}_1^\pm} \geq m_{\tilde{\eta}_1}$.

## I.C. Simplified Models

At ATLAS and CMS, two beams of protons collide at a centre of momentum energy on the order of 10 TeV, producing a slew of particles detected by the hadronic calorimeter, the electromagnetic calorimeter, and various other intrumentation for particle detection. When looking for signals due to supersymmetry, the two most popular processes to look for are $3^{rd}$ generation squark pair production (Figure 2(a)) and gluino pair production (Figure 2(b)).

Depending on the supersymmetric mass spectrum, the decay chain of these processes can be fairly complicated. A stop squark can either decay to a top and neutralino, or to a bottom and chargino, with the chargino decaying to a neutralino and a W boson. An sbottom squark can decay to a bottom quark and a neutralino, or to a top quark and a chargino, with the chargino




(a) Stop Squark

(b) Gluino

Figure 2: Tree level supersymmetric pair production

decaying to a neutralino and a W boson. Gluino pair production combines these two processes, with each gluino decaying to either a stop/antistop pair or to a sbottom/antisbottom pair. Clearly, the number of possibilities to study quickly becomes unmanageable.

How is this then studied phenomenologically? Significant computational power is required to simulate each decay channel, even for a single mass spectrum. There is no easy way of covering the entire parameter space, but the usual method is to consider simplified models. A simplified model assumes that there is only one possible process through which SUSY particles can only decay. By constructing signal regions that focus on this single decay mode, a good estimate can be made for the mass exclusion region.

Due to its popularity, there has been an extensive amount of work done to search for signs of NSUSY. Past and current papers regarding this search for NSUSY assume these simplified models. Many of these searches assume that stop squarks decay 100% of the time to a top quark and a neutralino, while completely ignoring the possibility of having the stop decay to a bottom quark and a chargino. Many other searches also assume the opposite. However, in a SUSY mass spectrum where both $\tilde{t}_1 \to t\chi_1^0$ and $\tilde{t}_1 \to b\chi_0^+$ are allowed processes, having a 100% branching ratio to either decay mode is unrealistic. The branching ratio would inevitably fall somewhere between 0 and 1. In this paper, we explore the consequences of relaxing the assumption of 100% branching ratios. From now on, we will focus on the search for stop squark pair production, where either $\tilde{t}_1 \to t\tilde{\chi}_1^0$, or $\tilde{t}_1 \to b\tilde{\chi}_1^+$.

# II. Methodology

## II.A. Phenomenological Methods

The usual way to look for new physics at large particle accelerators is to compare the number of "events" that get observed by the detector to the number of events that the Standard Model predicts the detector *should* observe. Should there be any significant discrepancy between the number of observed events and the number of events predicted by the SM, this can be taken to be good evidence for physics beyond the Standard Model. We can relate the number of events that should be observed to the collider's integrated luminosity $\mathcal{L}$ by:

$$n_{events} = \mathcal{L} \cdot \sigma_{vis}, \tag{13}$$

where the visible cross-section $\sigma_{vis}$ is

$$\sigma_{vis} = \epsilon \cdot A \cdot \sigma. \tag{14}$$

Here, $\epsilon$ is the detector efficiency, which for the rest of this paper we take to be unity. $A$ is the kinematic acceptance for the analysis, which ranges between 0 and 1, and $\sigma$ is the total cross-section for the process under consideration. If we look in particular at stop squark pair production, then $\sigma \to \sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$, and $A \to A_{eq}$, where the equivalent acceptance $A_{eq}$ is, for our spectra of interest,

$$A_{eq} = A_{TT}BR_T^2 + 2A_{TB}BR_TBR_B + A_{BB}BR_B^2. \tag{15}$$

Here, the subscripts T and B denote the decay channels $\tilde{t}_1 \to t\tilde{\chi}_1^0$ and $\tilde{t}_1 \to b\tilde{\chi}_1^+$, respectively. For the NSUSY mass spectra that we consider, technically the second neutralino $\tilde{\chi}_2^0$ *does* enter the spectrum, though it is always more massive than the chargino. In this work however, we only consider the stop decay modes T and B, so $BR_T + BR_B = 1$. The factors $A_{XY}$ are the kinematic acceptances, assuming that the stop and antistop decay via the modes X and Y, respectively.

When either $BR_T$ or $BR_B$ is assumed to be precisely unity, equation (15) takes on a particularly simple form that only involves a single kinematic acceptance. With this assumption relaxed, all three kinematic acceptances must be included. Computationally speaking, the calculation of the equivalent acceptance then requires three times as much runtime, since each process ( $\tilde{t}_1\bar{\tilde{t}}_1 \to t\bar{t}\chi_1^0\chi_1^0$,

$\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow t\bar{b}\chi_1^0\chi_0^-$, and $\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow b\bar{b}\chi_1^+\chi_1^-$ ) must be fully simulated. However, once this has been completed we can write the equivalent acceptance solely as a function of $BR_T$:

$$A_{eq} = A_{TT}BR_T^2 + 2A_{TB}BR_T(1 - BR_T) + A_{BB}(1 - BR_T)^2 \tag{16}$$

With this in hand it is a simple matter to start excluding regions of SUSY parameter space, though now exclusion confidence is a function of stop branching ratio. In most SUSY papers, the $CL_s$ statistic[3] is used to determine the exclusion regions for sparticle masses. Its definition is

$$CL_s = \frac{P(n_{events} < data|SUSY)}{P(n_{events} < data|SM)}, \tag{17}$$

or assuming that the probability density for the number of events is gaussian,

$$CL_s = \frac{\Phi(\frac{n_{data}-\nu_{s+b}}{\sigma_{s+b}})}{\Phi(\frac{n_{data}-\nu_b}{\sigma_b})}. \tag{18}$$

Here $\nu_b$ is the number of background events predicted by the Standard Model for a particular signal region. $\nu_{s+b}$ is the number of SM background events, plus the number of signal events that should be seen if SUSY does exist in nature. The $\sigma_{b,s+b}$ are the associated errors on the number of events, and $\Phi(z)$ is the cumulative distribution function of the normal distribution. The probability with which we may exclude the SUSY model is then $\alpha = 1 - CL_s$.

