Light Stop Notes

by Flip Tanedo

Abstract

These are notes on light stops. Usually I hand write these notes, but since there are multiple references it's easier to keep track of them in a single document.

1 Motivation

We would like to explore the phenomenology of models with light stops. Why?

1. **Experimental constraints on degenerate squarks**. Assuming degenerate squarks (e.g.invoking flavor-universal soft terms to avoid flavor-changing neutral current bounds) leads to a squark mass scale of over 1 TeV (in fact, maybe more like 1.5 TeV; see `1102.5290`). [Image: see H. Bachacou talk at Lepton-Photon '11.] However, if we only assume flavor universality in the first two generations, we can still avoid FCNC bounds while
2. **Natural SUSY**. The third generation *is* special. It's the stop loop that cancels the top loop that is the dominant contribution to the quadratic cutoff-dependence of the Higgs mass. As discussed below, there are only a few sparticles which you really *need* to be accessible at the early LHC, and the stop is the only (and most important) squark on this list.
3. **Little Hierarchy problem**. This is again saying the same thing slightly differently: naive application of experimental bounds suggest that the SUSY scale must be above the 1 TeV scale; if this is so, then why is the Higgs mass below the TeV scale? As explained above, the point is that while the rest of the SUSY spectrum may be heavy, a light stop can accommodate a light-ish Higgs without too much tuning. The stop is special: it has $\mathcal{O}(1)$ couplings to the Higgs (Yukawa) as well as strong couplings to the color sector.
   - 1% tuning implies stops below 1 TeV. Other sfermions can be five times heavier without costing any fine-tuning.
4. **Light stops can be generated from RG running alone**. See Stephen Martin. This is due to the negative contribution to the running coming from the Yukawa interaction.
   - e.g. light stops through gauge mediation. Usually we say gauge mediation is flavor blind, but recall Yael's seminar talk `1103.0292`, can use messenger–matter couplings to give flavor-dependence. General gauge mediation gives a tool for considering a stop NLSP (gravitino LSP since this is a low scale mediation).
5. **EW-scale baryogenesis**. The matter–antimatter asymmetry ("baryon asymmetry of the unvierse") can be explained through the CP phases in the MSSM that aren't in the SM. Requires baryon number violating processes to be out of equilibrium at nucleation temperature, which in turn requires the (sphaleron energy/critical temp) to be smaller than the expansion rate of the universe. The leading contribution to this ratio depends on the coupligns of light bosons to the Higgs. `0809.3760`.
   - Cultural note: EW baryogenesis is one popular option for the baryon asymmetry. Others include leptogenesis and Affleck-Dine.
   - However, DC et al. seem to have done a lot to exclude this story: `1203.2932`. (See their intro for references and reviews.) Since the Higgs is 125 GeV, EW baryogenesis in the MSSM would require (as per the Chicago analysis) a TeV scale left-handed stop and a 100 GeV right-handed stop. [By the way, DC continues to use italics to emphasize sentences in his papers.]
6. **Interesting phenomenology** that is different form other squark searches.

Other ways out:

- Some other protection mechanism is operative at the TeV scale and SUSY may live at the 10 TeV scale. e.g. "Schlittle Higgs" (SUSY little Higgs).

- 125 GeV "Higgs" is actually a (techni-)dilaton.

2 Effective\Natural\Minimal SUSY

The main idea is to consider the 'minimal' SUSY spectrum that should be accessible to the early LHC in order to solve the Hierarchy problem. The main ingredients are:

- Light third generation squarks (light-ish stops) at a few hundered GeV. These run in the Higgs loop and cancel the third generation Standard Model fermion loops.
- A not-too-heavy gluino (less than a couple of TeV) since these contribute to the Higgs mass at two-loop level. Note that the gluino tends to want to pull the stop mass up due to its large RG coefficient.
- Once you set the gluino mass, unification fixes the electroweak-ino masses to be in the few hundred GeV range (since the spectrum is given by the ratio of gauge couplings).
- The Higgsinos are also in the same light-ish ballpark since they get their masses from the μ term, the same source as the Higgses. What about soft breaking terms? You can't write any by symmetries.

2.1 Main References

- Papucci, Ruderman, Weiler, `1110.6926`. Natural SUSY Endures.
- Brust, Katz, Lawrence, Sundrum, `1110.6670`. SUSY, the 3rd Gen, and the LHC.
- Kats, Meade, Reece, Shih, `1110.6444`. The Status of GMSB After 1/fb at the LHC.
- Older papers with the same basic ideas:
  - `1007.3897`. Effective SUSY at the LHC
  - `hep-ph/9607394`. The More Minimal Supersymmetric SM. (Cohen, Kaplan, Nelson), seems to be the original reference.

2.2 Review: Higgs in the MSSM

$$\Delta m_h^2(\text{stops}) = \frac{3}{4\pi^2}\cos^2\alpha\, y_t^2 m_t^2 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right). \text{(small mixing } \alpha)$$

Alternate derivation: integrate out stops completely and check their contribution to the Higgs quartic interaction. In the decoupling limit $m_{A^0} \gg m_Z$, then the Higgs mass can saturate bounds:

$$m_h^2 = m_Z^2 \cos^2 2\beta + (\text{loops}).$$

Including the effect of stop mixing, we have

$$\begin{aligned} m_h^2 = {} & m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\sin^2\beta\, y_t^2 \left[m_t^2 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + c_{\tilde{t}}^2 s_{\tilde{t}}^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln\left(\frac{m_{\tilde{t}_2}}{m_{\tilde{t}_1}^2}\right)\right] \\ & + \frac{3}{4\pi^2}\sin^2\beta\, y_t \frac{c_{\tilde{t}}^2 s_{\tilde{t}}^2}{m_t^2}\left((m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln\left(\frac{m_{\tilde{t}_2}}{m_{\tilde{t}_1}^2}\right)\right) \end{aligned}$$

Note that since $y_t \sim m_t$, the prefactor $y_t^2 m_t^2 \sim m_t^4$, which is usually how this dependence is written.

2.2.1 Comments on the calculation, effective potential method

It may be helpful to understand the origin of the terms above. From the *Sparticles* book (section 10.6) we note that there are three ways to calculate these corrections.

1. Direct calculation from diagrams

2. Use the RG flow from the SUSY scale down to to the weak scale. See `hep-ph/9308335`.
3. Effective potential.

The effective potential method is not as numerically accurate, but is pedagogically more clear. The loop level effective potential is

$$V^{(1)}(Q) = V^{(0)}(Q) + \frac{1}{64\pi^2}\mathrm{STr}\,\mathcal{M}^4(h)\left[\ln\frac{\mathcal{M}^2(h)}{Q^2} - \frac{3}{2}\right].$$

Here $V^{(0)}$ is the tree level potential with renormalized couplings at the scale Q. Note that the supertrace vanishes in the supersymmetric limit, so as expected the potential is protected by SUSY and is corrected only to the extent to which SUSY is broken. The factor of 3/2 is a relic of $\overline{\mathrm{MS}}$ renormalization, see Peskin (11.78); e.g. it is associated with the freedom to add a finite counter term that is a quartic polynomial in h (see Hugh Osborn's AQFT notes).

We now focus on the contributions from the stops to the Higgs potential. In the absence of stop mixing (which we address below) and assuming equal soft masses $\tilde{m}$ for the stops, we have the following field-dependent masses:

$$\begin{aligned} m_t^2(h) &= y_t^2|h_u|^2 \\ m_{\tilde{t}}^2 &= \tilde{m}^2 + y_t^2|h_u|^2, \end{aligned}$$

where we drop $O(g^2_{\mathrm{EW}})$ contributions from D-terms. The point now is to consider the contributions to the supertrace, remembering the weighting by the degree of freedom for a particle of a given spin. The top is a Dirac fermion with four degrees of freedom, each stop is a complex scalar with two degrees of freedom each. There is also a color factor of three. The loop-level correction is thus

$$\Delta V^{(1)} = \frac{3}{16\pi^2}\left[m_{\tilde{t}}^4\left(\ln\frac{m_{\tilde{t}}^2}{Q^2} - \frac{3}{2}\right) - m_t^4\left(\ln\frac{m_t^2}{Q^2} - \frac{3}{2}\right)\right].$$

The next step is to minimize the loop corrected potential. Since $\Delta V^{(1)}$ only involves h_u, the tree-level constraints on m_{H_d} are unchanged (see the Appendix):

$$m_{H_d}^2 + |\mu|^2 - b\tan\beta + \frac{m_Z^2}{2}\cos 2b = 0.$$

On the other hand, the (2,2) element of the mass matrix for the CP even Higgses is changed. You can go ahead and take second derivatives using *Mathematica* (and be careful with factors of 3 which weren't working out in my code), and you end up with a correction to the CP even Higgs mass matrix (on the 2–2 element) of

$$\frac{3}{4\pi^2}y_t^2 m_t^2 \ln\frac{m_{\tilde{t}}^2}{m_t^2},$$

where it is also common to restore $\sin\beta = v_u/v$ dependence through $m_t = y_t v_u$. You can go through the diagonalization, but the punchline is that now the upper bound on the Higgs mass is

$$m_h^2 < m_Z^2\cos^2 2\beta + \frac{3}{4\pi^2}y_t^2 m_t^2\ln\frac{m_{\tilde{t}}^2}{m_t^2}.$$

This alleviates the tree-level bound that the Higgs shouldbe lighter than the Z.

