LHC expectations for extensions of minimal supersymmetry

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Bethe Forum: SUSY breakdown confronting LHC and other data

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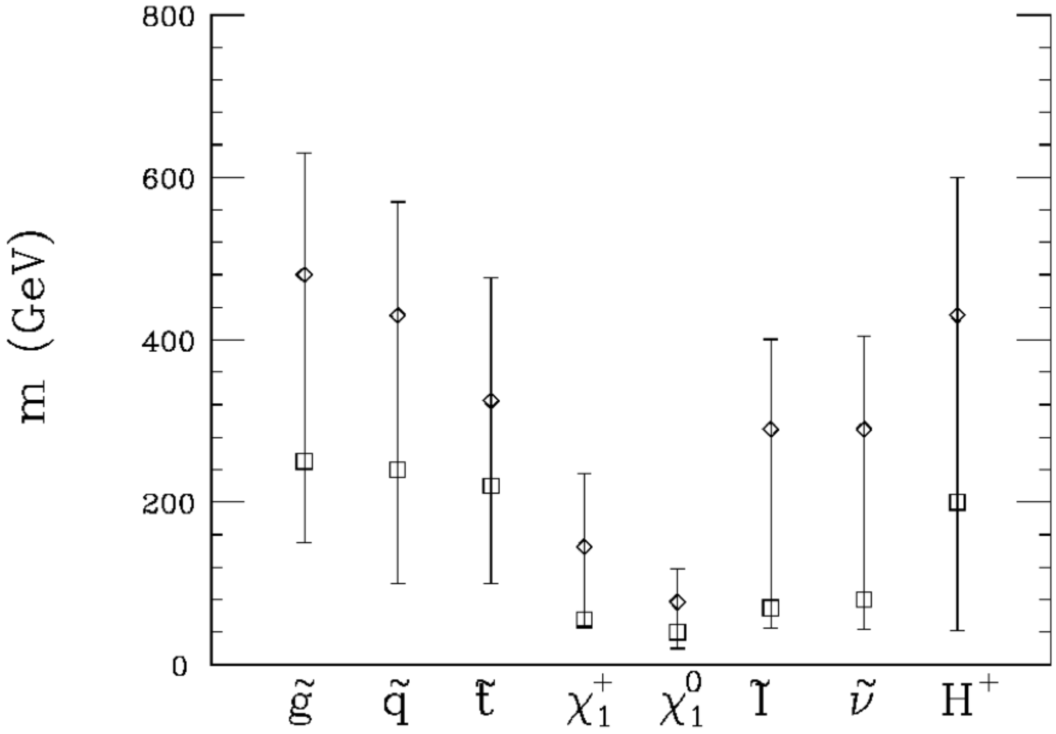
Some hiding places for SUSY at the LHC

- Just heavy
  beyond LHC14 reach? PeV-scale? semi-split? split? super-split?
- Long cascade decays
  Soft decay products. The pessimistic opposite of Simplified Models.
- Compressed mass spectra
  Low $M_{\rm eff}$ and H_T, soft decay products, reduced $E_T^{\rm miss}$
- Stealth SUSY, hidden valleys
  (Fan Reece Ruderman 1105.5135, Strassler Zurek 0604261, 0607160),
  e.g. low $E_T^{\rm miss}$ from nearly degenerate $\tilde{S}$, S.
- Nearly degenerate Higgsino-like LSPs
  $\tilde{H}^{\pm} \rightarrow \tilde{H}^0$ has very small phase space. Baer Barger Huang 1107.5581,
  Han Kribs A.Martin Menon 1401.1235; Baer, Mustafayev, Tata 1409.7058
- R-parity violation
  no (or small) $E_T^{\rm miss}$, lots of jets if B violated, use jet substructure techniques
- Dirac gauginos
  naturally heavy gluinos, suppressed $\tilde{Q}\tilde{Q}$ production

Should we have expected to find SUSY at the LHC by now?

A perspective from the previous millenium: “Naturalness and superpartner masses or when to give up on weak scale supersymmetry”, Anderson and Castaño, hep-ph/9412322:



However, everything changed by mid-2012 with the discovery of the Higgs boson; favors **heavy** and/or highly mixed stops.

The well-known little hierarchy problem:

$$m_Z^2 = -2(|\mu|^2 + m_{H_u}^2) + \mathcal{O}(1/\tan^2\beta) + \text{loop corrections.}$$

Often claimed to imply:

"Natural SUSY requires light Higgsinos."

but there are important loopholes mentioned below.

Taken at face value, however, need small $|\mu|^2$ and small:

$$\begin{aligned} m_{H_u}^2 \quad &= \quad 1.82\hat{M}_3^2 - 0.21\hat{M}_2^2 + 0.16\hat{M}_3\hat{M}_2 - 0.32\hat{A}_t\hat{M}_3 \\ &\quad -0.07\hat{A}_t\hat{M}_2 - 0.64\hat{m}_{H_u}^2 + 0.36\hat{m}_{Q_3}^2 + 0.28\hat{m}_{u_3}^2 + \ldots \end{aligned}$$

where LHS is at the TeV scale and RHS parameters are inputs at $M_{\rm GUT}$.

Naively, large gluino mass M_3 implies large $m_{H_u}^2$, which implies large $|\mu|^2$, and disturbing fine-tuning.

To get small μ, arrange for cancellation in:

$$m_{H_u}^2 = 1.82\hat{M}_3^2 - 0.21\hat{M}_2^2 + 0.16\hat{M}_3\hat{M}_2 - 0.32\hat{A}_t\hat{M}_3 -0.07\hat{A}_t\hat{M}_2 - 0.64\hat{m}_{H_u}^2 + 0.36\hat{m}_{Q_3}^2 + 0.28\hat{m}_{u_3}^2 + \ldots$$

Find UV completions in which the cancellation is "natural".

- Original focus point: Very large $m_0^2 = \hat{m}_{H_u}^2 = \hat{m}_{Q_3}^2 = \hat{m}_{u_3}^2$

  Chan, Chattopadyay, Nath 9710473; Feng Matchev Moroi 9908309, 9909334.

- FP $M_h = 125$ GeV. $\hat{m}_{H_u}^2 : \hat{m}_{Q_3}^2 : \hat{m}_{u_3}^2 : A_t^2 = 1 : 1{+}x{-}3y : 1{-}x : 9y$

  Feng Matchev Sanford 1112.3021, Feng Sanford 1205.2372

- NUHM $\hat{m}_{H_u}^2 \neq m_0^2 = \hat{m}_{Q_3}^2 = \hat{m}_{u_3}^2$

- "Mirage mediation", compresses gaugino masses at TeV scale

  Choi, Falkowski, Nilles, Olechowski, Pokorski, hep-th/0411066, hep-th/0503216; Choi, Jeong, Kobayashi, Okumura hep-ph/0612258; Baer, Barger, Serce, Tata hep-ph/1610.06205; ...

- Non-universal gaugino masses: $\hat{M}_3 \sim 0.3\hat{M}_2$. Compressed spectrum, small $|\mu|$. SPM 0703097, 1312.0582

A non-universal gaugino mass framework

If F-terms that break SUSY in a linear combination of the singlet $\mathbf{1}$ and adjoint $\mathbf{24}$ reps of $SU(5)$:

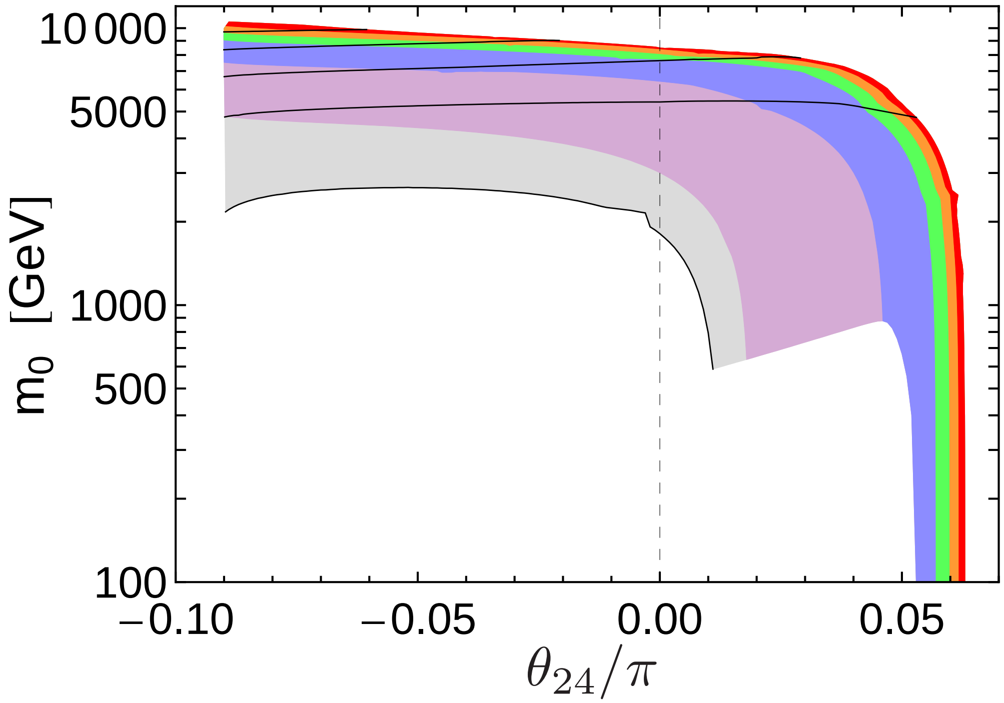
$$
\begin{aligned}
M_1 &= m_{1/2}(\cos\theta_{24} + \sin\theta_{24}) \\
M_2 &= m_{1/2}(\cos\theta_{24} + 3\sin\theta_{24}) \\
M_3 &= m_{1/2}(\cos\theta_{24} - 2\sin\theta_{24})
\end{aligned}
$$

where $m_{1/2}$ is an overall mass scale and θ_{24} is an angle.

Note $\theta_{24} = 0$ corresponds to mSUGRA, while $\theta_{24} = \pm\pi/2$ is a pure adjoint F-term.