## II.B. Replicated Analyses

Without a particle collider phenomenologists rely on experimental groups to obtain data to which the predictions of various models can be compared. In this work we have used the SM background estimation and corresponding analysis of two ATLAS papers. These conference notes are ATLAS-CONF-2012-166, which for the sake of nomenclature we call the Single Lepton (SL) analysis,[4] and ATLAS-CONF-2013-001, which we call the Double Bottom Jet (DBJ) analysis.[5] We briefly exhibit their analysis structure, data, and exclusion results.

### II.B.1. Single Lepton Analysis

This analysis worked with a data set corresponding to an integrated luminosity of 13.0 fb$^{-1}$ at a CM energy of $\sqrt{s} = 8$ TeV. The group defined six signal regions, each targeting separate regions of

SUSY parameter space. Signal regions 1 through 5 target the stop to top/neutralino decay mode, while signal region 6 targets the stop to bottom/chargino decay mode. Their SM background estimation, with the observed number of events, is tabulated in Table 1. For the full outline on kinematic cuts used in this analysis, please see the original conference note.

| $n_{events}$ | SR1 | SR2 | SR3 | SR4 | SR5 | SR6 |
|---|---|---|---|---|---|---|
| SM background | 34 ± 5 | 14 ± 3 | 125 ± 17 | 9.6 ± 1.5 | 4.3 ± 1.1 | 325 ± 36 |
| Observed | 40 | 21 | 133 | 12 | 8 | 314 |

Table 1: SM background estimation with observed number of events for each signal region of the Single Lepton analysis

This paper quotes two benchmark cross-sections for the pair production of stop squarks: they calculate $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$=(5.6±0.8)pb for a stop mass of 250 GeV, and $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$=(25±4)fb for a stop mass of 600 GeV. This can later be compared our own pair-production cross-sections.

They also quote four benchmark kinematic acceptances, each at different mass points, which we denote by ($m_{\tilde{\chi}_1^0}$,$m_{\tilde{\chi}_1^\pm}$,$m_{\tilde{t}_1}$). For SR3, they find A=0.06% at the point (50,–,250). In SR4, they find A=0.9% at the point (200,–,500). For SR5, they find A=2.8% at the point (1,–,650). These three benchmark points assume the branching ratio $BR_T$=100%. For SR6 at the point (150,300,350), they find that A=0.7% under the assumption that $BR_T$=0.

With this data and under the assumption that the stop always decays through the top/neutralino mode, the group was able to exclude stop masses between 225 and 560 GeV for a massless neutralino, and neutralino masses between 0 and 175 GeV if the stop had a mass of ~500 GeV. Under the assumption that the stop always decays through the bottom chargino decay mode, the group could exclude stop masses between 0 and 350 GeV if the neutralino was massless and the chargino had a mass of 150 GeV.

### II.B.2. Double Bottom Jet Analysis

This analysis worked with a data set corresponding to an integrated luminosity of 12.8 $fb^{-1}$ at a CM energy of $\sqrt{s}$ = 8 TeV. The group defined seven signal regions, all of which targeted the stop to bottom/chargino decay mode. Their SM background estimation, with the observed number of events, is tabulated in Table 2. For the full outline on kinematic cuts, please see the original conference note.

This analysis was first introduced in the conference note ATLAS-CONF-2012-165,[6] and was

| $n_{events}$ | SR1 | SR2 | SR3 | SR4 | SR5 | SR6 | SR7 |
|---|---|---|---|---|---|---|---|
| SM background | $176 \pm 25$ | $71 \pm 11$ | $25 \pm 4$ | $7.4 \pm 1.7$ | $95 \pm 11$ | $203 \pm 35$ | $27 \pm 5$ |
| Observed | 172 | 66 | 16 | 8 | 104 | 207 | 21 |

Table 2: SM background estimation with observed number of events for each signal region of the Double Bottom Jet analysis

used to target sbottom pair production. Weeks later the same group reused the analysis to target stop pair production.[5] With this data, and under the assumption that the stop always decays through the bottom chargino decay mode, the group could exclude stop masses between 175 and 580 GeV if the neutralino had a mass of ~100 GeV and the chargino had a mass of between 100 and 105 GeV. They were also able to exclude neutralino masses between 0 and 300 GeV if the stop has a mass of ~500 GeV and the mass difference between the chargino and neutralino was less than 5 GeV. The paper notes that these limits weaken by 100 GeV in the case that the chargino–neutralino mass difference is increased to 20 GeV.

## II.C. Software

The masses and decay widths of all supersymmetric particles are calculated using the SUSY-HIT[7] package. There are specific options that must be changed for results to agree with other programs. In *sdecay.f*, the hard-coded QCD corrections to 2-body QCD decay, multi-body decay, loop induced decays and supersymmetric top decays are turned off. In *suspect2_lha.in*, the general MSSM option is used, with an arbitrary EWSB scale set at 246 GeV. The option for Higgs sector inputs is set to use the MA_pole and MU(EWSB) parameters, while the option for radiative corrections to squark and gluino masses is disabled. All other options are set to their default values. The stop, sbottom, and stau trilinear couplings are kept at -120 GeV, with the trilinear couplings for all other fermionic superpartners set to zero.

NLO K-factors, the quantum corrections due to the coloured coupling of stop pair production, is calculated using Prospino[9] v2.1. MadGraph5[10] v1.5.5 is used to calculate the leading order cross-sections of all processes. MadGraph5 incorporates both Pythia[11] and PGS;[12] Pythia is used to simulate the showering of particles from the parton level processes, and PGS simulates the readout from an LHC-type detector.

MadGraph has various inputs that need to be adjusted. In *run_card.dat*, the chosen parton distribution function is set to CTEQ611, all parton level cuts are disabled, and jet clustering is done with the anti kT algorithm; all other settings are set to their default value. The *param_card.dat* that is needed to run a process is taken from the output of SUSY-HIT.