One curiosity is that the correction to the Higgs mass is only logarithmically dependent on the stop mass, whereas one might naively expect a power law dependence, e.g. from explicit mass insertions of the soft terms required to bypass the vanishing supertrace. This is resolved by the observation that the shift in the tree-level parameter $m_{H_2}^2$ is indeed proportional to $m_{\tilde{t}}^2 - m_t^2$. One way to see this is to consider $\partial V/\partial H_u$ with the loop level effective potential. This gives an expression for $m_{H_u}^2$, analogous to the unchanged tree-level $m_{H_d}^2$ expression above. Now, however, there is a correction of the form

$$-\frac{3y_t^2}{16\pi^2}\left[2m_{\tilde{t}}^2\left(\ln\frac{m_{\tilde{t}}^2}{Q^2} - 1\right) - 2m_t^2\left(\ln\frac{m_t^2}{Q^2} - 1\right)\right].$$

Thus even though the shift in m_h appears to only be logarithmically dependent on SUSY breaking, a large splitting between the stop and top would lead to a fine-tuning in $m_{H_2}^2$. (At least I think this is the logic? See the *Sparticle* book section 10.6.)

Another remark on the scale dependence: our correction to m_h^2 is independent of $\ln Q$. This dependence cancels against the Q dependence of running quantities in the tree-level potential, as is generally true in effective potential calculations. The Q dependence of the loop-level piece is

$$\frac{\partial \Delta V^{(1)}}{\partial \ln Q} = -\frac{3}{8\pi^2}\tilde{m}^2\left(y_t^2|H_2|^2+\frac{1}{2}\tilde{m}^2\right).$$

The first term cancels the Q dependence in $m_{H_2}^2|H_2|^2$ and the second term is a field-independent contribution to the cosmological constant.

2.2.2 Stop mixing

Recall that the off-diagonal terms in the stop mass matrix take the form $m_t(A+\mu^*\cot\beta)$. The A term is a soft-breaking trilinear term analogous to the Yukawa term. (Indeed, it is often normalized so that A is the rescaling of the coefficient relative to the Yukawa, hence the m_t dependence.) The μ-dependent term comes from the F-term contribution to the potential, where you have $|\partial W/\partial H|^2$ which contains a mixing term between the μ-term and the Yukawa term.

The additional contributions to the Higgs mass from stop mixing go like products of sines and cosines of the mixing angle and the difference between the two masses. Explicit formulae can be found in your favorite references, e.g. Martin's review (8.1.25 in version 6) or the *Sparticle* book (section 10.6). For now we just won't make a big deal about this.

2.3 The gluino

Stops produced indirectly from gluino decays lead to same-sign dilepton signatures (because the gluinos are Majorana) or jets + MET. These constrain the gluino to be heaveir than 900-ish GeV. This, however, is still compatible with naturalness since the gluino only contributes at one loop to the stop and hence only at two loop to the Higgs.

3 Aspects of the light stop

3.1 The 125 GeV Higgs

The most general Lagrangian for effective Higgs couplings is given in `1002.1011`. It takes the form...

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}(\partial h)^2 - V(h) + \frac{v^2}{4}(D\Sigma^\dagger D\Sigma)\left[1+2a\frac{h}{v}+b\frac{h^2}{v^2}+\cdots\right]\\ &\quad -m_i\bar{\psi}_{Li}\Sigma\left(1+c\frac{h}{v}+\cdots\right)\psi_{Ri}+h.c.\\ &\quad +c_g\frac{\alpha_s}{4\pi}\frac{h}{v}G^2+c_\gamma\frac{\alpha}{4\pi}\frac{h}{v}F^2\\ V &= \frac{1}{2}m_h^2h^2+d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3+d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4\end{aligned}$$

This is mean to describe a general situation in which a light scalar h exists in addition to the vectors and Goldstones of electroweak symmetry breaking. We've assumed flavor universality, but in principle c is a general matrix. The c_g and c_γ couplings are small and often negligible. We invoke custodial symmetry so that the Goldstones describe the coset SO(4)/SO(3) which can be described using

$$\Sigma = e^{i\sigma_a\pi^a/v}$$

Working at a sufficiently low energies relative to the strong scale we are allowed to perform this derivative expansion. In the Standard Model, $a=b=c=d=1$. This allows us to repackage the h into the usual nonlinear expansion of H,

$$U=\left(1+\frac{h}{v}\right)\Sigma.$$

As described in `hep-ph/0703164`, the effective couplings can be interpreted in terms of the Goldstone boson equivalence theorem. a controls $2\to 2$ longitundinal boson scattering, $\mathcal{A}\simeq\frac{s}{v^2}(1-a^2)$. Pertubative unitarity is satisfied when $b=a^2$. The amplitude for longitudinal vector boson scattering into fermions is

$$\mathcal{A}(\pi\pi\to\psi\bar{\psi})=\frac{m_\psi\sqrt{s}}{v^2}(1-ac),$$

since $a=b=c=1$ in the SM, this is weakly coupled at all scales. The pseudo-Goldstone Higgs models predict values of the effective couplings (model-independent-ish) which depend of v/f.

3.1.1 The role of $h\to\gamma\gamma$

We note that $\Gamma(h\to\gamma\gamma)/\Gamma(h\to\gamma\gamma)_{\mathrm{SM}}\sim a^2$, coming from the W loop. Note, however, that there is also a contribution from the top loop which is ∼5 times smaller and dependent on c. Note, also, that the production mechanisms depend on these parameters, in particular gluon fusion depends on c while vector boson fusion depends on a.

3.1.2 Calculation via low energy theorems

The loop induced $h\to VV$ interaction can be calculated in a simple way using the **Higgs low energy theorems** which relate this rate to the β-function of the relevant gauge group. This is intuitively clear since at low energies the h can be thought of as a slowly varying excitation of the vev v, and thus one can just look at the VV loop-level interaction (given by the β function) and replace $v\to v+h$.

For a pedagogical description, see "A Primer on Higgs boson Low-Energy Theorems" by Dawson and Haber[1]. For references to original work and an application to the composite Higgs model, see `1206.7120`.

This means that the contribution of stops to the $h\to\gamma\gamma$ rate is given by the MSSM QED β functions, which should be readily available in, say, the SUSY primer. (But this doesn't seem to include threshold effects—i.e. it seems that we need the Higgs contribution to the stop mass.)

3.1.3 125 GeV Higgs status with respect to SUSY

The best global fit is (cited from `1208.2673`)

$$c_g^2=\frac{\Gamma(h\to gg)}{\Gamma_{\mathrm{SM}}(h\to gg)}\approx 0.7 \qquad c_\gamma^2=\frac{\Gamma(h\to\gamma\gamma)}{\Gamma_{\mathrm{SM}}(h\to\gamma\gamma)}\approx 2.1.$$

What does this mean with respect to the MSSM?

- Stau loops can increase c_γ without affecting c_g. Carena et al. `1112.3336`, Wang et al. `1207.0990`, Giudice et al. `1207.6393`. See also a more recent Chicago group paper on light staus: `1205.5842`.
- Once you increase c_γ, you can then reduce both c_γ and c_g simultaneously with light stops.

3.2 Light stops from RG

[From Stephen Martin.] The first and second generation sfermion masses run according to

$$16\pi^2\frac{d}{dt}m_i^2=-\sum_{a=1}^{3} 8C_a(i)\,g_a^2\,|M_a|^2+\frac{6}{5}Yg_1^2\,\mathrm{Tr}[Y_i\,m^2]$$

1. `http://www.osti.gov/bridge/servlets/purl/5960988-Dk3lmn/5960988.pdf`

where $C_a(i)$ are the Casimir terms for each gauge group. Observe that the $|M_a|^2$ (gaugino) terms are negative. This means that the sfermion masses m_i grow in the IR; we can heavy (first and second generation) sfermions automatically due to the gaugino contribution to the sfermion masses.

For the third generation, however, things are different due to the size of the Yukawas and the soft trilinear couplings (A terms). These enter in particular combinations that we call

$$X = 2|y|^2\left(m_H^2 + m_D^2 + m_{\tilde{f}_3}^2\right) + 2|A|^2$$

where H refers to the relevant type of Higgs (H_u for X_t, H_d for X_b and X_τ), m_D^2 refers to the relevant doublet, $m_{\tilde{f}_3}^2$ is the relevant right-handed sfermion mass, and A is the relevant trilinear soft term. The $X_{t,b,\tau}$ tend to be positive.