Non-universal gaugino masses with $M_3 = 2000$ GeV, $A_0 = 0$, $\tan\beta = 10$:

SPM 1312.0582



Red: $\mu < 500$ GeV

Orange: $\mu < 750$ GeV

Green: $\mu < 1000$ GeV

Dashed vertical line = mSUGRA

Top edge = Focus Point SUSY

Bottom left edge = M_h too small

Bottom right edge = LSP charged

Left edge = $M_{\text{Wino}} < 100$ GeV

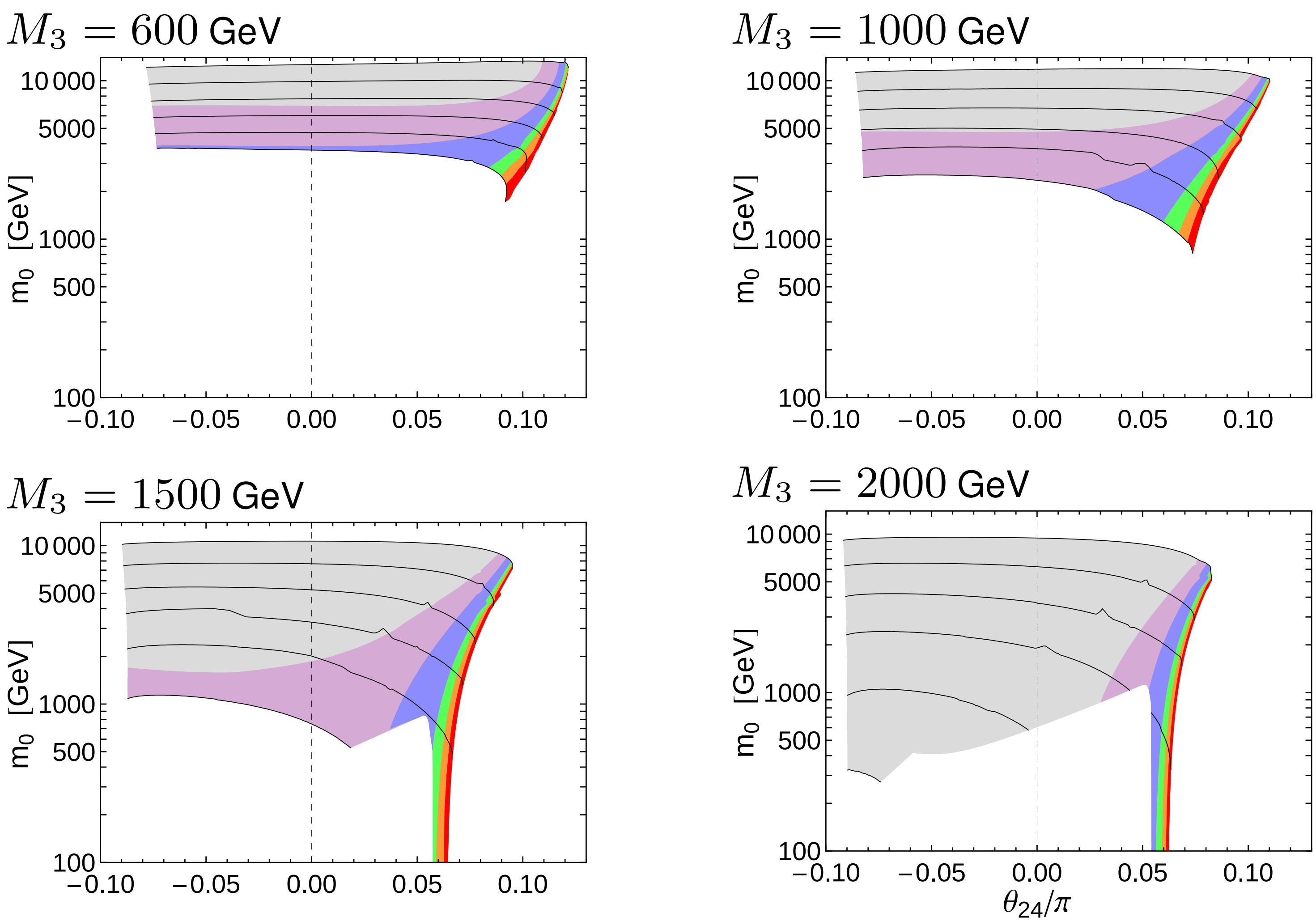
Right edge = small M_3/M_2

The Focus Point region is continuously connected to a semi-natural region with small μ and the rest of the SUSY spectrum compressed and heavy.

Note: SUSY flavor problem solved by gaugino mass domination.

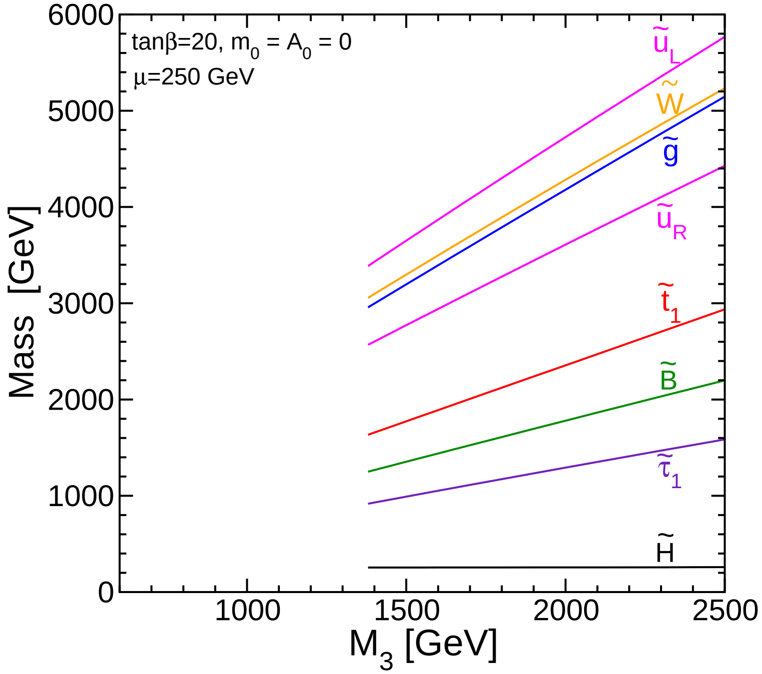
[Here: $m_0^2 \ll M_1^2, M_2^2, M_3^2$, but more generally $m^2_{\text{scalars}} \ll M_1^2, M_2^2, M_3^2$]

For larger stop mixing ($A_0/M_3 = -1$), can have $M_h = 125$ GeV with lighter sparticles. Focus Point disappears, but semi-natural region with small M_3/M_2 lives on:

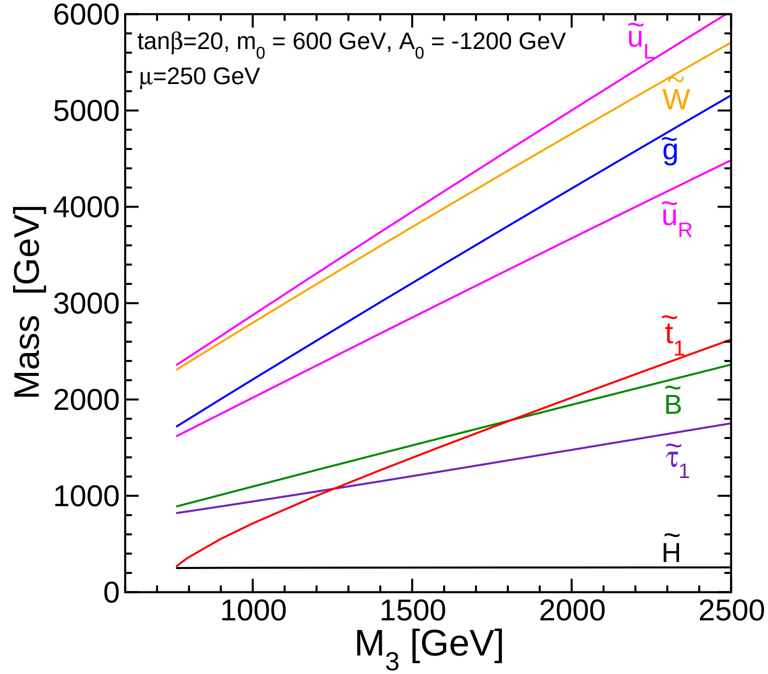


Sample mass spectra for “semi-natural” SUSY

Small stop mixing

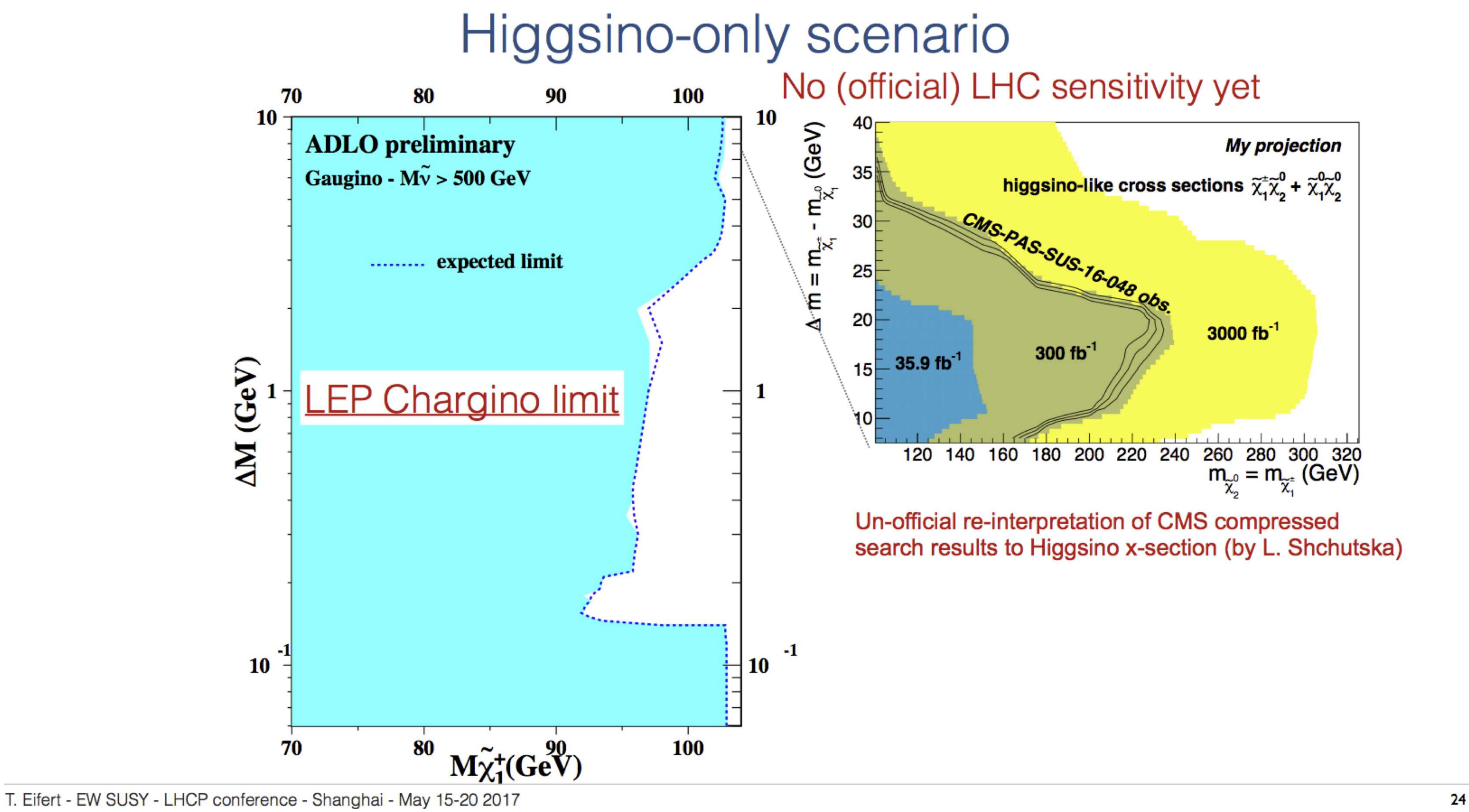


Large stop mixing



- θ_{24} is tuned to keep $\mu = 250$ GeV fixed.
- Left cutoff is set by $M_h > 123$ GeV according to SuSpect.
- Gluino and up, down squarks safely out of reach of present LHC bounds
- Might be looking for just Higgsinos (maybe stops, if lucky).

From Till Eifert’s talk at LHCP conference in Shanghai:



General lessons from $M_h = 125$ GeV:

- It is not at all surprising that SUSY hasn't shown up yet
- Essentially no LHC limits on light almost pure Higgsinos
- In fact, expecting SUSY to show up in the future at LHC requires some optimism

However, there are possibilities that justify the required optimism, if one extends minimal SUSY.

Good ways of getting $M_h = 125$ GeV include:

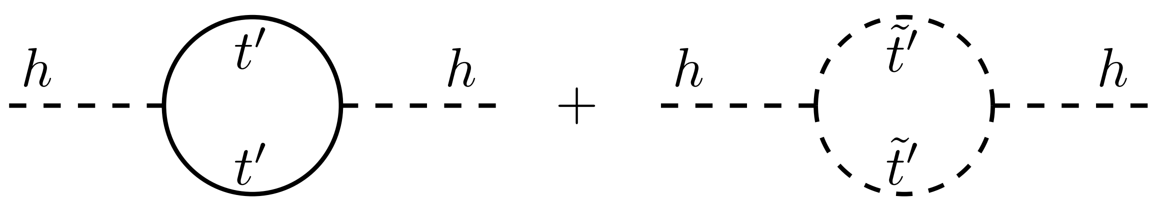
- Large A_t term, top-squark mixing.
- New F-terms: NMSSM and cousins.
  $W = \lambda S H_u H_d \qquad \rightarrow \qquad \Delta M_h^2 = \lambda^2 v^2 \sin^2(2\beta)$
- New D-term contributions to Higgs quartic coupling.
- New vector-like quarks with large Yukawa couplings
  - ⋆ Decoupling for precision EW observables and Higgs production/decay
  - ⋆ **Non**-decoupling and positive contributions to M_h

    Moroi, Okada 1992; Babu, Gogoladze, Kolda hep-ph/0410085,
    Babu, Gogoladze, Rehman, Shafi 0807.3055, SPM 0910.2732.
  - ⋆ In particular, an easy and natural fix for M_h in GMSB.

    Endo, Hamaguchi, Iwamoto, Yokozaki 1108.3071, 1112.5653, 1202.2751,
    Evans, Ibe, Yanagida 1108.3437, Nakayama, Yokozaki 1204.5420, SPM and J.Wells, 1206.2956

New vector-like quarks t', b' and leptons τ' and their spin-0 superpartners $\tilde{t}'$, $\tilde{b}'$, and $\tilde{\tau}'$, with large Yukawa couplings to the Higgs sector.

- Maintain gauge coupling unification
- Decouple from most quantities of interest, including potentially dangerous contraints from
  - W, Z amplitudes
  - Higgs production rate
- Do **not** decouple from the Higgs boson mass prediction:



Can get $\Delta M_h \approx$ 5 to 20 GeV from this, so that top squarks and other superpartners can easily be within the reach of LHC.

New vector-like quarks can raise the Higgs mass

New superfields: $Q, \overline{Q},\ U, \overline{U},\ E, \overline{E}\ = \mathbf{10} + \overline{\mathbf{10}}$ of $SU(5)$.

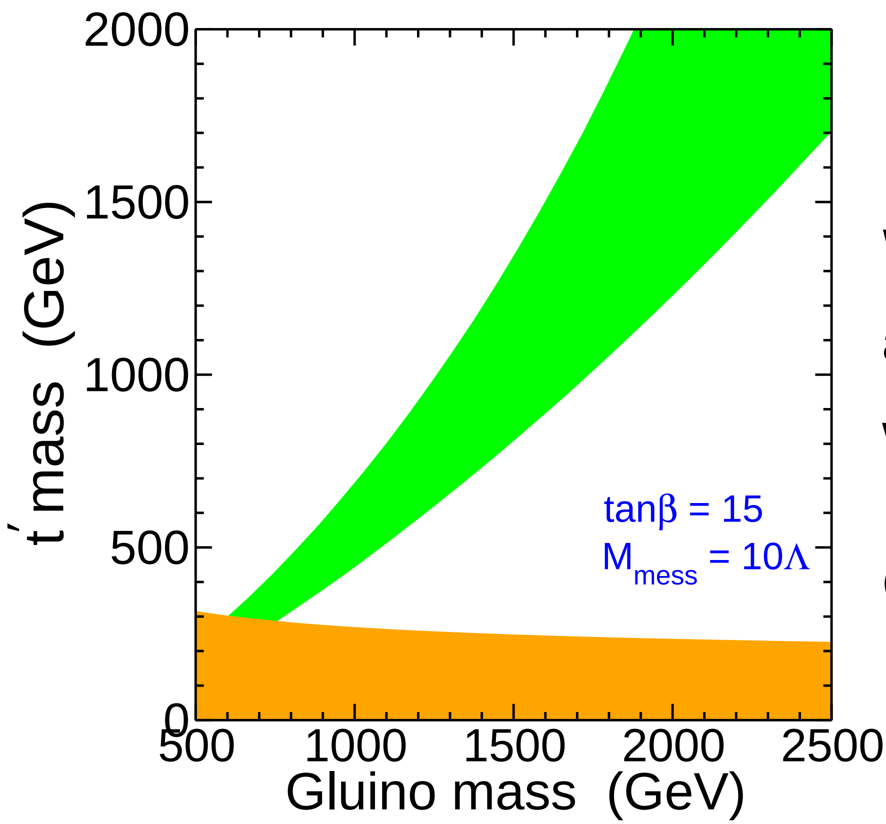
Exotic new quarks t_1', t_2', b', τ' and scalar partners.

$$t_1', t_2' \text{ mass matrix} = \begin{pmatrix} M_Q & kv_u \\ 0 & M_U \end{pmatrix}$$

$$\Delta M_h^2 \approx \frac{3}{4\pi^2} k^4 v^2 \left[\ln(x) - \frac{1}{6}\left(5 - \frac{1}{x}\right)\left(1 - \frac{1}{x}\right)\right], \qquad x = M_S^2/M_F^2$$

There is an IR fixed point at $k = 1.0$ to 1.05. Large positive ΔM_h^2.

For example, in minimal GMSB models, the green region below is compatible with $M_h = 125 \pm 3$ GeV, when vectorlike t' quarks, squarks $\tilde{t}'$ are included with Yukawa coupling at the IR-stable quasi-fixed point:

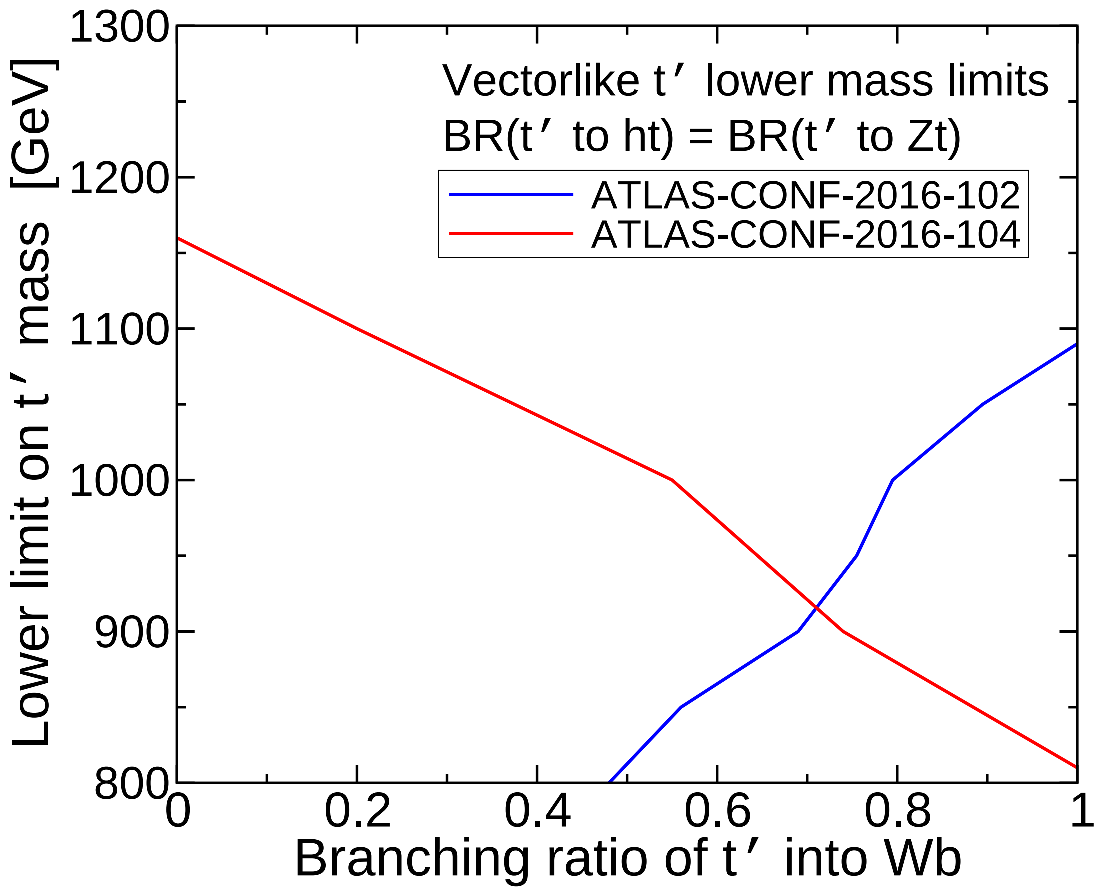


Without the vectorlike quarks and squarks, **none** of this plane would give $M_h = 125$ GeV.

(Work with James Wells, 1206.2956)

Vectorlike quarks also appear in many other extensions of the Standard Model, so the LHC experimentalists are all over it.

Lower mass limits for a t', from recent ATLAS data:

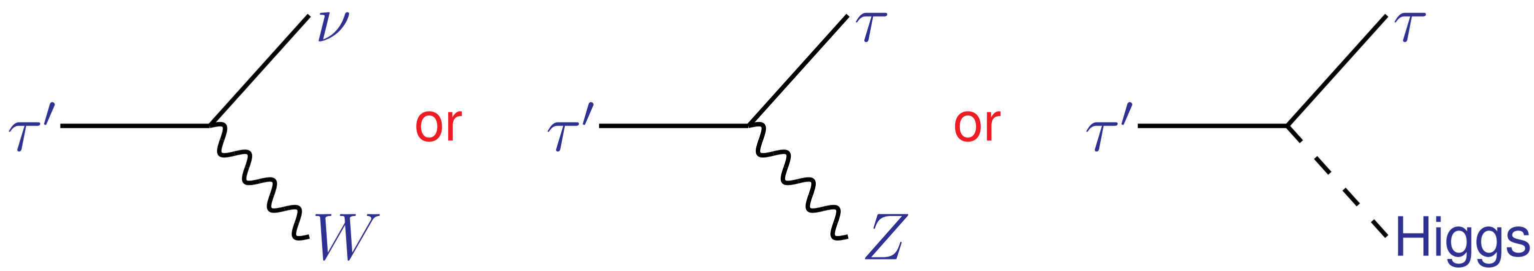


Also need a vectorlike lepton τ' for gauge coupling unification.

Heavy, vectorlike lepton, charge$= -1$, spin$= \frac{1}{2}$, weakly interacting.

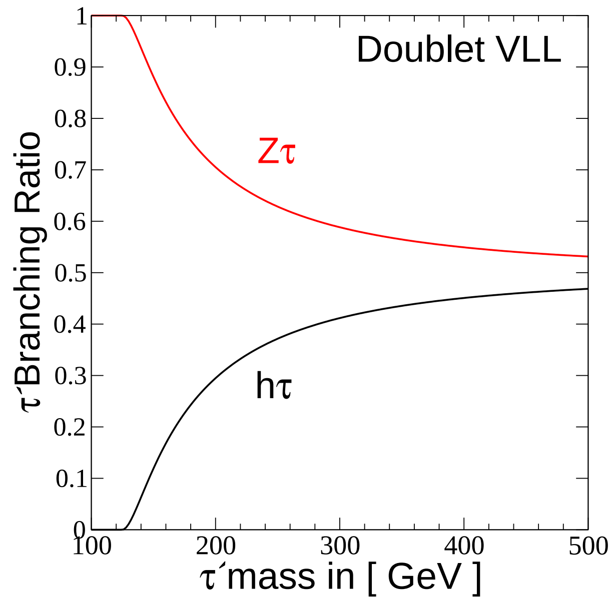
Pair produced, but with a much lower rate than a vectorlike quark.

Possible decays:



No published searches or limits from the LHC yet!

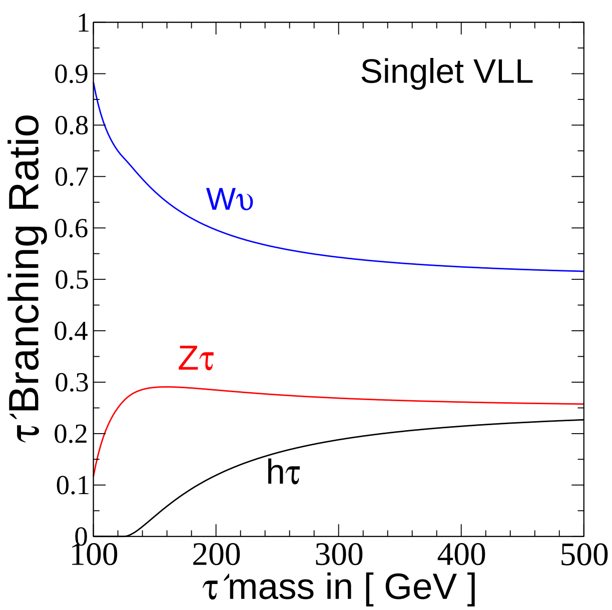
In arXiv:1510.03456, my PhD student Nilanjana Kumar and I studied the discovery prospects using multi-lepton final states, which depend greatly on whether the τ' is an electroweak doublet or singlet. . .



Doublet VLL (not the prediction of SUSY model)

Also has doublet partner ν', with $\nu' \rightarrow \tau W$ always.

Should be able to rule out (or discover!) $M_{\tau'} < 250$ GeV, even with 8 TeV LHC data from before 2016. Reach should be much improved by now. CMS search coming soon?



Singlet VLL (the prediction of SUSY model)

Very difficult! We found no LHC discovery or exclusion reach in this case at all, at least until a major luminosity upgrade.

Perhaps a different search strategy can do better.

Does natural SUSY really require small $|\mu|$?

Proposals for decoupling the Higgsino mass from the MSSM Higgs naturalness problem:

- Dimopoulos, Howe, March-Russell, “Maximally Natural Supersymmetry”, 1404.7554,
- Cohen, Kearney, Luty, “Natural Supersymmetry without Light Higgsinos”, 1501.01962.
- Nelson and Roy, “New Supersoft Supersymmetry Breaking Operators and a Solution to the μ Problem”, 1501.03251
- SPM, 1506.02105

Usual lore: a SUSY-breaking Higgsino mass is not among the allowed soft terms. More generally, fermion masses, non-holomorphic scalar cubic interactions, and Dirac gaugino masses:

$$\mathcal{L}_{\text{non-standard soft}} = -\frac{1}{2}\mu^{ij}\psi_i\psi_j - c_i^{jk}\phi^{*i}\phi_j\phi_k - m_{Da}\psi^a\lambda^a$$

were said by Girardello and Grisaru to lead to quadratic divergences.

However, only claimed true if there is a gauge singlet; not so in the MSSM.

Two better reasons to not consider a SUSY-breaking Higgsino mass term

$$\mathcal{L}_{\text{non-standard soft}} = -\tilde{\mu} H_u H_d \ :$$

- It is **redundant**! Just shift the superpotential μ term to absorb $\tilde{\mu}$, with the only cost being to introduce non-standard scalar interactions $\phi^2\phi^*$ terms .
- In most SUSY breaking models, it **is** induced, as we will see below, but is just very small compared to other sources of SUSY breaking.

Suppose, however, that all SUSY-breaking terms are suppressed by $1/M^3$, where M is some large mass scale.

Confession: I do not know how to make a UV completion of this type of model. I will simply parameterize the SUSY-breaking effects with the F-term of a chiral superfield spurion X, subject to some rules. . .

A set of model-building criteria:

- The F-term spurion X carries a conserved charge not shared by MSSM fields. Only X^*X can appear, not X or X^* separately.
- No MSSM quark or lepton superfield couplings to spurions. No flavor violation; technically natural.
- All terms communicating SUSY-breaking to the MSSM sector are suppressed by $1/M^3$. Terms like $\frac{1}{M^2}\int d^4\theta\, X^*X\, \Phi^*\Phi$ do not appear.

The last assumption is the most problematic one; there is no symmetry forbidding the terms with $1/M^2$ suppression.

One perhaps could imagine that some kind of geographical isolation of SUSY breaking could give the desired requirement of $1/M^3$ suppression.

With these assumptions, all SUSY-breaking mass scales proportional to $\langle F\rangle^2/M^3$.

In the MSSM$+X$, the complete set of leading SUSY-breaking terms are the $\frac{1}{M^3}\int d^4\theta X X^*$ integrals of the 8 combinations:

$\mathcal{W}^{\alpha a}\,\mathcal{W}^a_\alpha$ = Majorana gaugino masses, $a = 1, 2, 3$

$\nabla^\alpha H_u\,\nabla_\alpha H_d,\qquad H_u\,\nabla^\alpha\nabla_\alpha H_d,\qquad H_d\,\nabla^\alpha\nabla_\alpha H_u,$

$H_u^*\,e^V\,\nabla^\alpha\nabla_\alpha H_u,\qquad H_d^*\,e^V\,\nabla^\alpha\nabla_\alpha H_d$

Technical aside: $\nabla_\alpha\Phi = e^{-V} D_\alpha(e^V\Phi)$

where $V = 2g_a V^a t^a$, with t^a the matrix generator for the rep of Φ, and

$$D_\alpha = \frac{\partial}{\partial\theta^\alpha} - i(\sigma^\mu\theta^\dagger)_\alpha\partial_\mu$$

is the "chiral covariant derivative".