### II.D. Event Production and Analysis

The soft mass variables, exhibited in §I.B. as parameters of the supersymmetric Lagrangian, are input by hand to SUSY-HIT. The soft masses of all particles that are not required by naturalness to be light are set to 5 TeV. The $\tilde{g}$ soft mass parameter $M_3$ is fixed at 1 TeV, while the soft mass parameter $m_{Q_3}$, common to $\tilde{t}_L$ and $\tilde{b}_L$, is fixed at 5 TeV. The remaining soft mass parameters $M_1$, $M_2$, and $m_{U_3}$ are then varied in a gridlike manner: $M_1$ ranges from 1 to 351 GeV in steps of 50 GeV, the difference in soft masses $M_2 - M_1$ ranges from 1 to 101 GeV in steps of 20 GeV, and $m_{U_3}$ ranges from 100 to 550 GeV in steps of 50 GeV.

For each mass spectrum gridpoint, the output file of SUSY-HIT is used as input to the MadGraph/Pythia/PGS software trifecta. For each mass point 50k events are generated, and the output is analyzed by in-house software which attempts to replicate the analyses described in §II.B.. From this production line of software we are able to read out production cross-sections for stop/antistop pairs, NLO K-factors, and kinematic acceptances for each signal region. This entire analysis is repeated thrice: once for the $\tilde{t}_1\bar{\tilde{t}}_1 \to t\bar{t}\chi_1^0\chi_1^0$ process, once for the $\tilde{t}_1\bar{\tilde{t}}_1 \to t\bar{b}\chi_1^0\chi_0^-$ process, and once for the $\tilde{t}_1\bar{\tilde{t}}_1 \to b\bar{b}\chi_1^+\chi_1^-$ process.

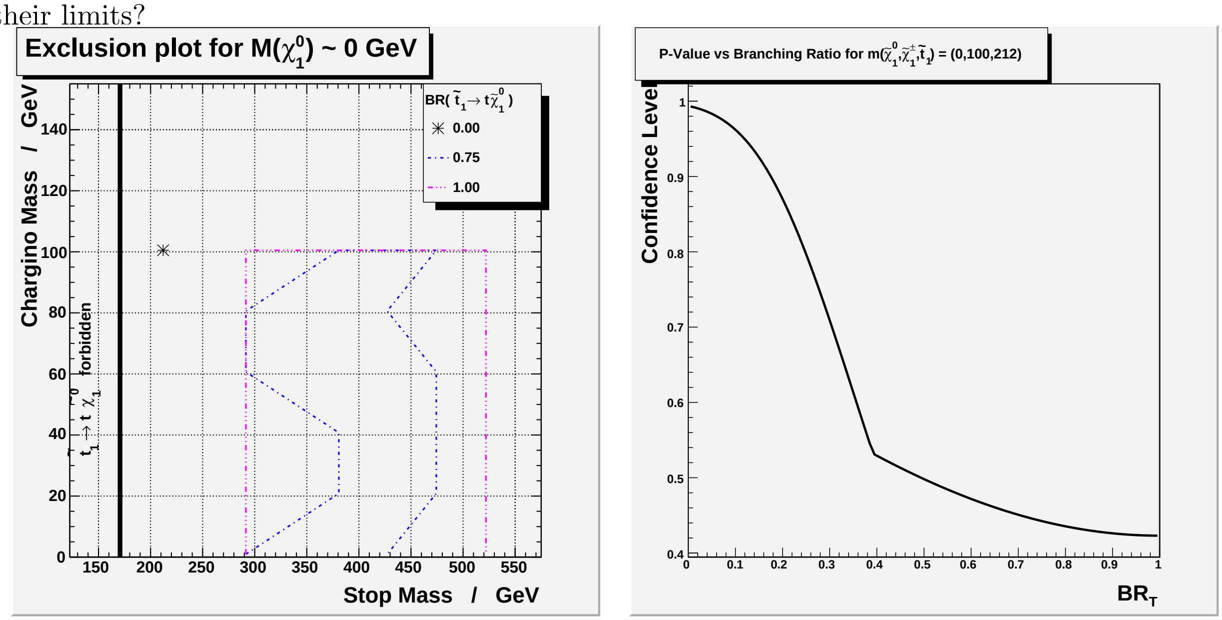
Equipped with all the necessary variables, we apply equation (15) to each signal region, from which we may determine $A_{eq}(BR_T)$ for that particular signal region. This directly leads through equations (13) and (14) to the number of SUSY events that should be seen in the signal region, assuming that particular mass spectrum. Then from the CL$_s$ presciption we can determine the probability of excluding the mass spectrum in that signal region. All signal regions being equally valid, the exclusion probability is taken to be the maximum probability allowed by any of the signal regions.

The exclusion probability as a function of BR$_T$ is made for each mass point; a select few of these curves are shown in the results section. With the gridlike scan we are able to show exclusion contours for fixed values of the branching ratio BR$_T$. These contours are shown in the results section.

# III. Results

## III.A. Single Lepton Analysis

To weigh the legitimacy of our results, we compare the exclusion regions quoted by the Single Lepton analysis paper to the exclusion regions presented here. For a massless neutralino, they were able to exclude stop masses between 225 and 560 GeV assuming that the stop decayed 100% of the time by the top/neutralino mode. Referring to figure 3, and by focusing on the $\mathrm{BR}_T$=1.00 exclusion curve, we are able to exclude stop masses between 290 and 520 GeV. Our exclusion region lies comfortably within their exclusion region, so we may confidently say that our replication of their analysis does not overestimate the exclusion limits. Can we understand why we underestimate their limits?