Note that both the Yukawa and the soft trilinear term generate stop mixing upon electroweak symmetry breaking.

3.2.1 Effect on the Higgses

The Higgs RG equations are

$$\begin{aligned} 16\pi^2 \frac{d}{dt} m_{H_u}^2 &= 3X_t - 6g_2^2|M_2|^2 - \frac{6}{5}g_1|M_1|^2 + \frac{3}{5}g_1^2 \mathrm{Tr}[Y_i m^2] \\ 16\pi^2 \frac{d}{dt} m_d^2 &= 3X_b - 6g_2^2|M_2|^2 - \frac{6}{5}g_1|M_1|^2 + \frac{3}{5}g_1^2 \mathrm{Tr}[Y_i m^2] + X_\tau. \end{aligned}$$

Since the Xs are positive, they encourage the Higgs masses to decrease in the IR. Since $m_{H_u}^2$ is sensitive to X_t, we would expect the up-type Higgs mass to run lighter... even negative. Indeed, this is precisely what we need for electroweak symmetry breaking. Huzzah.

3.2.2 Effect on the third generation

The stop soft masses run according to:

$$\begin{aligned} 16\pi^2 \frac{d}{dt} m_{Q_3}^2 &= -\frac{33}{3}g_3^2|M_3|^2 - 6g_2^2|M_2|^2 - \frac{2}{15}g_1^2|M_1|^2 + \frac{1}{5}g_1^2 \mathrm{Tr}[Y_i m^2] + X_t + X_b \\ 16\pi^2 \frac{d}{dt} m_{U_3}^2 &= -\frac{32}{3}g_3^2|M_3|^2 - \frac{32}{15}g_1^2|M_1|^2 + \frac{4}{5}g_1^2 \mathrm{Tr}[Y_i m^2] + 2X_t. \end{aligned}$$

First we might worry that the stop masses run negative. Note that the X terms appear with the same sign as in the Higgs mass running, but with smaller coefficients. Further, unlike the Higgs the squarks get a large negative contribution from gluinos. Thus its reasonable to believe that the Higgs can get a vev while the squarks do not.

4 Phenomenology: searches for stops

The light stop scenario avoids several "typical" collider searches for SUSY (e.g. large MET).

4.1 Stop simplified model and pre-LHC analyses

Matt notes that he and Patrick were the first to advocate studying simplified top partner models in `hep-ph/0601124`. Other papers:

- Ditops + MET: `0803.3820`
- `HEPTopTagger`, an algorithm for top tagging which can be used to reconstruct stops. `1006.2833`
- Boosted semileptonic tops: `1102.0557`

4.2 Stop production

- Direct stop production, all other sparticles decoupled. (See Beenacker)

- Production through heavier gluinos or squarks. (Cascades)

See hep-ph/9710451 (Beenakker et al) for NLO cross sections for stop production using Prospino.

4.3 Stop decay

4.3.1 Stop at a bump classification of experimental bounds (Maryland group)

RPV or no? LSP or no?

- Neutralino LSP? (CDF stop search)
- Sneutrino LSP? (D0 stop search)
- Graviitino LSP? (only recent dedicated searches, ongoing downstairs)

One constraint on models is that the stop branching ratio cannot be so small that it leads to a displaced vertex. This is especially constraining on stop LSPs in RPV models where the stop decays through a coupling which is small due to experimental constraints on RPV. As a good rule of thumb, we need $1/\Gamma \leqslant 1$ mm.

4.3.2 Light Stop Signs classification (Harvard group)

Focus on $\tilde{t} \to bW^+\chi^0$, divided into three categories:

- **Three body decay**. Stops are so light that its decay must go throughan off-shell top. The $m_{\ell b}$ and m_T distributions will be very different from top decay and may be a good handle. (See Peskin and Chou.) unfortunately, this region suffers from low acceptance, but "probably deserves a closer look in the future."
- **Two body decay**. For stops much heaver than the top, the top decay product may be on shell and the neutralino/gravitino may carry large MET. While a simple MET cut helps, there are more sophisticated ways to use this. MET in the top background comes from W leptonic decays; thus one can play with transverse mass cuts on semileptonic decays or a cut on m_{T2}. See references in Matt's paper. (e.g. 1205.2696, stop searches in 2012)
- **Stealth stop**. For very light LSP, e.g. gravitino in low scale SUSY mediation, one can have $m_{\tilde{t}}$ just above m_t so that the gravitino momentum is negligible. These are effectively "one-body" decays that are very hard to separate from top pair production. Unlike compressed spectra scenarios, events do not become more distinctive when recoiling against an additional hard jet. (See "Stealth SUSY Sampler.")

4.4 Cut and count

The simplest searches are "cut-and-count": pick a sufficiently distinct signal with cuts that sufficiently reduce SM background and just count the total number of events. Usually there are so few events that one cannot plot a kinematic distribution (which would provide an additional handle for discriminating against the SM), so it is critical to have the background under control.

Two good handles for this are:

- Multi leptons: the SM doesn't like to produce lots of hard leptons. $\geqslant 4$ lepton events are exceptionally rare.
    - ATLAS: ATLAS-CONF-2012-001
    - CMS: SUS-11-013
    - In addition to real lepton production (e.g. from weak gauge bosons), backgrounds come from fake leptons. For example, b-jets produce leptons wich can accidentally pass the isolation efficiencies at ar ate of 1.5%. You also have to worry about internal and external photon conversions when a photon produces a hard and soft lepton.

- Same-sign leptons: for example, from the pair production of Majorana particles like the gauginos. For example, see Allanach and Gripaios: `1202.6616`.
  - CMS: `1205.6615`, `SUS-12-017-pas`

4.5 Stop NLSP

Katz and Shih explored the phenomenology of a stop NLSP that decays to a gravitino and a top (which may be off shell) `1106.0030`. (This scenario was studied 13 years earlier by Peskin in `hep-ph/9909536`) Thus one looks for $\tilde{t} \to Wb\tilde{G}$. The relevant couplings can be obtained by looking at the Goldstino couplings to the supercurrent, for details, see the appendix of their paper. They focus on prompt decays and ignore cases where the stop may have a displaced vertex or may even be reasonably long-lived.

4.5.1 Stop–Goldstino couplings

From Giudice & Rattazzi (`hep-ph/9801271`) eq. (3.5)

$$\mathcal{L} = -\frac{k}{F}\left(\bar{\psi}_L\gamma^\mu\gamma^\nu\partial_\nu\phi - \frac{i}{4\sqrt{2}}\bar{\lambda}^a\gamma^\mu\sigma^{\mu\nu}F^a_{\nu\rho}\right)\partial_\mu\tilde{G} + h.c.$$

where the first term is the χSF coupling and the second is the VSF coupling. Actually: the $\partial_\nu\phi$ should be replaced by $D_\mu\phi$, this will give a $\tilde{t}bW^+\tilde{G}$ coupling.

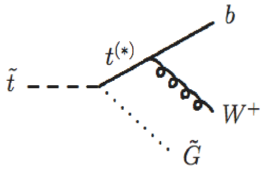
* Actually, and even better expression comes from Kats & Shih (`1106.0030`), see their Appendix A:

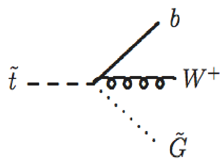
$$\mathcal{L}_{\tilde{t}t\tilde{G}} = \frac{i}{F}\partial_\nu\tilde{t}^*\partial_\mu\bar{\tilde{G}}\gamma^\nu\gamma^\mu(c_{\tilde{t}}P_L + s_{\tilde{t}}P_R)t + h.c.$$

$$\mathcal{L}_{\tilde{t}Wt\tilde{G}} = \frac{i}{\sqrt{2}F}gW^+_\nu\tilde{t}^*\partial_\mu\bar{\tilde{G}}\gamma^\nu\gamma^\mu P_L b + h.c.$$

Next use $\gamma^\mu\partial_\mu\tilde{G}{=}0$ (on-shell condition) so that $\partial_\mu\bar{\tilde{G}}\gamma^\nu\gamma^\mu \to 2\partial^\nu\bar{\tilde{G}}$.

It's worth noting that this has not yet been implemented in the latest FeynRules models. Matt Reece has a UFO model on his website: `http://www.physics.harvard.edu/~mreece/stopnlsp/`, and the Shih/Katz group also has their own proprietary code. I've also developed my own FeynRules model. This should be standardized in the near future.