Consider the first three Higgs-related terms first. . .

The μ problem is solved by the Higgs terms:

$$\frac{c_7}{2M^3}\int d^4\theta\, X X^*\, \nabla^\alpha H_u\, \nabla_\alpha H_d \quad = \quad -\tilde{\mu}\tilde{H}_u\tilde{H}_d$$

is a mass term for the Higgsinos **only**, with $\tilde{\mu} = c_7\langle F\rangle^2/M^3$.

There are also separate μ terms for the H_u and H_d scalars:

$$\frac{c_8}{4M^3}\int d^4\theta\, X X^* H_u\, \nabla^\alpha\nabla_\alpha H_d \quad = \quad \mu_u H_u F_{H_d} \;\rightarrow\; -|\mu_u|^2|H_u|^2 + \ldots$$

$$\frac{c_9}{4M^3}\int d^4\theta\, X X^* H_d\, \nabla^\alpha\nabla_\alpha H_u \quad = \quad \mu_d H_d F_{H_u} \;\rightarrow\; -|\mu_d|^2|H_d|^2 + \ldots$$

where $\mu_u = c_8\langle F\rangle^2/M^3$ and $\mu_d = c_9\langle F\rangle^2/M^3$.

So, the MSSM gets 3 distinct μ parameters, all naturally of the same order as the gaugino masses.

The Higgsino mass $\tilde{\mu}$ is completely distinct from the parameters μ_u and μ_d that enter into the Higgs scalar potential at tree-level, and so the Higgsino mass is decoupled from the Higgs potential at tree-level.

Nelson and Roy 1501.03251 did an analogous thing in the Supersoft Dirac gaugino case.

More generally, this shows that thinking of μ as a supersymmetric parameter may turn out to be not appropriate.

The usual supersymmetric μ can be obtained by taking the particular combination $c_7 = c_8 = c_9$, which amounts to the single term:

$$\frac{1}{4M^3} \int d^4\theta \, X X^* \, D^\alpha D_\alpha (H_u H_d),$$

leading to:

$$\tilde{\mu} \; = \; \mu_u \; = \; \mu_d .$$

But, in the present context, this particular combination is not special.

But wait, there's more!

There are two other SUSY-breaking terms involving the Higgs fields:

$$\frac{1}{4M^3}\int d^4\theta\; c_{10} X X^*\, H_u^*\, e^V \nabla^\alpha \nabla_\alpha H_u \;+\; c_{11} X X^*\, H_d^*\, e^V \nabla^\alpha \nabla_\alpha H_d.$$

They add to the scalar-sector μ terms, without affecting the Higgsino masses.

$$\begin{aligned} \mu_u' &= c_{10}\langle F\rangle^2/M^3, \\ \mu_d' &= c_{11}\langle F\rangle^2/M^3. \end{aligned}$$

When combined with the μ_u and μ_d from above, get. . .

Scalar soft SUSY-breaking potential becomes:

$$\begin{aligned} -\mathcal{L}_{\rm soft} &= |\mathcal{M}_u|^2|H_u|^2 + |\mathcal{M}_d|^2|H_d|^2 + bH_uH_d \\ &\quad + H_u\bar{\tilde{u}}\mathbf{a_u}\tilde{Q} + H_d\bar{\tilde{d}}\mathbf{a_d}\tilde{Q} + H_d\bar{\tilde{e}}\mathbf{a_e}\tilde{L} \\ &\quad + H_d^*\bar{\tilde{u}}\mathbf{c_u}\tilde{Q} + H_u^*\bar{\tilde{d}}\mathbf{c_d}\tilde{Q} + H_u^*\bar{\tilde{e}}\mathbf{c_e}\tilde{L} \end{aligned}$$

where:

$$|\mathcal{M}_u|^2 = |\mu_u|^2 + |\mu'_u|^2, \qquad |\mathcal{M}_d|^2 = |\mu_d|^2 + |\mu'_d|^2,$$

$$b = B\mu = \mu_u\mu'_d + \mu_d\mu'_u$$

$$\mathbf{a_u} = \mu'_u\mathbf{y_u}, \qquad \mathbf{a_d} = \mu'_d\mathbf{y_d}, \qquad \mathbf{a_e} = \mu'_d\mathbf{y_e},$$

$$\mathbf{c_u} = \mu_d\mathbf{y_u}, \qquad \mathbf{c_d} = \mu_u\mathbf{y_d}, \qquad \mathbf{c_e} = \mu_u\mathbf{y_e}.$$

Get both “standard” (holomorphic) and “non-standard” (non-holomorphic) scalar cubic terms, on an equal footing. Flavor-preserving, depends on four parameters μ_u, μ_d, μ'_u, μ'_d. All scalar terms comparable to, but independent of, the Higgsino mass $\tilde{\mu}$ as well as the gaugino masses M_1, M_2, M_3.

Usually, gaugino masses are taken to be Majorana:

$$\mathcal{L}_{\rm Majorana} = -\frac{1}{2} M_a \lambda^a \lambda^a.$$

However, by introducing new chiral superfields $A^a \supset (\phi^a, \psi^a)$ in the adjoint rep, can have Dirac gaugino masses:

$$\mathcal{L}_{\rm Dirac} = -m_{Da} \psi^a \lambda^a.$$

These have a long history as "non-standard" SUSY breaking:

Fayet 1978; Polchinski,Susskind 1982; Hall,Randall 1991; Jack,Jones 1999; Fox,Nelson,Weiner 2002; Kribs,Poppitz,Weiner 2007; Benakli,Goodsell 2008,2010; Choi,Drees,Freitas,Zerwas 2008; Plehn,Tait 2008, Kribs,Okui,Roy 2010, Carpenter 2010; Benakli,Goodsell,Staub,Porod 2010,2014, Abel,Goodsell 2011; Goodsell 2012; Kribs,A.Martin 2012,2013; Csaki,Goodman,Pavesi,Shirman 2013; Benakli 2014; Nelson,Roy 2015; Carpenter,Goodman 2015; Alves,Galloway,McCullough,Weiner 2015; . . .

“Supersoft” operator (Fox, Nelson, Weiner 0206096) gives Dirac gaugino masses:

$$\mathcal{L} = \frac{1}{M} \int d^2\theta \, \mathcal{W}'^{\alpha} \mathcal{W}^a_{\alpha} A^a$$

where $\mathcal{W}'^{\alpha} = \langle D \rangle \theta^{\alpha}$ is a D-term spurion for SUSY breaking, and $\mathcal{W}^a_{\alpha} = \lambda^a_{\alpha} + \ldots$ are the MSSM gauge group field strength superfields.

The result is Dirac gaugino masses accompanied by “supersoft” scalar interactions:

$$\begin{aligned} \mathcal{L} &= -m^2_{Da}(\phi^a + \phi^{a*})^2 - \sqrt{2} g_a m_{Da} (\phi^a + \phi^{a*})(\tilde{q}^*_i t^a \tilde{q}_i) \\ &\quad - m_{Da}(\psi^a \lambda^a + \text{c.c.}) \end{aligned}$$

where $\tilde{q}_i$ are the MSSM scalars, and

$$m_{Da} = \langle D \rangle / M.$$

Supersoft SUSY breaking has many interesting properties, not all good...

Supersoft theories of Dirac gauginos predict:

- Relation between the Dirac gaugino mass, the real scalar adjoint mass, and the non-holomorphic SUSY-breaking term $\phi^a \tilde{q}_i^* \tilde{q}_i$ coupling is maintained by RG running. (Jack and Jones, 9909570)
- No UV divergent corrections to soft parameters; scalars do not get positive corrections to (mass)^2 from RG running involving gauginos.
- Real scalar adjoint gets a tree-level mass $2m_{Da}$, but imaginary scalar adjoint remains massless. ("Lemon-twist" operator can make it tachyonic.)
- No Higgs quartic interactions $(g^2 + g'^2)/8$ in the low-energy effective MSSM Lagrangian. Integrating out the scalar adjoints removes them. Problematic for $M_h = 125$ GeV.
- Supersafe from CP- and flavor-violation constraints. (Kribs, Poppitz, Weiner 0712.2039)
- Supersafe from early detection at LHC. (Kribs, A. Martin, 1203.4821)

An alternative (SPM 1506.02105): Dirac gaugino masses can also arise from F-term breaking with $X = \theta\theta\langle F\rangle$:

$$\mathcal{L} = -\frac{1}{M^3}\int d^4\theta\, X^* X\, \mathcal{W}_a^\alpha\, \nabla_\alpha A^a \;=\; -m_{Da}\psi^a\lambda^a$$

where

$$m_{Da} = \sqrt{2}\langle F\rangle^2/M^3.$$

Notes:

- there are no accompanying supersoft scalar interactions here; M_h is full-strength
- the Higgsino mass story fits into this framework; assume all SUSY-breaking is suppressed by $1/M^3$.

Similarly,

$$\frac{c_4}{4M^3}\int d^4\theta\, X X^*\, \nabla^\alpha A^a\, \nabla_\alpha A^a \quad = \quad -\frac{1}{2}\mu_a \psi^a \psi^a$$

is a Majorana mass for the adjoint chiral fermions, with $\mu_a = c_4 \langle F \rangle^2/M^3$.

Another term of the same order:

$$\frac{c_5}{4M^3}\int d^4\theta\, X X^*\, A^a\, \nabla^\alpha \nabla_\alpha A^a \quad = \quad m_a \phi^a F_a \quad \rightarrow \quad -m_a^2 |\phi^a|^2$$

gives the same **positive definite** $(\text{mass})^2$ to both the real and imaginary parts of the adjoint scalar, with $m_a = c_5 \langle F \rangle^2/M^3$.

This eliminates the problem of a massless or tachyonic scalar adjoint, which plagues the Supersoft version of Dirac gaugino masses due to the so-called "lemon-twist" operator!

The gaugino masses obtained in this framework are general:

$$\mathcal{L} = -\frac{1}{2}\begin{pmatrix}\lambda^a & \psi^a\end{pmatrix}\begin{pmatrix}M_a & m_{Da}\\ m_{Da} & \mu_a\end{pmatrix}\begin{pmatrix}\lambda^a\\ \psi^a\end{pmatrix}$$

Each of M_a and m_{Da} and μ_a are $\langle F\rangle^2/M^3$ multiplied by dimensionless couplings in this framework, so any hierarchy is possible, or they could be all of comparable size.