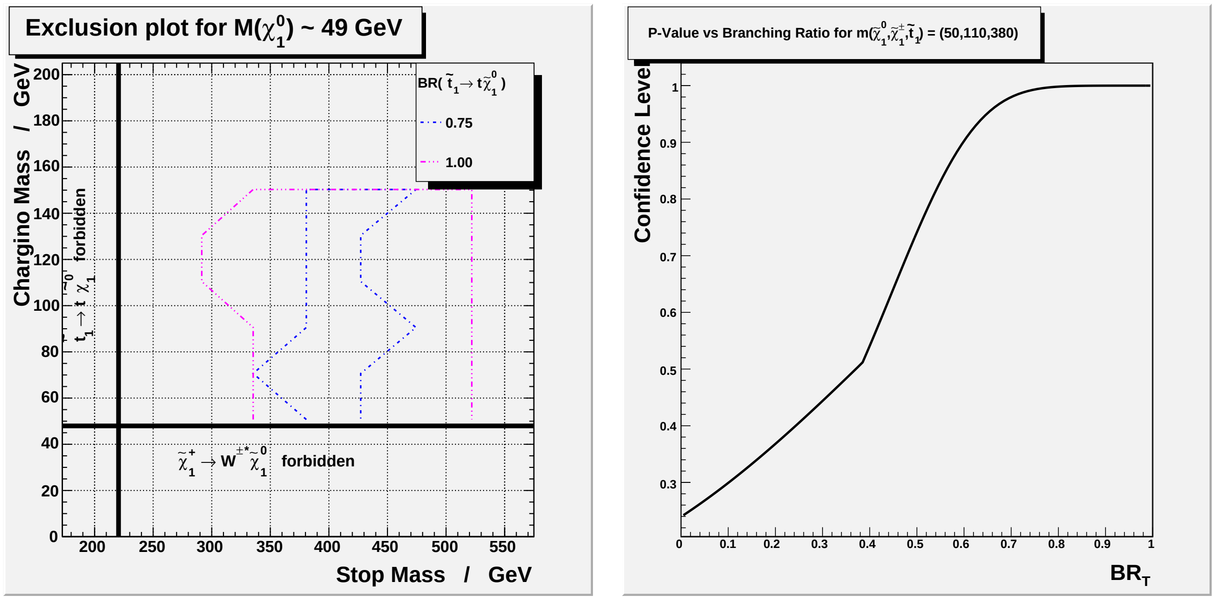



(a) Exclusion zones at the 95% CL

(b) $(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{t}_1})$ = (0,100,212)

Figure 3: Data for massless neutralinos. The exclusion probability as a function of $\mathrm{BR}_T$ is shown for the single point that is excluded when $\mathrm{BR}_T$=0

Our analysis gives a production cross section $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$=(4.068±0.003)pb and $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$=(21.40±0.02)fb for $m_{\tilde{t}_1}$=250 and $m_{\tilde{t}_1}$=600, respectively. We note that both the production cross-sections and its associated error are smaller in our analysis. By equation (13), and under the assumption that the kinematic acceptances are the same in both our analysis and the ATLAS paper, our estimate for the number of expected SUSY events, as well as its the error on this number of events, will be less than that quoted by the ATLAS paper. The combined effect this has on equation 17, however,




(a) Exclusion zones at the 95% CL

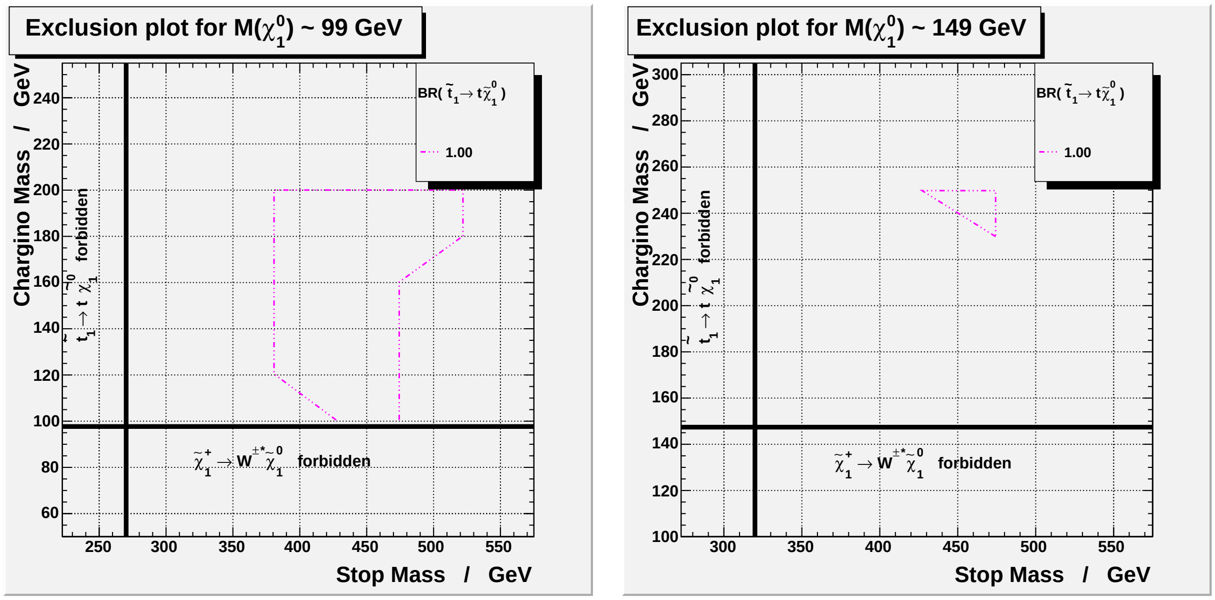
(b) ($m_{\tilde{\chi}_1^0}$,$m_{\tilde{\chi}_1^\pm}$,$m_{\tilde{t}_1}$) = (50,110,380)

Figure 4: Data for 49 GeV neutralinos. The exclusion probability as a function of BR$_T$ is shown for a point on the left edge of the BR$_T$=0.75 exclusion zone.

remains unclear. The signal+SM distribution would be pulled closer to the SM only distribution (compared to the ATLAS analysis), which by itself can only increase the value of the CL$_s$ statistic. However, the signal+SM distribution would also be much narrower, and depending on whether the signal region has an excess or deficiency in data, this could either decrease or increase the value of CL$_s$.

Let us now compare kinematic acceptances to the paper's benchmark values. In SR3, at the mass point (50,–,250), our acceptance ranges between 0.004% and 0.022%. In SR4, at the mass point (200,–,520), our acceptance ranges between 0.388% and 0.47%. In SR5, at the mass point (1,–,650), our acceptance was about 0.908%. IN SR6, at the mass point (150,300,350), our acceptance was roughly 0.37%. The kinematic acceptances quoted by the ATLAS paper are generally two to three times larger than those used in this work. The source of these discrepancies is unknown, but the effects are clear: the number of SUSY signal events are underestimated relative to the original Single Lepton analysis. This underestimation increases the CL$_s$ variable, which in turn decreases the exclusion probability.