The stop decay rate is:

$$\Gamma(m_{\tilde{t}} < m_t) \sim \frac{\alpha}{\sin^2\theta_W}\frac{(m_{\tilde{t}} - m_W)^7}{128\pi^2 m_W^2 F^2}$$

$$\Gamma(m_{\tilde{t}} > m_t) \sim \frac{m_{\tilde{t}}^5}{16\pi F^2}\left(1 - \frac{m_t^2}{m_{\tilde{t}^2}}\right)^4.$$

The difference comes from whether the top decays through the intermediate top diagram or through the four-point interaction. Restricting to prompt decays for $m_{\tilde{t}} < m_t$ requires F to be as small as possible, e.g. $F \sim (10\,\text{TeV})^2$. Longer lived stops, e.g. collider-stable, are also possible, but are not the main subject of this paper. The best limit currently comes from ATLAS, $m_{\tilde{t}} > 300$ GeV `1103.1984`, though there are also nontrivial bounds on this scenari from BBN (`hep-ph/0701229`, `0811.1119`).

4.5.2 General Stop NLSP phenomenology

To leading order the stop decay amplitude depends on the stop mass and its mixing angle with the heavy stop. The contribution from virtual charginos and sbottoms also contribute, but it turns out that these do not strongly affect the phenomenology, `hep-ph/9909536` (Chou & Peskin).

For $m_{\tilde{t}} < m_t$, the four-point and three-point (with subsequent top decay) decay diagrams are comparable, whereas for higher stop masses the intermediate top diagram dominates so that the decay effectively becomes two body: $\tilde{t} \to \tilde{G}t$.

4.5.3 Kinematic distributions

As before, the main **background** comes from ditop. Katz and Shih give kinematic distributions for sample stop masses (from 120 to 200 GeV) relative to the ditop background for:

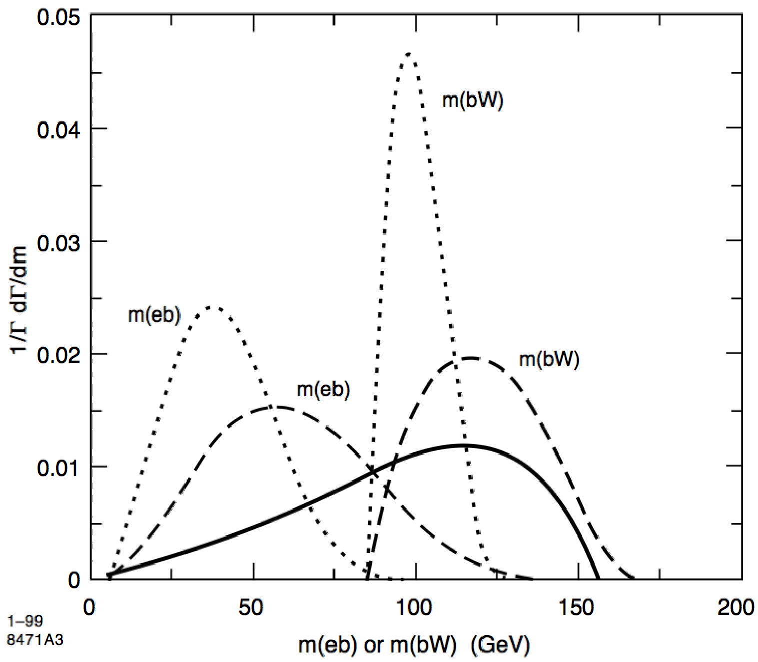
- Lepton p_T
- b-jet p_T: stops lighter than the top give softer b-jets.
- MET (all hadronic, lepton+jets, dilepton)
- m_T: stops have a high m_T tail in the leptons+jets channel.
- H_T (scalar sum of jet p_T): somewhat lower values for H_T for stops in leptonic channels
- $m_{\ell b}$ (invariant mass of lepton and b-quark at parton level) for different lepton pairings. Note that this is not currently used in any exisiting analyses (as of the writing of that paper) and can be a useful distinguishing variable.

I really can't tell by eye if these distributions are discriminating... doesn't look like it, and anyway it's clear that there are limits where the stop looks very much like a top.

For stops lighter than the top, the b-jets are much softer due to kinematics. This is due to a Jacobian peak in p_{bT} in the top frame when there is an on-shell top. On the other hand, for the 3-body decay (from the 4-point interaction), the distribution is different.

4.5.4 Comments from Peskin and Chou ('99)

Here's a plot from Peskin and Chou `hep-ph/9909536` with the distribution of $m_{\ell b}$. Plotted are a stop with mass 130 GeV (dotted) and 170 GeV (dashed) for a scenario where the lightest chargino is light ($m_2 \sim 200$ GeV) and wino-like. The solid line is the m_{eb} spectrum for a top quark. The distribution has good discriminating power against tops.



Unfortunately, the other scenarios that they present (Higgsino like lightest chargino, mixed lightest chargino, heavy lightest chargino) do not give as much separation between the distributions.

Another handle they present is the longitudinal W polarization. Top decays tend to be highly longitdinally polarized. In the SM,

$$r = \frac{\Gamma(W_0)}{\Gamma(W_{\text{all}})} = \frac{1}{1 + 2m_W^2/m_t^2} \approx 0.71.$$

In the light stop scenario, this ratio is a function of the chargino mixing matrices. The point, however, is that one can variations between $r = 0.4$ and 0.9.

4.5.5 Searching for stop NLSP, part I: Ditop analyses

The first class of searches are those where the stop events are hidden in the ditop data. The hope is that we would just have to see a deviation from what we expect. In the next sub-sub-section we discuss explicit stop searches. The hidden-in-the-top-data searches can be categorized based on the W decays:

- **Dileptonic** (5%): 2 leptons, 2 jets, MET. Cleanest, $S/B\sim 2$. However, very small branching ratio so that the statistical uncertainty is roughtly of the same size as the systematic.
- **Lepton + jets** (35%): Larger branching ratio, but large W+jets background—require b-tag to beat this down.
- **Jets + MET** (10%): zero lepton events where at least one W decays to $\tau\nu$ with $\tau\to$hadrons. QCD background is hard. Most stops fall in this category due to gravitino. Cut and count is no good against the QCD background, but more sophisticated neural network techniques may be helpful. The CMS group is working on something along these lines with a giant maximum likelihood calculator.
- **Fully hadronic** (50%): QCD background is hard.

A typical set of requirements (lepton, 4+ jets, MET) lead to $S/B\sim 4$ with systematic uncertainty $2\times$statistical. Katz and Shih explain that many additioanl top quark properties are not as useful as one would hope since they use matrix elements or neural networks to kill background and are thus likely to discriminate against stop events as well. Other properties require an accurate reconstruction of the ditop event so that the stop events (with missing momentum due to the gravitino) tend to be rejected as background. More practically, since the experimentalists' codes are proprietary, it is inaccessible to phenomenologists.

4.5.6 Searching for stop NLSP, part II: explicit stop searches

The GMSB-inspired stop NLSP scenario presents some opportunities for novel experimental searches. Some of these searches can be reinterpreted from existing ditop-like signatures.

- Stop decay via virtual chargino, $\tilde{t}\to b\ell^+\tilde{\nu}$. `1009.0266, 0811.0459, D0 Note 5937-CONF, 1009.5950`. The neutrino can either be the LSP or can decay invisibly the a neutrino and a neutralino/gravitino. Signatures are similar to the $\tilde{t}\to W^+ b\tilde{G}$ decay dilepton channel.
- Another ditop-like signature is $\tilde{t}\to b\big(\tilde{\chi}_1^+\to W^{(*)}\nu\tilde{\chi}_1^0\big)$.
- A similar signature is $\tilde{t}\to b(\tilde{\chi}_1^+\to \ell\nu\tilde{\chi}_1^0)$. `0912.1308, CDF Note 9439, FERMILAB-THESIS-2010-16`. CDF has an algorithm to reconstruct the stop mass which helps discriminate against top events. However, there are four invisible particles and two particles (chargino and neutralino) with unknown mass, the reconstruction is imperfect. With an assumption for the chargino mass, there is a stop-mass-like quantity that they can construct which has a distribution which is peaked roughly at the stop mass.
- Other searches: b-jets + MET `1103.4344`, search for heavy top partner `ATLAS-CONF-2011-036`.

4.5.7 Searching for stop NLSP, part III: other searches

We now consider some additional regions of stop NLSP parameter space.

- **Displaced decays**. The stop can be naturally long lived. For decays between 100 μm and 0.5 m from the interaction point, a displaced vertex can be tagged. One can avoid heavy flavor displaced vertices (background) by looking at distances above 1 cm, for which this may be uased as a discriminator against the Standard Model. Stops hadronize, possibly into charged particles which leave tracks with large amounts of energy lost through ionization.
- **Stoponium**. One can form a near-threshold stop bound state. The annihilation rate into gg can be of order $\Gamma^{-1}\sim 10^{-13}$ m, for nearly degenerate top and stop. Stopnoium would give a diphoton resonance that could allow a precise stop mass measurement in a few years at the LHC.