Many LHC studies, see e.g. Choi et al, 0808.2410 and 0812.3586; Kribs and A. Martin 1308.3468, Kribs and Raj 1307.7197

If $m_{Da} \gg M_a, \mu_a$, then the gauginos are Dirac-like. I will assume this below, and consider simple features of the RG evolution and the low-energy spectrum.

Gauge coupling unification

If we add vector-like fields $L + \overline{L}$ and $2 \times (e + \overline{e})$, then the gauge couplings will unify. (Fox, Nelson, Weiner 2012.)

At 1-loop order:

$$\begin{aligned} 16\pi^2\, \beta(g_1) &= \frac{42}{5} g_1^3, \\ 16\pi^2\, \beta(g_2) &= 4 g_2^3, \\ 16\pi^2\, \beta(g_3) &= 0, \end{aligned}$$

g_3 runs slowly

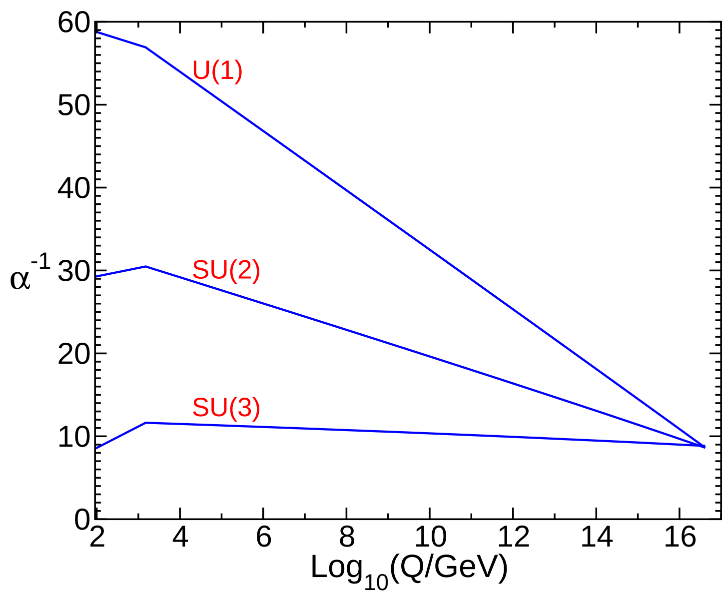
and the Dirac gaugino masses run as:

$$\begin{aligned} 16\pi^2\, \beta(m_{D1}) &= \frac{42}{5} g_1^2 m_{D1}, \\ 16\pi^2\, \beta(m_{D2}) &= 2 g_2^2 m_{D2}, \\ 16\pi^2\, \beta(m_{D3}) &= -6 g_3^2 m_{D3}. \end{aligned}$$

Dirac wino, bino masses shrink in IR

Dirac gluino mass grows fast in IR

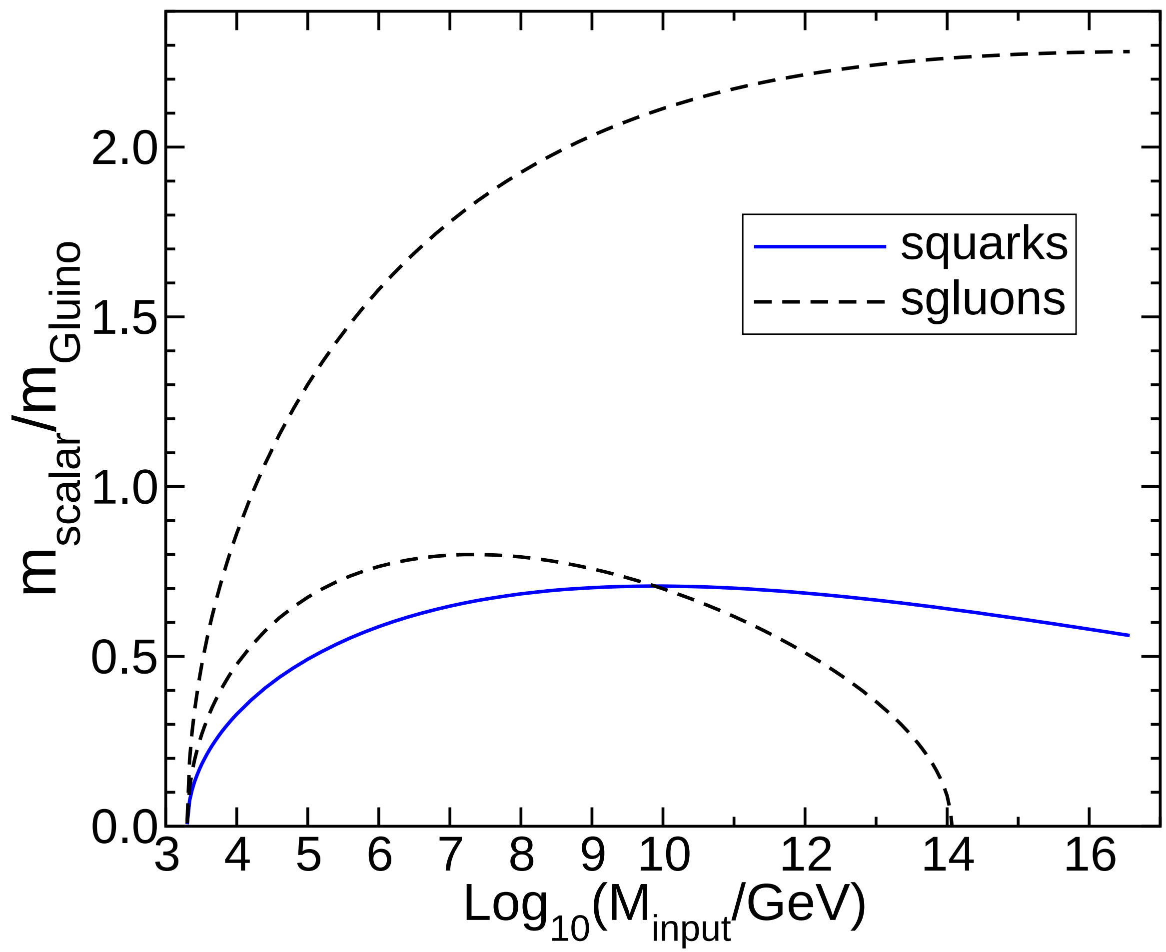
Running of gauge couplings with MSSM + Dirac gauginos and vector-like $L + \overline{L}$ and $2 \times (e + \overline{e})$ at the weak scale:



The usual supersoft Lagrangian is a fixed point of the RG running, but with mixed stability properties:

- $SU(3)_c$ sector: IR stable fixed point, but only weakly attractive
- $SU(2)_L$ and $U(1)_Y$ gaugino sectors: supersoft fixed point **not** IR stable

If Dirac gluino masses dominate over all other forms of SUSY breaking, get prediction for the ratios of tree-level $m_{\rm squark}$ and $m_{\rm sgluon}$ to $m_{\rm gluino}$, as a function of the input scale $M_{\rm input}$:



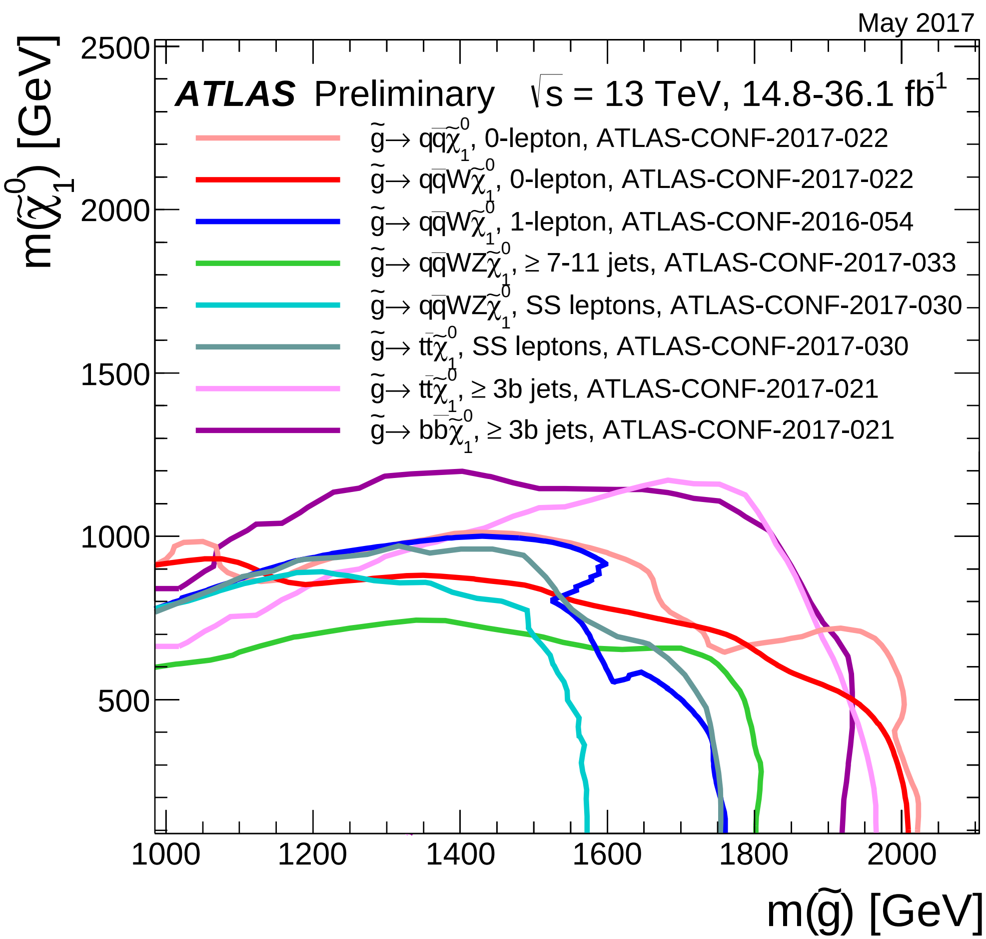
Summary

- Given $M_h = 125$ GeV, no surprise that SUSY eludes the LHC
- Light pure Higgsinos are a very difficult signal; no bounds yet (?)
- Vector-like quarks and leptons can accomodate $M_h = 125$ GeV with lighter squarks accessible to LHC
- Vector-like isosinglet leptons are a tough challenge
- Model-building ideas for decoupling Higgsinos from naturalness of the Higgs potential
  - 3 distinct μ parameters for Higgsinos and Higgs scalars H_u, H_d
  - Soft scalar $\phi^2\phi^*$ terms of the same order
  - Dirac gaugino masses without supersoftness

- Higgs quartic couplings not diminished
- Tree-level positive scalar adjoint squared masses
- Positive RG contributions to Higgs, sfermion masses from Dirac gaugino masses
- Can this be realized in some reasonable UV completion?