We still have other exclusion regions to compare, though we now expect smaller exclusion zones. The ATLAS paper is able to exclude neutralino masses between 0 and 175 GeV if the stop squark has a mass of 500 GeV, assuming BR$_T$=100%. Looking at the exclusion zones for figures




(a) (b)

Figure 5: Exclusion zones at the 95% confidence level for 99 and 149 GeV neutralinos

3(a), 4(a), 5(a), and 5(b) for a 100% stop to top/neutralino branching ratio, we see that we can only exclude neutralinos between 1 and 101 GeV for a stop mass of 500 GeV, where $m_{\tilde{\chi}_1^0}$=101 GeV is only excluded if we happen to look at larger chargino mass values. We are able to exclude a range of neutralino masses between 1 and 151 GeV if we take the stop mass to be 450 GeV. In the case of excluding $m_{\tilde{\chi}_1^0}$=151 GeV, we need to take the mass of the chargino to be 80 to 100 GeV more massive than the neutralino.

The ATLAS paper also quotes an exclusion of stop masses between 0 and 350 GeV for massless neutralinos in the case of 150 GeV charginos. Our mass grid did not extend past a 100 GeV neutralino–chargino mass splitting, so we are unable to we are unable to compare our results to this exclusion region.

An interesting effect can be seen in figures 5(a) and 5(b). We expect that the exclusion space for $BR_T$=100% should be independent of the chargino's mass; after all, there is no chargino in the decay chain $\tilde{t}_1 \to t\chi_1^0$. However this is not what is observed; these figures clearly show that the mass exclusion zones for the stop squark is dependent on the mass of the chargino.

The first explanation for this is that statistical fluctuations in event topologies, originating from the simulations done by Madgraph/Pythia/PGS, just happened to give stronger kinematic acceptances in those regions of higher/lower exclusion probability. This is good motivation for including the 95% CL $\pm 1\sigma$ regions around exclusion curves, but was not done to avoid clutter.

The second explanation for the chargino mass dependence of the exclusion regions is that these exclusion plots are created by grouping together all the mass points with the same soft mass $M_1$. The chargino mass is increased by varying the soft mass $M_2$, which by equation (8) has an influence on the mass of the neutralino. This influence is small, but across the domain of each plot the neutralino mass could vary by as much as 2 GeV.

## III.B. Double Bottom Jet Analysis

Looking at figure 9(a), we are able to exclude stop masses between 290 and 570 GeV for chargino masses of ~100 GeV. This is almost exactly what the ATLAS paper was able to exclude, with our differences being easily explained by the choice of mass points with which we scanned the soft mass parameters.

Referring again to figure 9(a), but at a chargino mass of ~120 GeV, we can exclude stop masses between 290 and 520 GeV. The ATLAS group reports that the stop exclusion weakens by 100 GeV if the chargino-neutralino mass splitting is increased to 20 GeV; our exclusion only weakens by 50 GeV.

Referring now to the exclusion plots for neutralino masses of 0 to 248 GeV, we see that if the stop mass is fixed at 500 GeV and the chargino-neutralino mass splitting is less than 5 GeV, we are able to exclude neutralino masses between 49 and 248 GeV. No points could be excluded at a neutralino mass of ~300 GeV, which is why there is no figure for exclusion zones at that mass. If we keep the stop mass at 500 GeV and boost the chargino–neutralino mass splitting to 20 GeV, these results do not weaken. This contrasts with the exclusion zone weakening by 100 GeV, as reported by this ATLAS paper.

Let us now compare the exclusion results of the Double Bottom Jet paper to our own. This ATLAS group always looks at the $\tilde{t}_1\bar{\tilde{t}}_1 \to b\bar{b}\chi_1^+\chi_1^-$ process, so we need to compare their results to our $\mathrm{BR}_T$=0 exclusion curves.

Unfortunately, neither the original Double Bottom Jet sbottom search paper, nor its counterpart with the stop search, quote any benchmark cross-sections or kinematic acceptances. It is then fairly hard to figure out exactly where our exclusion discrepancies arise. Our stop pair production cross-sections most likely suffer from the same underestimation as those in the previous subsection.

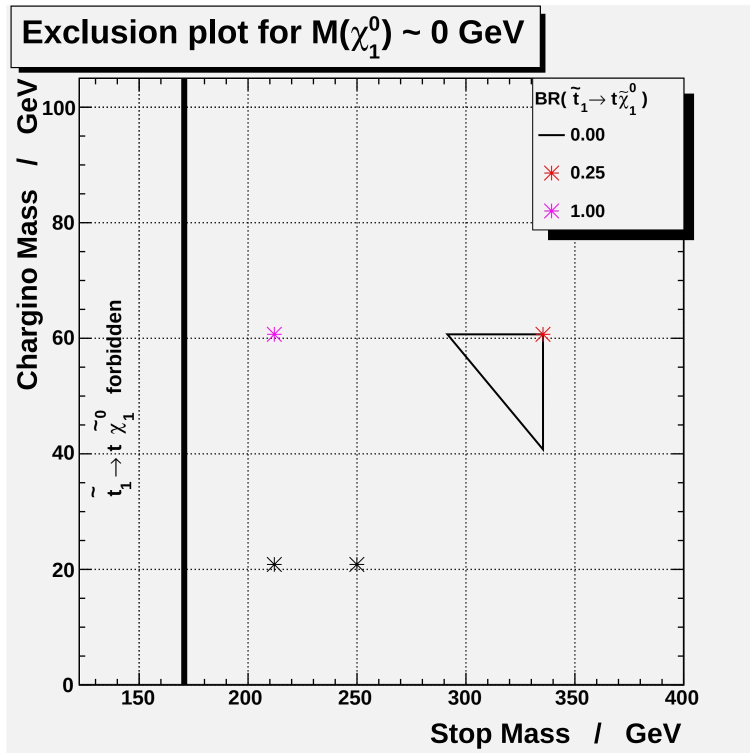
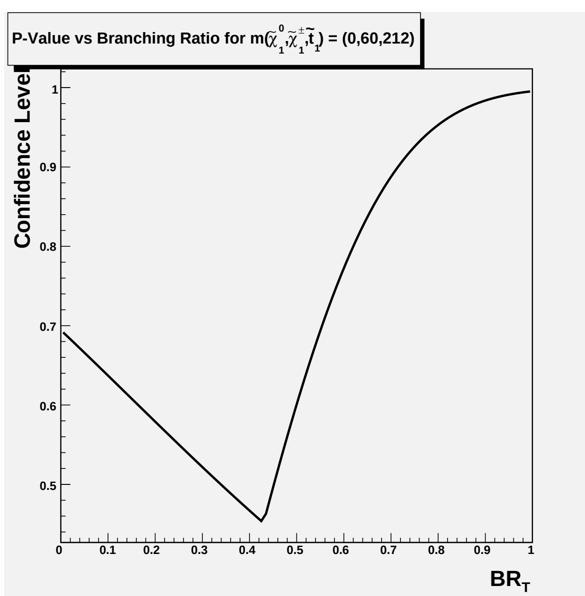
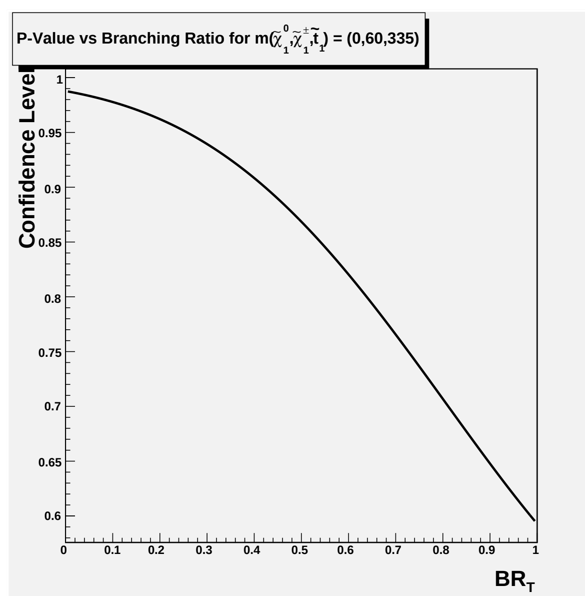