- **Flavor violation, SS2L**. Stop to charm and neutralino/Gravitino may become a dominant decay if there are new sources of flavor violation. In this case, the Tevatron could exclude stops up to 180 GeV if $m_{\tilde{t}} - m^0_\chi \gtrsim 50$ GeV. With even small flavor violation, mesino oscillations `hep-ph/9909349` can convert stops into antistops and lead to same-sign dilepton events with jets and MET. See also `1207.6794` for $t \to ch$, which may be relevant.

4.6 Bump hunting

Brust, Katz, and Sundrum presented a bump search for RPV models `1206.2353`. In these models, the stop is indeed the LSP, but this decays into two jets via the RPV coupling $\Delta W \supset t_R d_R d_R$. (These RPV couplings individually have to be so small to avoid proton decay and flavor bounds that it's sufficient just to turn on one coupling at a time.) This means that you can get signatures which are devoid of MET and leptons. Existing cut and count searches aren't optimized for this sort of signal since they miss out on the dijet decay.

The BKS paper presented an alternate search based on reconstructing the resonances of the dijet decay of the stops. They consider cascade decays of heavier squarks into the light stops. They focus on sbottom decays rather than heavy stop decays since the latter decays are more model-dependent: the heavy stop to light stop-Z and light stop-h decays depend on the left-right stop mixing. Meanwhile, they focus on: $\tilde{b} \to W^{(*)}\tilde{t}$. The strategy is:

1. Tag events with two isolated leptons and "moderate" MET (to kill the Drell-Yan dilepon contribution)
2. Cluster the jets with a large radius. If you miss jet components then you can't reconstruct the resonance.
3. If the event contains 4+ jets, then we have to play combinatoric games. Since we assume that these jets come from the light stops, we can bias our combinatoric searches by minimizing the difference between reconstructed invariant masses.

Background: top pair production with dileptonic decays ($100 \times$ signal), but one can cut away most of the other backgrounds. So one has to use an additional discriminator: the hardness of the event. In ditop events, the hardness of the event correlates with the hardness of the leptons and MET. In the signal, however, there may only be a mild splitting between the stop and sbottom (by assumption in the model) so that typically one cannot emit an on shell W. This means there's relatively low lepton p_T and MET even if the overall event is hard. So the simplest thing to do is to cut the high MET and high lepton p_T tail. One can do better, however, by defining dimensionless variables in where these quantities are scaled by the total event hardness.

4.7 Light [Stealth] Stop Signs `1205.5808`

Harvard group. Focuses on the stealth stop window, $m_t \lesssim m_{\tilde{t}} \lesssim 250$ GeV, look for new handles on this difficult region. The difficulty, recall, comes mainly from the fact that these stops decay into stops and a relatively soft neutralino/gravitino so that these effectively look like top decays.

Note that at 7 TeV, the stop cross section is only a sixth of the top cross section for degenerate stop/top. This drops rapidly for larger masses. Thus we need as many handles as we can get since simply measuring the total rate for events passing top selection is not enough.

4.7.1 Spin semi-correlation

The most important fact of the stealthy regime is that stops are spin zero and are produced without spin correlations. Thus the stop and antistop decays are completely uncorrelated. What does this buy us?

Suppose we have a sample of 'top' events which include stealthy stops. The real top decays are spin correlated, while the stops *slightly* wash out this correlation. Melnikov and Schulze `1103.2122` showed that these correlations are stable with respect to NLO corrections, which is a unique property for our handles of stealth stops.

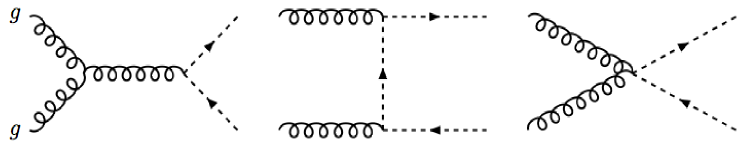
They focused on looking at, for example, the distribution of $\Delta\phi(\ell^+, \ell^-)$. I'll not go into this further since spin correlation techniques are a whole separate bag of worms. See the paper for a discussion and references.

4.7.2 Stop versus top production

The stop production rate is suppressed relative to the top production near threshold. There are two reasons for this.

1. $gg \to t\bar{t}$ has t- and u-channel singularities which are regulated by m_t. On the other hand, di-stop production does not have such a singularity. This is because the only diagram which looks like it could give such a singularity. This can lead to the use of a rapidity gap as a discriminator. This explains why the gg production channel for tops and stops are different (68 pb vs 11 pb).

2. Stop production is p-wave in the s-channel (that's a confusing way of saying it) production from the $q\bar{q}$ initial state. This is because the stop final states must carry angular momentum; the production goes through an s-channel gluon which is spin-1. This means the production rate goes like β^3 (where β is the velocity) near threshold. This suggests looking at higher p_T where stop production might be enhanced. This, however, is less interesting at the LHC due to the parton PDFs. This explains why the $q\bar{q}$ production channel for tops and stops are different. (23 pb vs 1.6 pb.)



Indeed, the stop production cross section from gluinos is given to leading order by:

$$\sigma(gg \to \tilde{t}\,\tilde{t}^*) = \frac{\alpha_s^2 \pi}{s}\left[\beta\left(\frac{5}{48} + \frac{31 m^2}{24 s}\right) + \left(\frac{2m^2}{3s} + \frac{m^4}{6s^2}\right)\log\frac{1-\beta}{1+\beta}\right]$$

where $\beta^2 = 1 - 4m^2/s$ is the subprocess velocity.

4.7.3 Rapidity Gaps

The gluon to (s)top production cross sections are, in the massless limit:

$$\begin{aligned} \sigma(\text{stop}) &= \frac{5\alpha_S^2 \pi}{48 s} \\ \sigma(\text{top}) &= \frac{\alpha_S^2}{24 s}(t^2 + u^2)\left(\frac{1}{tu} - \frac{9}{4s^2}\right). \end{aligned}$$

The top singularities are regulated by the top mass so that it ends up being $\log s/m_t^2$ enhanced. You can also see this using MHV amplitudes,

$$\begin{aligned} \mathcal{M}(1^+, 2^-, 3_\varphi, 4_\varphi) &= i e^2 \frac{[13]\langle 23\rangle}{\langle 13\rangle [23]} = e^2 \times \text{phase} \\ \mathcal{M}(1^+, 2^-, 3^-, 4^+) &= i e^2 \frac{[14]\langle 23\rangle}{\langle 13\rangle [23]} = e^2 \sqrt{\frac{u}{t}} \times \text{phase}. \end{aligned}$$

They note that the top production case corresponds to the "familiar splitting function ameliorating the ple in a t-channel diagram to the squareroof of a pole in the amplitude." The two results are related by a SUSY Ward identity.

They then look at the effect of this on the rapidity distribution Δy between the top and anti-top. They noted that the effect of the shape can be mimicked by increasing the renormalization scale.

4.8 Kinematic variables with endpoints for background

"Stop the top background," Bai, Cheng, Callicchio, and Gu. `1203.4813`.

4.9 Tagging boosted tops from stop decay

- `1205.5816`: Stolarski, Kaplan, and Rehermann.

- 1205.2696: Plehn, Spannowski, Takeuchi.

4.10 MET and M_T shapes

1205.5805. Alves, Buckley, Fox, Lykken, Yu (Tien-Tien).

5 Review of Work: UV theories

Common theme: the third generation is special through compositeness. Otherwise you have to figure out a way to explain flavor structure; compositeness does this 'automatically' e.g. through a small splitting in anomalous dimensions at the high scale.

5.1 Supersymmetric warped extra dimension

Uses XD localization and 'emergent' (See below) or 'partial' supersymmetry hep-ph/0302001.

- General problem: gauginos are external to the strong dynamics (compare to McSSM) and need to be both light and have supersymmetric couplings to avoid dangerous quadratic divergences in the Higgs mass. However, the gauginos are part of the elementary sector (which feels SUSY breaking strongly) and neither assumption holds automatically, requiring some model building.
- Automaticatically inherits nice features of RS: e.g. hierarchical Yukawas
-

5.1.1 Emergent SUSY 0909.5430

Stringily-motivated; suppose SUSY is high scale but "vestiges" of supersymmetry are 'accidentally' redshifted down to the TeV scale. In the dual sense, this is emergent/accidental supersymmetry in the strong sector. SUSY no longer solves the big Hierarchy problem (which is now solved by warping), but it does address the Little Hierarchy problem.

- Goes on to extend this idea: replace non-SUSY weakly coupled sector with the weakly-coupled sector of **split supersymmetry**: light gauginos. Suppresses dominant Higgs radiative corrections in the little Hierarchy.
- Higgs is a composite state whose mass happens to be light compared to the dynamical scale. (The usual problem in composite models.) Introduces a 'little' μ-problem, despite being technically natural.
- Also became a prototype for his effective SUSY work with Katz et al.