Backup slides

LHC constraints on masses of Gluino vs. Lightest Supersymmetric Particle



Different lines correspond to different possible gluino decays.

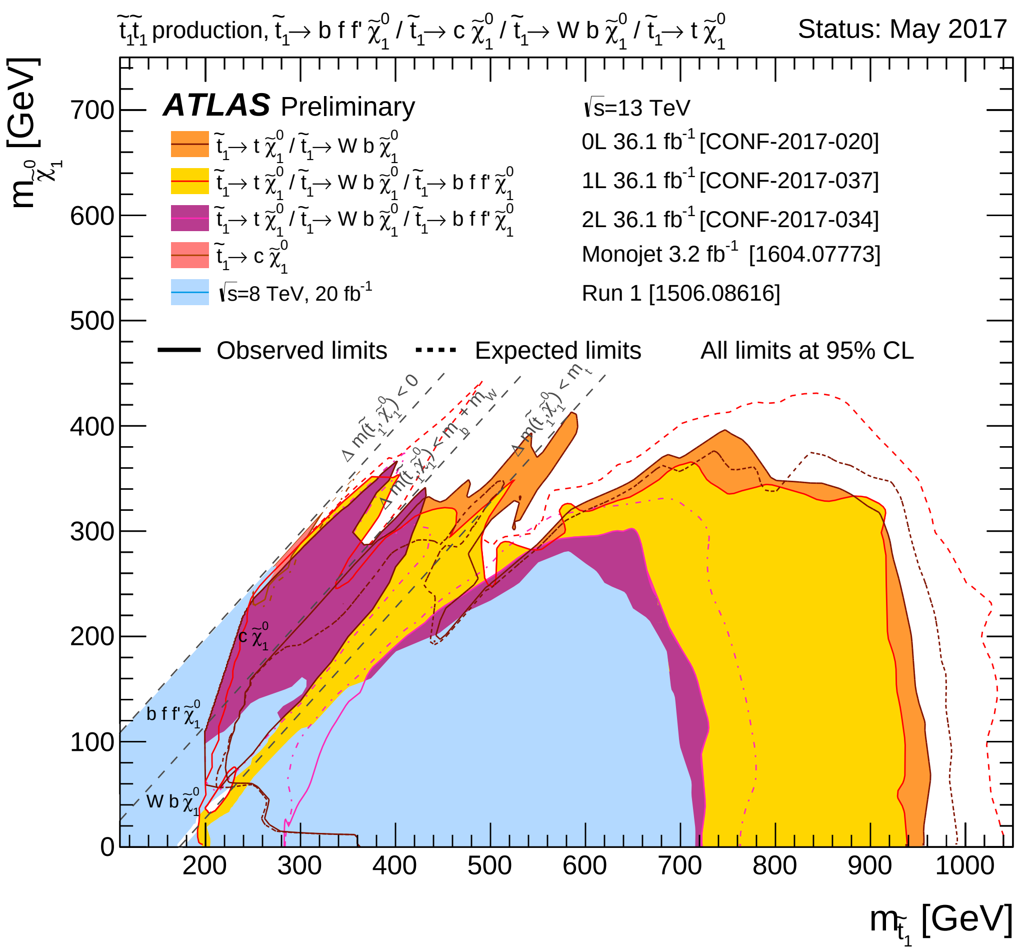
Searches have constrained $M_{\text{gluino}} \lesssim 2000$ GeV,

but

No constraints at all for $M_{\text{LSP}} \gtrsim 1200$ GeV, or much less, depending on the decay mode.

"Compressed supersymmetry": Small mass differences = weaker signals.

LHC constraints on masses of Top-Squark vs. Lightest Supersymmetric Particle



Searches have constrained

$M_{\text{stop}} \lesssim 950$ GeV,

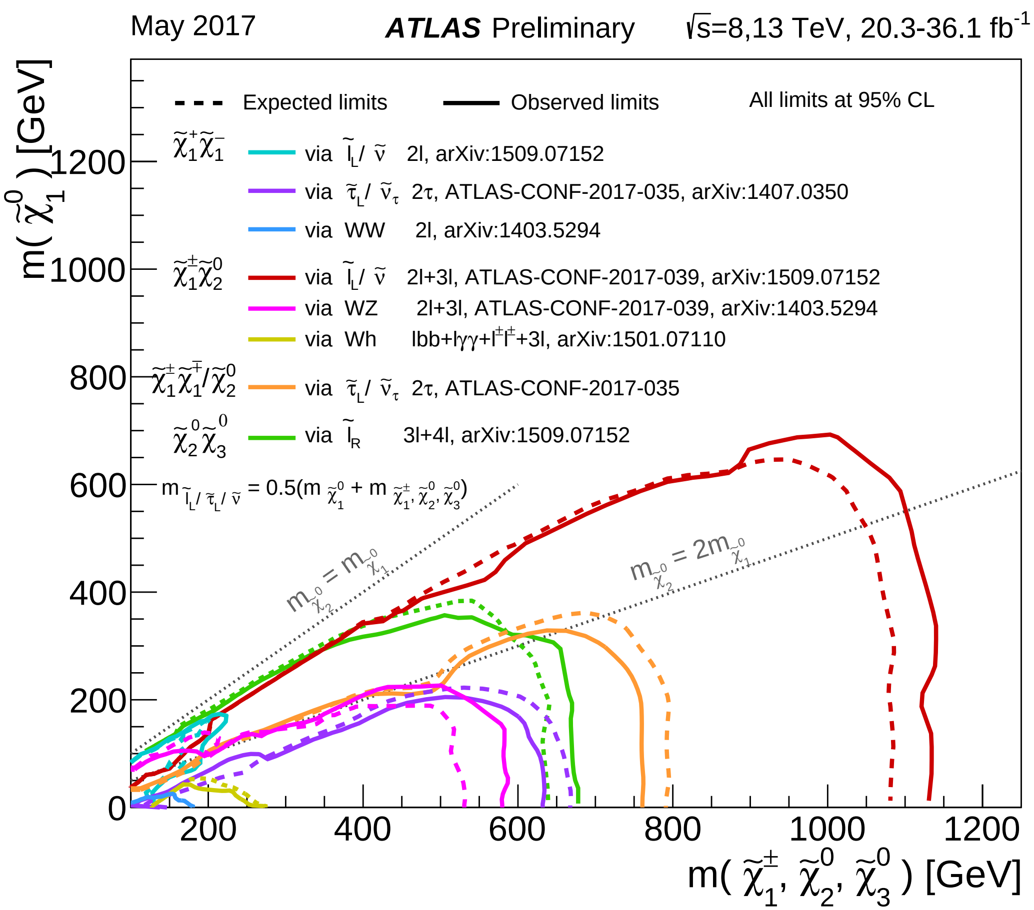
but

No constraints at all for

$M_{\text{LSP}} \gtrsim 350$ GeV,

except for thin slivers.