Figure 6: Exclusion at the 95% confidence level for a near massless neutralinos

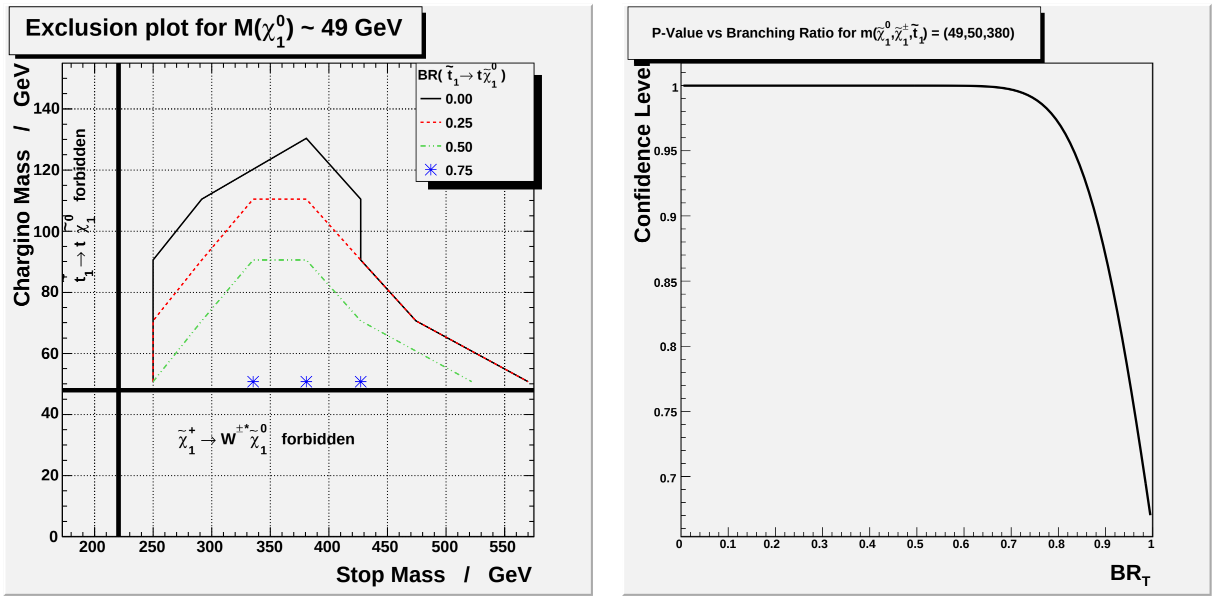



(a) $(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{t}_1})$ = (0,60,212)




(b) $(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{t}_1})$ = (0,60,335)

Figure 7: Exclusion probabilities as a function of BR$_T$ for the only points excluded for BR$_T$=1.00 (a) and BR$_T$=0.25 (b) in the massless neutralino scenario.




(a) Exclusion zones at the 95% CL

(b) ($m_{\tilde{\chi}_1^0}$,$m_{\tilde{\chi}_1^\pm}$,$m_{\tilde{t}_1}$) = (49,50,380)

Figure 8: Data for 49 GeV neutralinos. The exclusion probability as a function of BR$_T$ is shown for the middle excluded point at BR$_T$=0.75.