5.1.2 Partially supersymmetric, pseudo-Goldstone Higgs 1004.5114

By Redi and Gripaios. Supersymmetric Randall-Sundrum. Understood to be SO(5)/SO(4) pseudo-Goldstone Higgs. Maps onto the 'More Minimal SUSY'ic SM.' Different from Raman's model in that it's really supersymmetrizing the minimcal composite Higgs model. Thie Higgs only couples derivatively to the strong sector, Yukawas obtained through mixing with elementary sector.

- Regarding gaugino problem: assume SUSY breaking in elementary sector is large compared to the compositeness scale but soft, so couplings are approximately supersymmetric. Gaugino masses then require an approximate R-symmetry that is respected by SUSY breaking.
- Generation of Higgs potential is different from non-supersymmetric case. In minimal composite Higgs, required Higgs potential to come from loop-level couplings to fermions (e.g. top). However, for the SUSY MCH, a quartic of the correct order of magnitude is automatically generated and mass terms are only generated at loop level when SUSY is broken. This avoids problems composite Higgs models that have a high compositeness scale.

5.2 Deconstructed third generation 1103.3708

See Jack's talk last year. The quiver diagram can be understood as a deconstruction of the general framework above.

5.3 Composite MSSM 1201.1293

Another handle on strong coupling is Seiberg duality. This is again a variation of the same theme above.

See my separate notes on McSUSY. For references see `arXiv:1106.3074` (Csaki, Shirman, Terning, "A Seiberg Dual for the MSSM") and `arXiv:1201.1293` (Csaki, Randall, Terning, "Light Stops from Seiberg Duality"). For background, see my Seibergology notes.

5.4 Flavor mediation 1203.1622

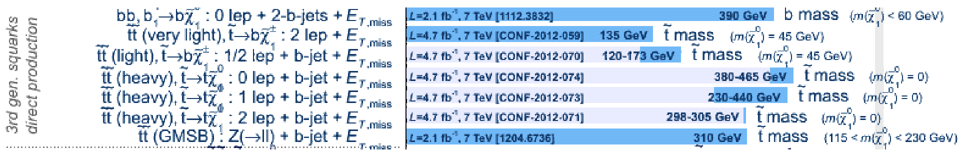
Explicit flavor structure introduced in messengers. For related ideas, see Yael's seminar talk last week.

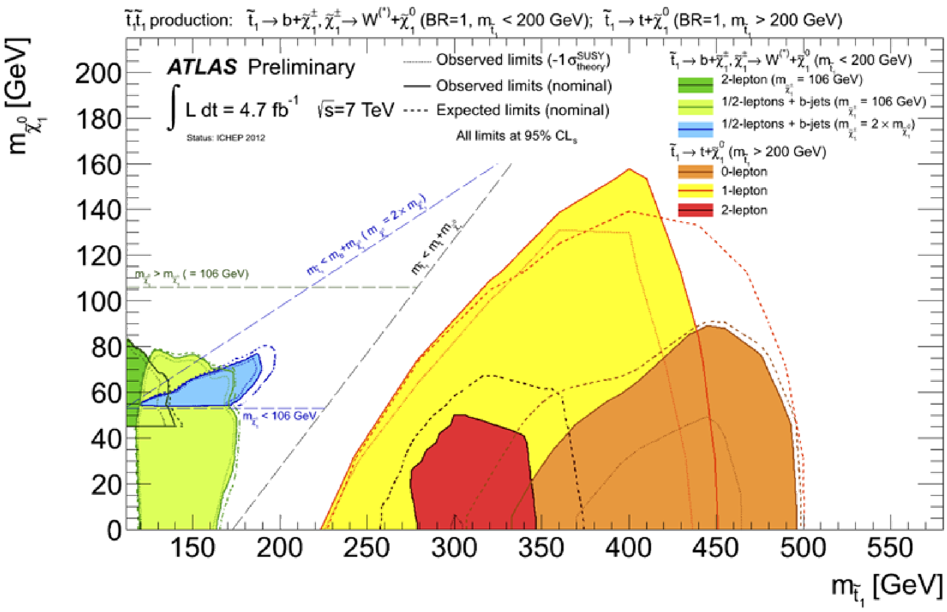
6 Experimental bounds

6.1 General squarks

Searches for first and second generation squarks have been very restrictive. However, as we explained above, these bounds have essentially no impact on fine-tuning in the MSSM.

6.2 Stops after ICHEP 2012





6.2.1 ATLAS-CONF-2012-059: 7 TeV 4.7/fb

Search for light stops.

Signal: 2 leptons + jets + MET

Bounds: assuming $\tilde{t} \to b\chi^+$ with $m_{\chi^+} = 106\,\mathrm{GeV}$, fixes $m_{\tilde{t}} > 130\,\mathrm{GeV}$ for $m_{\chi^0} < 65\,\mathrm{GeV}$.

6.2.2 ATLAS-CONF-2012-070: 7 TeV 4.7/fb

Search for light stops with mass around (or lighter) than the top mass. Look for one or two leptons, large MET, light flavor jets, and b-jets.

Signal: 1 or 2 leptons + 1 or 2 b-jets + jets + MET

Bounds: Assuming $\tilde{t} \to b\chi^+$. Excludes $120\,\mathrm{GeV} < m_{\tilde{t}} < m_t$ for $m_{\chi^0} \sim 55\,\mathrm{GeV}$.

6.2.3 ATLAS-CONF-2012-071: 7 TeV 4.7/fb

Search for medium-mass stop partners decaying to t and neutral non-interacting particle. Sensitive up to stop masses up to 200 GeV. Direct pair production of top partners (stop or spin-1/2 partner) with $\tilde{t} \to t\chi^0$. Look for two leptons in final state.

Signal: 2 leptons + jets + MET.

Bounds: Rules out a $m_{\tilde{t}} \approx 300\,\mathrm{GeV}$ decaying to a massless neutralino, assuming a signal that is 1σ below the central value.

6.2.4 ATLAS-CONF-2012-073: 7 TeV 4.7/fb

Search for direct heavy stop production; events with an isolated lepton, jets, and MET, with $\tilde{t} \to t\,\mathrm{LSP}$.

Signal: 1 lepton + jets + MET

Bounds: Rules out $230\,\mathrm{GeV} < m_{\tilde{t}} < 440\,\mathrm{GeV}$ for massless LSP.

6.2.5 ATLAS-CONF-2012-074:

Heavy stop assuming $\tilde{t} \to t\,\mathrm{LSP}$ with both quarks decaying hadronically.

Signal: 0 lepton + jets + MET

Bound: excludes $370\,\mathrm{GeV} < m_{\tilde{t}} < 465\,\mathrm{GeV}$ for massless LSP.

6.3 Stop NLSP

See the Stop NLSP section above for the Katz and Shih analysis of past Tevatron and LHC bounds. Here we review their section 4, which describes some of the current (at the time) bounds on the stop NLSP scenario.

The searches which are most sensitive are those which:

- are more accepting of soft jets, or
- use more discriminating variables such as m_T or some kind of reconstructed stop mass.

6.3.1 Cut and count

The expected number of stop events is

$$N_{\tilde{t}\tilde{t}^*} = \left(\frac{\varepsilon_{\tilde{t}\tilde{t}^*}}{\varepsilon_{t\bar{t}}}\right) \times \left(\frac{\sigma_{\tilde{t}\tilde{t}^*}}{\sigma_{t\bar{t}}}\right) \times N_{t\,\bar{t}}.$$

The first factor is the relative acceptance for stop pair production. The second factor is the relative production cross section. Armed with this information, one can calculate exclusion confidence levels. Here are the results:

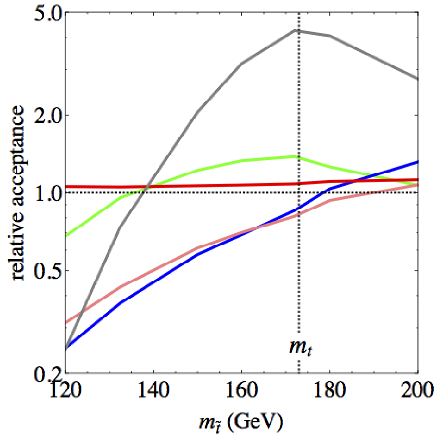


Figure 9: Acceptances of $\tilde{t}\tilde{t}^*$ events relative to those of $t\bar{t}$ events for the pre-tag sample of the CDF $t\bar{t}$ cross section measurement in the dilepton channel [15] (blue), the D0 stop search in the $e\mu$ channel (up to selection 1) [28] (red), the b-tagged sample of the CDF stop search in the dilepton channel [30] (green), the pre-tag sample of the ATLAS $t\bar{t}$ cross section measurement in the dilepton channel [20] (pink) and the ATLAS top partner search [14] (gray).