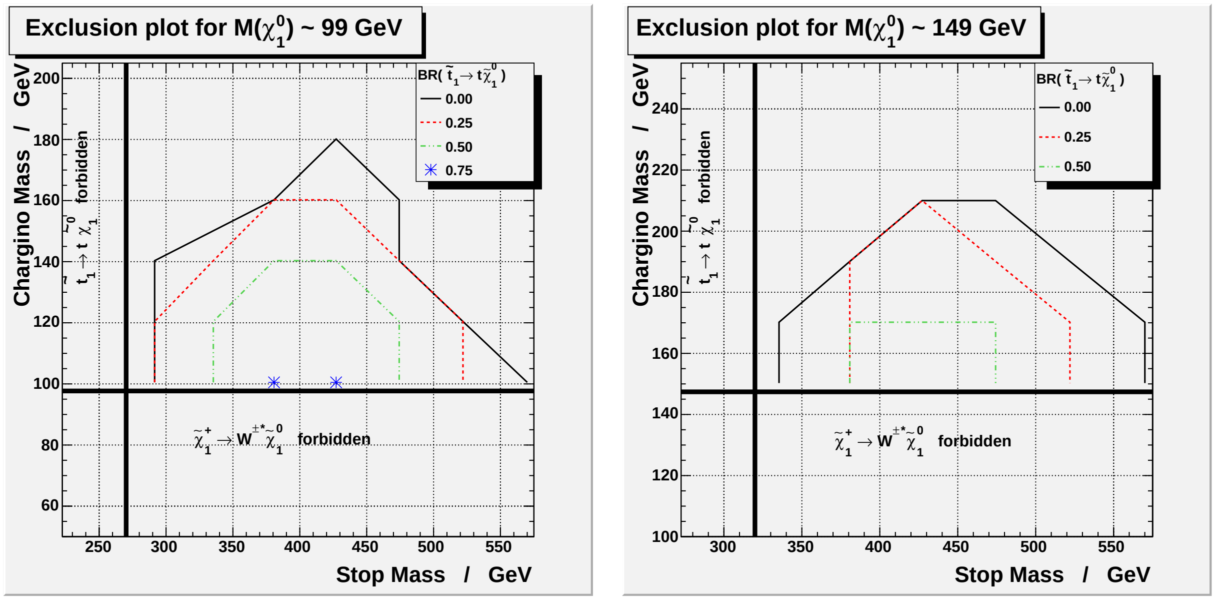
To investigate how much influence our kinematic acceptances have on exclusion limits, we compare acceptances on the border between excluded and not excluded regions. We hope that this will help us determine where the problem may lie.

To look at exclusion discrepancies that arise due to kinematic acceptances, we look at the quoted exclusion where the stop is fixed at a mass of ~500 GeV, while the chargino–neutralino mass difference is less than 5 GeV. According to the ATLAS 2013 paper, by using their analysis we should be able to exclude both massless neutralinos, and neutralinos at 300 GeV. The acceptances at these mass points, as well as their closest neighbouring excluded mass points, are tabulated in Table 3. Due to our choice of mass grid, the closest we can get to a stop mass of 500 GeV is $m_{\tilde{t}_1}$=520 GeV.

| ($m_{\tilde{\chi}_1^0}$,$m_{\tilde{\chi}_1^\pm}$,$m_{\tilde{t}_1}$) | SR1 | SR2 | SR3 | SR4 | SR5 | SR6 | SR7 |
|---|---|---|---|---|---|---|---|
| (0,1,520) | 0.00052 | 0.00048 | 0.00048 | 0.00040 | 0.00034 | 0.00002 | 0.00000 |
| (50,51,520) | 0.01866 | 0.01626 | 0.01332 | 0.00954 | 0.01296 | 0.00086 | 0.00070 |
| (249,250,520) | 0.01456 | 0.01146 | 0.00714 | 0.00308 | 0.01006 | 0.00122 | 0.00084 |
| (298,300,520) | 0.01336 | 0.01004 | 0.00464 | 0.00154 | 0.00946 | 0.00146 | 0.00064 |

Table 3: Comparing kinematic acceptances on the border of the exclusion contour for BR$_T$=0. With 50k events, the error on each acceptance is $1\times10^{-5}$

Referring to table 3, we can tell that something odd is occurring in the mass region $0 \leq m_{\tilde{\chi}_1^0} \leq$




(a) (b)

Figure 9: Exclusion zones at the 95% confidence level for 99 and 149 GeV neutralinos

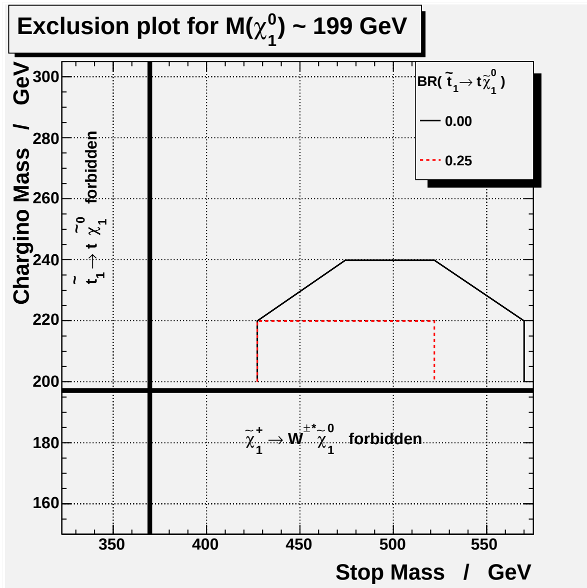
50 GeV: the acceptances are over a magnitude smaller than those in the mass region m$_{\tilde{\chi}_1^0}$ ≥50 GeV. This has the effect of significantly suppressing the number of SUSY signal events in the region $0 \leq m_{\tilde{\chi}_1^0} \leq 50$ GeV, making it impossible to exclude that region of SUSY's parameter space.

The fact that we can not exclude the mass region m$_{\tilde{\chi}_1^0}$ > 250 GeV can be easily explained. Almost all the acceptances decrease ever so slightly, and this may result in the acceptances dropping below the threshold value needed for exclusion. As shown in the previous section, our cross-section for stop pair production is underestimated with respect to ATLAS analyses; if our $\sigma_{\tilde{t}_1\bar{\tilde{t}}_1}$ was equal to that used by the ATLAS group, we should be able to exclude m$_{\tilde{\chi}_1^0}$ <=300 GeV.

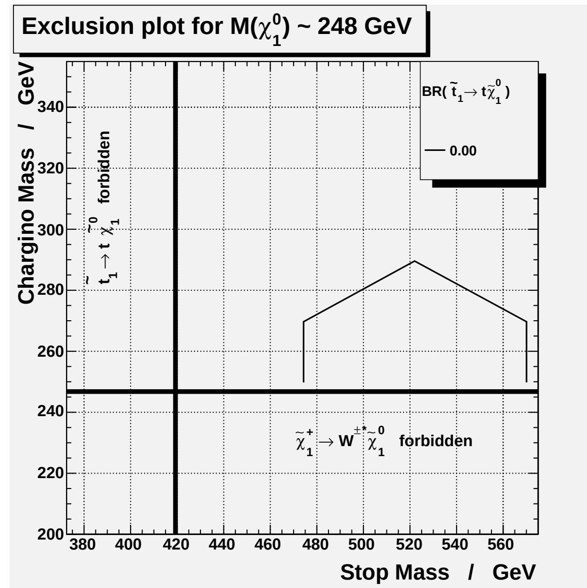
## IV. Discussion

Even with the above disagreements involving the replicated analyses, we can still look at the main focus of this paper: studying the effects of allowing BR$_T$ to vary between 0 and 1. As a disclaimer, this work only considered mass spectra in which both decay modes $\tilde{t}_1 \to t\chi_1^0$ and $\tilde{t}_1 \to b\chi_0^+$ were kinematically accessible. The exclusion space in which the chargino is assumed to be heavier than the stop is obviously not affected by branching ratio considerations, since BR$_T$ is fixed at unity.

It is important to notice that the exclusion limits for all particles involved weaken when the branching ratio departs from integer values. This makes sense, since each analysis was constructed




(a)




(b)

Figure 10: Exclusion zones at the 95% confidence level for 199 and 248 GeV neutralinos

to target a specific region of SUSY's parameter space; the Single Lepton analysis targets the $\tilde{t}_1 \to t\chi_1^0$ decay channel, while the Double Bottom Jet analysis targets the $\tilde{t}_1 \to b\chi_0^+$ decay mode.

Looking at the Single Lepton analysis, the exclusion probability is a very steep function of branching ratio. Exclusion zones vanish entirely for $\mathrm{BR}_T \leq 0.50$ at any neutralino mass. For neutralino masses above 50 GeV there is no exclusion for $\mathrm{BR}_T \leq 0.75$. There is an outlier to this; on the exclusion plot for massless neutralinos we are able to exclude a single mass point at a stop to top/neutralino branching ratio of 0. The exclusion confidence at this point, plotted in figure 3(b), is interesting; we can clearly see one signal region taking over from another at $\mathrm{BR}_T$=0.4, which boosts the confidence level enough to be able to exclude the point at $\mathrm{BR}_T$=0.

Looking at the Double Bottom Jet analysis, exclusion probability is a fairly weak function of branching ratio. Exclusion zones only vanish entirely when $\mathrm{BR}_T$ reaches 100%, with the only outlier being the single mass point $(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{t}_1})$ = (0,60,212). Stop and chargino masses can be excluded for $\mathrm{BR}_T$=0.75 up to neutralino masses of ~100 GeV, for $\mathrm{BR}_T$=0.50 up to neutralino masses of ~150 GeV, and for $\mathrm{BR}_T$=0.25 up to neutralino masses of ~200 GeV.

Without further studies it is hard to see how large an effect the incorporation of fractional branching ratios would have on the already excluded regions of NSUSY parameter space (see the ATLAS public results webpage, SUSY group[13]). From the two papers studied here, we can infer that if all analyses were rerun to include a non integer branching ratio, the mass exclusion regions would shrink significantly. Analyses that only considered the $\tilde{t}_1 \rightarrow t\chi_1^0$ decay mode would shrink if $\mathrm{BR}_T$ were decreased from 1, and analyses that only consider the $\tilde{t}_1 \rightarrow b\chi_0^+$ decay mode would shrink as $\mathrm{BR}_T$ were increased from 0.

The upshot of all this is that plotting exclusion regions by branching ratio allows experimentalists to drop any assumptions regarding the decay mode of the stop squark. The current NSUSY exclusion plot, published in March 2013, is segregated into two halves: one half assuming that $\tilde{t}_1 \rightarrow t\chi_1^0$, and one half assuming that $\tilde{t}_1 \rightarrow b\chi_0^+$. Why not consider both decay modes? There is an entire continuum of possible NSUSY scenarios that are not being considered if one assumes an integer valued branching ratio.

Experimentally speaking, it would be desirable to create an analysis that targets the kinematic topologies that would occur in the (likely) scenario that stop squarks have fractional branching ratios. The following analysis structure has been designed as a suggestion for this search.

When looking solely at the $\tilde{t}_1 \rightarrow t\chi_1^0$ decay channel, we expect to produce two tops and two neutralinos. The tops decay mostly to bottom quarks and the W boson. Since the bottom quarks are produced from the same particle as the W boson, their momenta are correlated. When looking solely at the $\tilde{t}_1 \rightarrow b\chi_0^+$ decay channel, we expect to produce two bottoms and two charginos. The charginos each decay to a neutralino and a W boson. Since the bottom quarks are *not* produced from the same particle as the W, their momenta are not correlated, as in any 3 body decay. Now, each bottom quark can be detected by the usual vertexing algorithms, and each W boson can be reconstructed if it decays hadronically. One could look for stop squarks with fractional branching ratios in the following way. Setting up three signal regions, we impose on each a large cut on missing momentum to account for the undetectable neutralinos. One could then categorize each signal region by the degree of correlation between each bottom jet/W boson pair (BW pair). SR1 would look for two correlated BW pairs, corresponding to the search for two stops decaying through the $\tilde{t}_1 \rightarrow t\chi_1^0$ decay mode. Conversely, SR2 would look for two uncorrelated BW pairs, corresponding to the search for two stops decaying through the $\tilde{t}_1 \rightarrow b\chi_0^+$ decay mode. Finally SR3 would look for one correlated BW pair and one uncorrelated BW pair, correspoding to each stop decaying through a different decay channel.

## V. Conclusions

Incorporating branching ratios into the search for NSUSY can weaken currently excluded mass regions of NSUSY's parameter space, but in the pursuit of covering all possible scenarios it should be taken into account. The computation time required to simulate all the required events would merely triple.

The replication of two ATLAS analyses lead to differing mass exclusion regions than those quoted by the original authors. Nevertheless, the analyses were used to show that allowing stop branching ratios to vary fractionally between 0 and 1 can shrink the original exclusion region. Steps should be taken to probe the stop's fractional branching ratio continuum to improve the confidence with which we may rule out NSUSY.

## VI. Acknowledgements

Thank you Dr. Gregoire for introducing me to the wonderful world of theoretical particle physics. It was a blast.

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