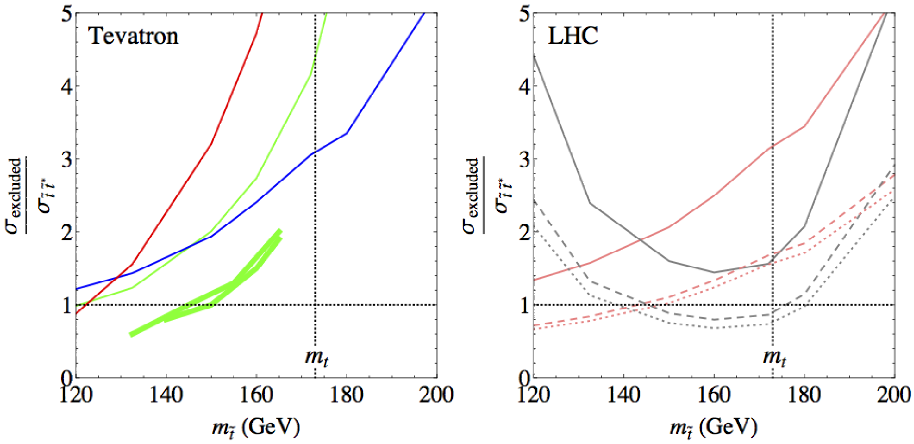


Figure 10: 95% CL excluded cross sections, relative to the theoretical stop cross section. On the left we present our limits from the Tevatron analyses: the pre-tag sample of the CDF $t\bar{t}$ cross section measurement in the dilepton channel [15] (blue), the D0 stop search in the $e\mu$ channel (up to selection 1) [28] (red), and the b-tagged sample of the CDF stop search in the dilepton channel [30] (green). The two thick green lines are obtained from the stop mass reconstruction procedure of [30]. The right plot presents our limits from the LHC analyses: the pre-tag sample of the ATLAS $t\bar{t}$ cross section measurement in the dilepton channel [20] (pink) and the ATLAS top partner search [14] (gray), where the solid lines are the actual limits (from 35 pb^{-1} of data) while the dashed and dotted lines are approximate expected limits for 300 and 3000 pb^{-1}, respectively.

Remarks on the self-consistency of their simulations:

- The use of these ratios and $N_{t\bar{t}}$ cause many systematic errors in the simulations to cancel. (This is a sanity check for the results.)
- Raw number $N_{t\bar{t}}$ agrees with experimental references at 30%.
- The stop cross section has a power law dependence on the stop mass, but the stop limits are not appreciably changed by 10% changes in the acceptance in either direciton.

Results, **very light stops** ~120 **GeV**

- Acceptance is affected significantly by the requirements on number and E_T of jets. Light stops tend to decay into *soft* b-jets.

- The acceptance is close to 1 only for the D0 stop search since it does not impose a requirement on the number of jets. This gives it the best cut-and-count exclusion for a 120 GeV stop.
- The b-tagged sample in the CDF search is relatively high, while other analyses have stricter jet E_T requirements leading to lower acceptences.

Results, ∼150 **GeV intermediate mass stops**

- b-jets are harder and are more efficient in passing selections, but reduced cross sections weaken the limits.
- ATLAS top partner search for leptons + jets has high acceptance because it cuts on $m_T >$ 120 GeV, which elminates the top backgroun.
- $\mathcal{O}(100)$/pb data should be able to reach 95% CL exclusion for stops up to 180 GeV, but beyond this one is limited by systematic errors.

6.3.2 Stop mass reconstruction

Based on `0912.1308, CDF Note 9439, FERMILAB-THESIS-2010-16`, which uses a dilepton stop mass reconstruction algorithm at CDF. The algorithm assumes a stop decay $\tilde{t} \to b\chi^+ \to \ell\nu b\chi^0$, but turns out to work also for the stop NLSP scenario by giving a much sharper mass distribution compared to the top that is centered at a different value. It seems like Katz and Shih mapped on stop NLSP parameter points to similar gravity mediated parameter points so that they could use the CDF analysis.

The result of this analysis gives a stop NLSP exclusion for $m_{\tilde{t}} < 150\,\text{GeV}$. This is the best limit in their paper. "This illustrates the power of using more discriminating variables in searching fo rnew physics in the ditop sample." Future directions include using the D0 stop search (which they could not reinterpret because it would require access to their data).

6.3.3 Other types of measurements

- Invariant mass of the lepton-b system. (See `hep-ph/9909536`) Can reduce ditop background. Ambiguities in pairing lepton and b-jet, but even incorrect pairing contributes in a similar way to the differences between distributions. This distrubtion has not been published (as of the Katz-Shih paper) since the 700/pb data from the Tevatron.
- b-jet p_T distribution. Is there a way to use the softness of b-jets from stop decay to separate the ditop background? Limiting factors: $p_T \geqslant 12\text{GeV}$ for proper reconstruction of b-jet p_T and efficiency decreases with p_T.
- **Displaced decays**. No dedicated searches as of the time of the Katz/Shih paper, though you can find some ideas from searches for hidden valley scenarios. Current ATLAS and CMS studies for charged stop-hadrons are not constraining due to the requirements of each search.

6.4 The gluino

Current bounds (from Han, Katz, Krohn, Reece) push the gluino above ∼900 GeV.

- `ATLAS-CONF-2012-004`: two same-sign leptons, jets and missing transverse momentum
- `1205.3933`: CMS, same-sign dileptons and b-tagged jets
- `CMS-PAS-SUS-11-027`: single lepton and jets using templates
- `ATLAS-CONF-12-037`: large jet multiplicities and missing transverse momentum

6.5 Flavor/Naturalness bounds on stop mixing

6.5.1 `1206.5303`: IAS Higgs couplings from natural SUSY

Defines ratio of Higgs couplings to SM values:

$$r_i = \frac{g_{hii}}{g_{hii}^{\text{SM}}}.$$

Writing $X_t = A_t - \mu/\tan\beta$, we have $r_G = r_t r_G^{\tilde{t}}$ with

$$r_G^{\tilde{t}} - 1 \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_{12}}^2}\right) + (D - \text{term contribution})$$

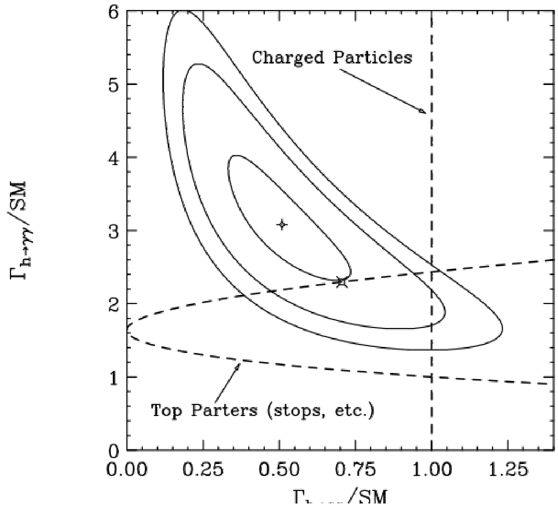
This can give a substantial effect for reasonably light ($\approx 250\,\text{GeV}$) stops: $r_G = 1.24$. This would give a 53% increase in gluon fusion Higgs production. A large stop mixing, however, could reduce this effect. This is limited by naturalness: a large X_t contributes to the weak scale tuning directly and through the requirement of larger diagonal soft masses.

Stronger constraints for stop mixing come from $B \to X_s\gamma$, which only allows new physics to contribute at about 30% of the loop-suppressed SM contribution. To avoid large tree-level SUSY contributions, it is typical to assume parameters in which such contributions cancel and measure the fine tuning. The result of the IAS group analysis is that to avoid cancellations to a level in one part per ten, we must have $A_t \mu \tan\beta / m_{\tilde{t}^2} < \text{few}$.

6.6 Fits to Higgs decay channels

6.6.1 `1207.1445`: Fermilab $h \to \gamma\gamma$ vs $h \to gg$ rates

1, 2, and 3σ contours for the global fit of the ICHEP 2012 Higgs data compared to the range of decay widths that can results from the addition of new charged particles or new charged-and-colored particles. Star marks the best fit for a top partner corresponding to $R_t = y_t / y_t^{\text{SM}} = -0.84$.



6.6.2 Isn't there also an Italian paper with a similar discussion?

Appendix A Review of the MSSM

Particle content, following Terning's conventions. Content based on Csaba's review.

χSF	SU(3)	SU(2)	U(1)	B	L
L	1	$\square$	$-\frac{1}{2}$	0	1
$\bar{E}$	1	1	1	0	−1
Q	$\square$	$\square$	$\frac{1}{6}$	$\frac{1}{3}$	0
U	$\bar{\square}$	1	$-\frac{2}{3}$	$-\frac{1}{3}$	0
D	$\bar{\square}$	1	$\frac{1}{3}$	$-\frac{1}{3}$	0
$H_1 = H_d$	1	$\square$	$-\frac{1}{2}$	0	0
$H_2 = H_u$	1	$\square$	$\frac{1}{2}$	0	0

The superpotential includes Yukawa terms and the μ term (flavor indices suppressed):

$$W = \lambda_u Q H_u \bar{U} + \lambda_d Q H_d \bar{D} + \lambda_L L H_d \bar{E} + \mu H_u H_d.$$

On top of this, the following terms are B or L violating and are removed by R-parity which is defined in terms of B, L, and the spin S by $R=(-)^{3B+L+2S}$,

$$W_{\not R} = \alpha_1 Q L \bar{D} + \alpha_2 L L \bar{E} + \alpha_3 L H_U + \alpha_4 \bar{D}\bar{D}\bar{U}.$$

Appendix B MSSM Higgs scalar potential

One of the most important parts of the MSSM is the scalar potential for the Higgs and the constraints from the requirement of electroweak symmetry breaking. See `hep-ph/9606414` for details.

B.1 Supersymmetric contribution

Recall that the general form of the scalar potential for a renormalizable supersymmetric theory is

$$V(\phi) = W_i^* W^i + \frac{1}{2}\sum_a g_a^2 (\phi^* T^a \phi)^2,$$

where the first term is the F-term contribution and the second is the D-term contribution. From the superpotential we can see that only the μ-term contributes to to F-term potential since the sfermions don't get vevs:

$$\Delta V_F(H_u, H_d) = |\mu|^2 |H_u|^2 + |\mu|^2 |H_d|^2.$$

The D-term potential is simpilified using $\sigma_{ij}\sigma_{kl} = 2\delta_{il}\delta_{jk} - \delta_{ij}\delta_{kl}$,

$$\begin{aligned}
\Delta V_F(H_u, H_d) &= \frac{1}{2} g^2 \Big(H_u^* \frac{\sigma}{2} H_u \Big)^2 + \frac{1}{2} g'^2 |H_u|^4 + (u \to d) \\
&= \frac{1}{2} g^2 (2|H_u^+|^2 |H_u^0|^2 - |H_u^0|^2 |H_u^+|^2) + \frac{1}{2} g'^2 (|H_u^0|^2 + |H_u^+|^2) + (u \to d, + \to -) \\
&= \frac{1}{8} (g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{1}{2} g^2 |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2.
\end{aligned}$$

B.2 Mass matrix in SUSY limit

Now let us write out the mass matrix for a complex scalar field ϕ in the basis $\Phi = (\phi, \phi^*)^T$ so that the mass matrix M^2 appears as $\frac{1}{2}\Phi^* M^2 \Phi$. Sub/superscripts i, j, k refer to derivatives with respect to ϕ or ϕ^* respectively, while subscripts a refer to the gauge group.

$$(M^2)^i{}_j = \begin{pmatrix} \bar{W}^{ik} W_{kj} + \frac{1}{2} D_a^i D_{aj} + \frac{1}{2}(D_a)^i_j D_a & \bar{W}^{ikj} W_k + \frac{1}{2} D_a^i D_a^j \\ \bar{W}^k W_{ikj} + \frac{1}{2} D_{ai} D_{aj} & \bar{W}^{jk} W_{ki} + \frac{1}{2} D_a^i D_{aj} + \frac{1}{2}(D_a)^i_j D_a \end{pmatrix}$$

B.3 SUSY breaking contributions

We now include soft SUSY breaking terms. These come in the form of holomorphic masses (B terms) and soft masses. (There are no holomorphic trilinear A terms by gauge invariance.)

$$\begin{aligned}
\Delta V_{\text{soft}}(H_u, H_d) &= m_{H_u}^2 (|H_u^0|^2 + |H_u^+|^2) + m_{H_d}^2 (|H_d^0|^2 + |H_d^-|^2) - B\mu (H_u \cdot H_d) \\
&= m_{H_u}^2 (|H_u^0|^2 + |H_u^+|^2) + m_{H_d}^2 (|H_d^0|^2 + |H_d^-|^2) - B\mu (H_u^+ H_d^- - H_u^0 H_d^0 + h.c.)
\end{aligned}$$

where we've written the B term with a factor of μ pulled out as a choice of convention. Note that it is also standard to write $b = B\mu$ (e.g. Stephen Martin's review).

B.4 Total Higgs scalar potential

As written in Martin's review (eq. 8.1.1 in version 6):

$$\begin{aligned}
V = & \; (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\
& + [b(H_u^+ H_d^- - H_u^0 H_d^0) + h.c] \\
& \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{1}{2} g^2 |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2
\end{aligned}$$

B.5 Electroweak symmetry breaking

[I've been sloppy with the sign of b, sorry.] Note that the supersymmetric potential is leads to a positive definite mass matrix whose vev is $\langle H_u\rangle = \langle H_d\rangle = 0$. Note, further, that we need $\langle H_u^+\rangle = \langle H_d^-\rangle = 0$; in the following we write H for H^0 for simplicity. In order to break electroweak symmetry, we need the soft SUSY breaking terms. Introducing some notation, the form of our potential is:

$$V = m_{H_1}^2|H_d|^2 + m_{H_2}^2|H_u|^2 - m_{12}^2(H_uH_d + h.c.) + (D\,\text{terms}).$$

One may worry about the negative contribution coming from the m_{12}^2 piece. The quartic contribution from the D term (given above) vanishes in the direction $|H_u| = |H_d|$ (they are "D-flat"), so this is a legitimate concern. In order for the potential to be bounded from below in this direction, we thus require

$$\begin{aligned} m_{H_1}^2 + m_{H_2}^2 &> 2|m_{12}^2|. \\ m_{H_1}^2 &= |\mu|^2 + m_{H_d}^2 \\ m_{H_2}^2 &= |\mu|^2 + m_{H_u}^2 \\ m_{12}^2 &= b = B\mu \end{aligned}$$

Observe that $b = B\mu$ alsways favors electroweak symmetry breaking. The D term contributions are given above. Requiring that we get a negative squared mass near $H_u = H_d = 0$ for one linear combination gives (by taking the determinant of the mass matrix)

$$b^2 > m_{H_1}^2 m_{H_2}^2.$$

You might worry that this is only sufficient and not necessary since one might have the mass matrix having *two* negative eigenvalues. However, the previous condition $m_{H_1}^2 + m_{H_2}^2 > 2|m_{12}^2|$ enforces that the trace of the mass matrix is positive. Thus EWSB requires that the mass matrix has exactly one negative eigenvalue. (Thanks to the *Sparticle* book for spelling this out.)

We thus have the bounds:

1. $2b < m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2$
2. $b^2 > (|\mu|^2 + m_{H_d}^2)(|\mu|^2 + m_{H_u}^2)$.

These relate supersymmetric in the superpotential to soft breaking terms, parameters which *a priori* are expected to be unrelated. Note that there is no solution for $m_{H_u}^2 = m_{H_d}^2$, if one expects these two to be equal at a high scale, then electroweak symmetry is unbroken at tree-level.

Comments on RG: One can consider the RG running of these parameters from the high scale down to the weak scale. A reasonable assumption is to only include the top Yukawa coupling and the gauge interactions. The relevant expressions are the β-functions for $m_{H_2}^2$, $m_{\tilde{t}}^2$, and $m_{\tilde{Q}_3}^2$. These are functions of the gaugino masses, the gauge couplings, the top Yukawa, and the top A-term. The main story is this: (see `hep-ph/9606414`): Loops involving the top Yukawa coupling want to make the up-type Higgs mass negative, this is indeed what we want for EWSB.

Let us assume that the neutral component of the Higgs doublets obtain vevs v_u and v_d. As usual, we define $v^2 = v_u^2 + v_d^2 = 2m_Z^2/(g^2 + g'^2) = (174\,\text{GeV})^2$ and $\tan\beta = v_u/v_d$. These vevs can be chosen to be real and positive. Using these relations we can write $\partial V/\partial H_{u,d}^0 = 0$:

$$\begin{aligned} \frac{\partial V}{\partial H_u^0} &= 2m_{H_2}^2 v_u - 2bv_d + \frac{1}{2}(g^2 + g'^2)(v_u^2 - v_d^2)v_u \\ &= 2v_u\left(|\mu|^2 + m_{H_u}^2 - b\cot\beta + \frac{m_Z}{2v^2}(v_u^2 - v_d^2)\right) \\ &= 2v_u\left(|\mu|^2 + m_{H_u}^2 - b\cot\beta - \frac{m_Z}{2}\cos 2\beta\right). \end{aligned}$$

Similarly for $\partial V/\partial H_d^0$, with a minus sign on the final term. We end up with the conditions:

$$\begin{aligned} m_{H_u}^2 + |\mu|^2 - b\cot\beta - \frac{m_Z}{2}\cos 2b &= 0 \\ m_{H_d}^2 + |\mu|^2 - b\tan\beta + \frac{m_Z}{2}\cos 2b &= 0. \end{aligned}$$

It is common to rearrange these into constraints on the parameters:

$$
\begin{aligned}
|\mu|^2 &= \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2} m_Z^2 \\
b &= \frac{(m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2)\sin 2\beta}{2|\mu|}.
\end{aligned}
$$