LHC constraints on Charginos and Neutralinos

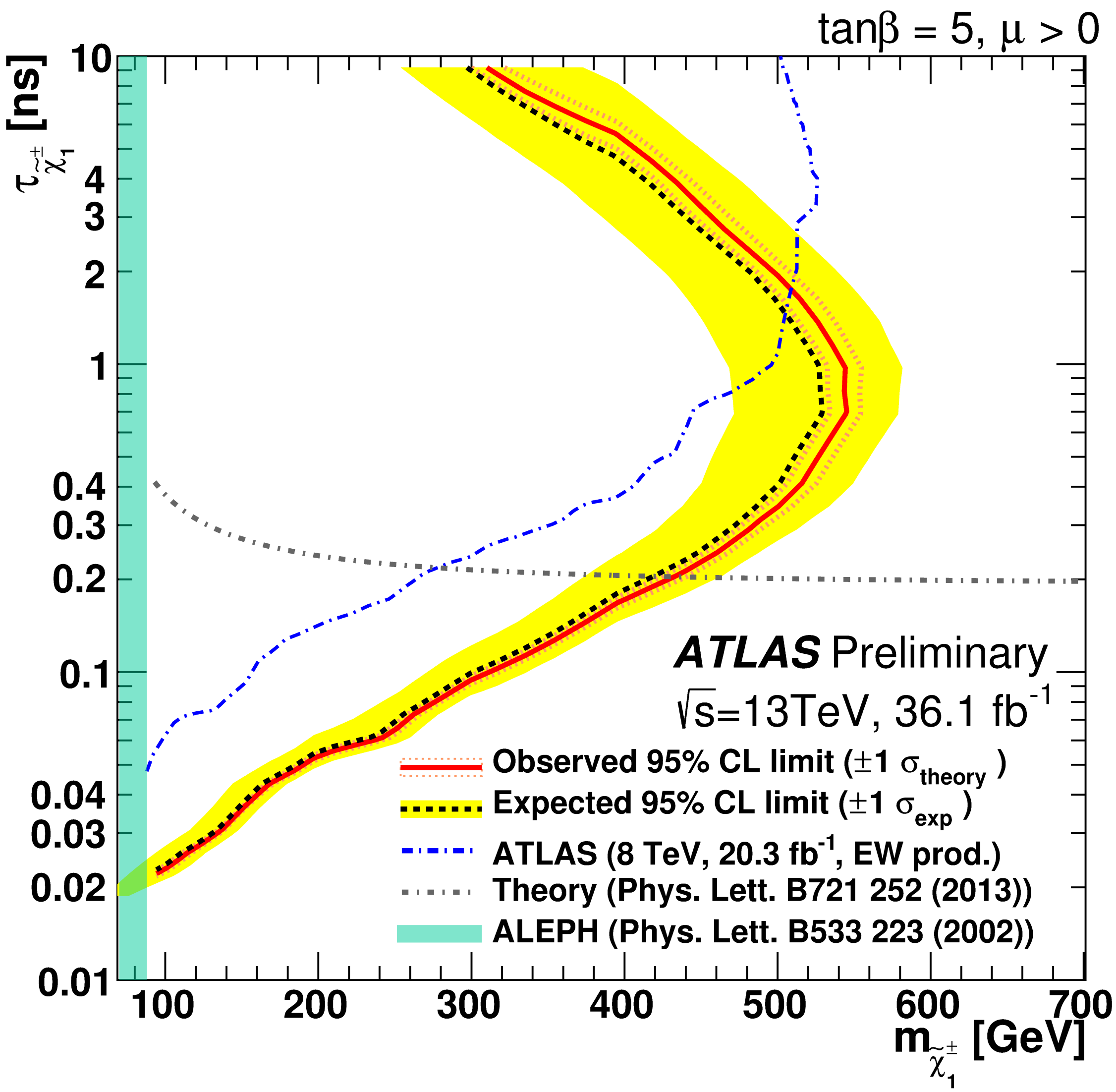


Slepton-mediated decays go beyond 1 TeV,

WZ decays go to 600-700 GeV,

Wh decays ("spoiler mode") are quite weak.

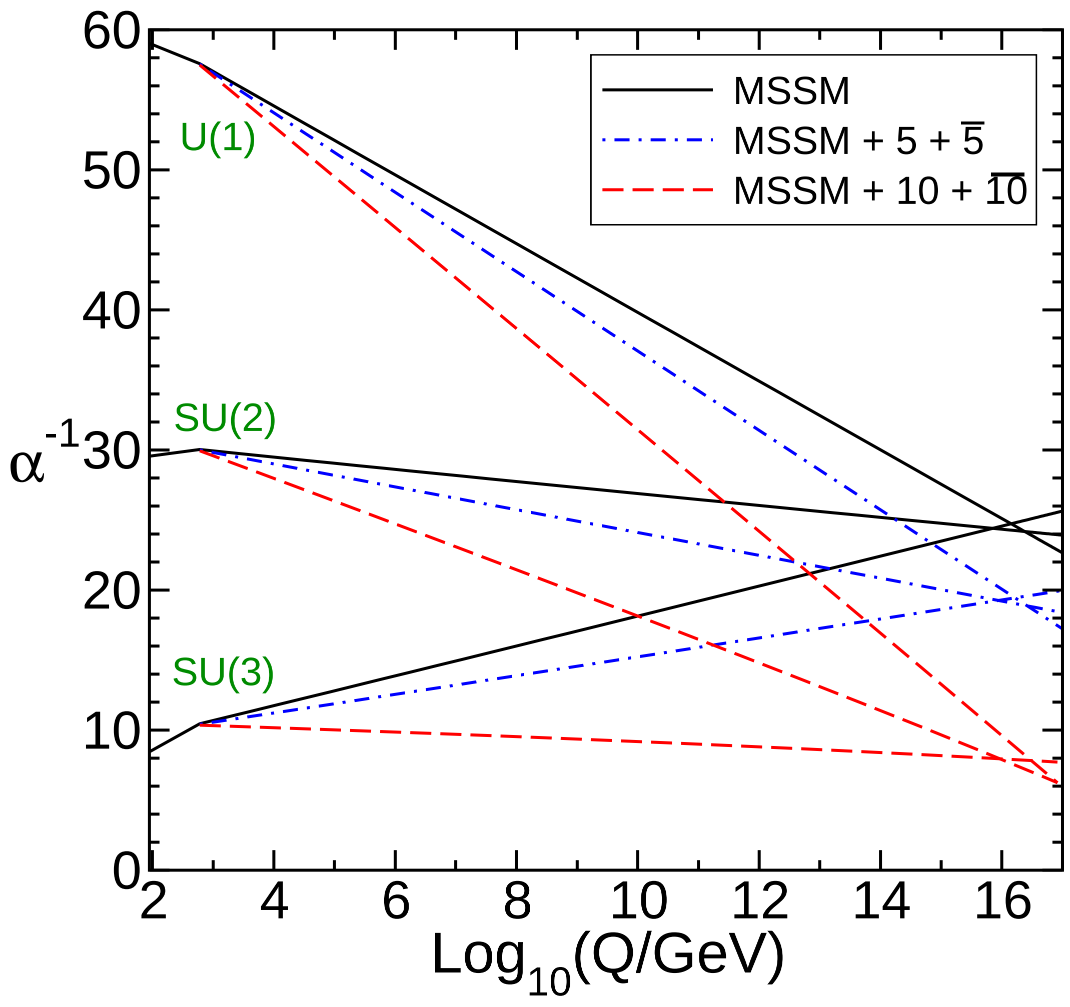
LHC constraints on Wino-like Charginos from disappearing tracks



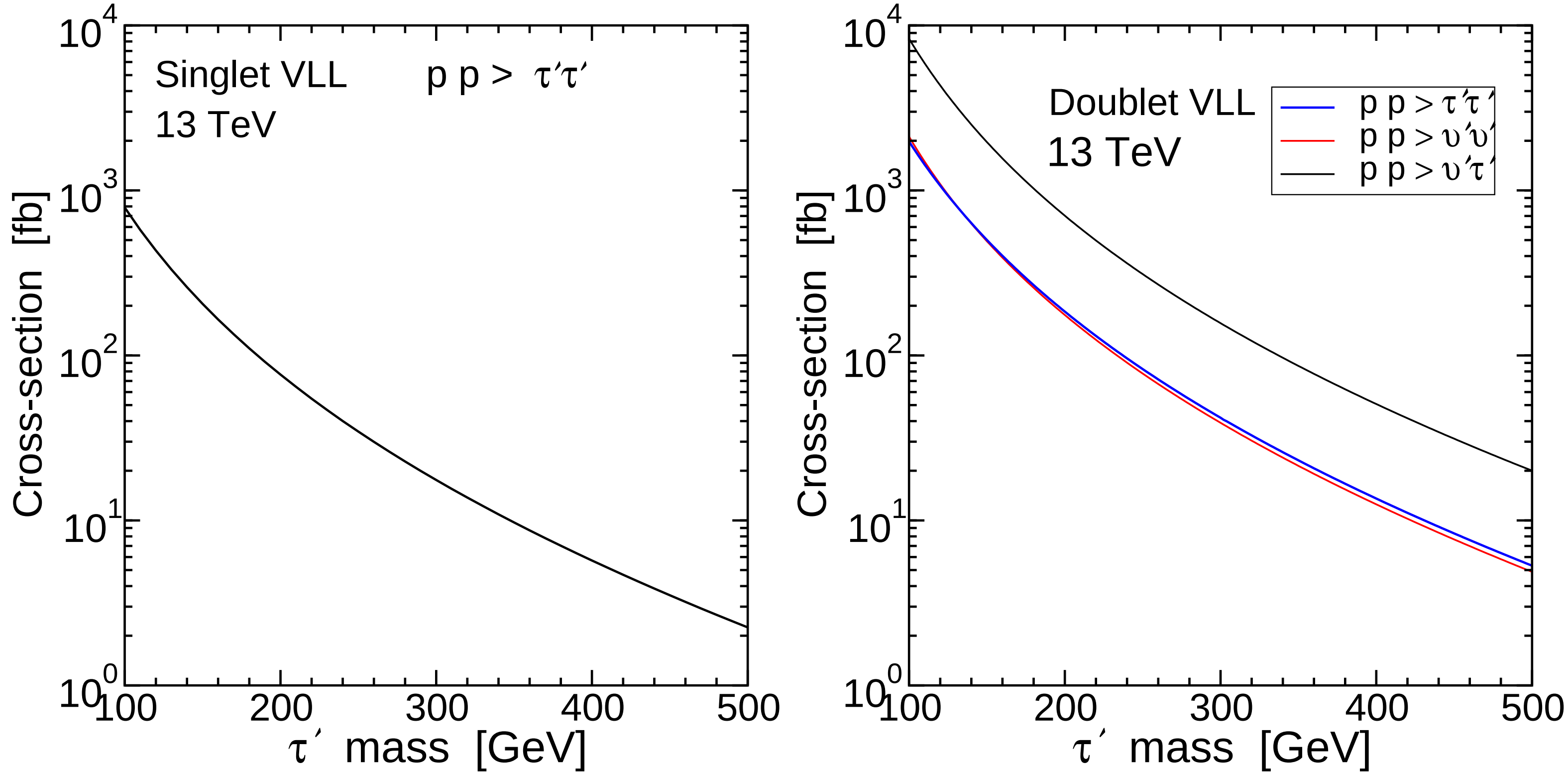
Pure Higgsino has shorter lifetime (by factor ~ 5) and smaller cross-section (by factor ~ 4)

Gauge coupling unification: Minimal Supersymmetry vs.

Supersymmetry with extra vectorlike supermultiplets



Production rates for vectorlike leptons at LHC:



Supersoft Dirac gauginos: the missing quartic interaction problem

$$\mathcal{L} = \sqrt{2} m_{Da} D^a (\phi^a + \phi^{a*}) + g_a D^a (\phi_k^\dagger t^a \phi_k) + \frac{1}{2}(D^a)^2$$

where $a =$ adjoint index, $k =$ chiral field indices, $t^a =$ gauge group generators.

Split adjoint scalars into real and imaginary parts:

$$\begin{aligned} R_a &= (\phi^a + \phi^{a*})/\sqrt{2}, \\ I_a &= i(\phi^a - \phi^{a*})/\sqrt{2}. \end{aligned}$$

After integrating out the auxiliary fields D^a:

$$\begin{aligned} \mathcal{L} &= -2m_{Da}^2 R_a^2 - 2g_a m_{Da} R_a (\phi_k^\dagger t^a \phi_k) - \frac{1}{2} g_a^2 (\phi_k^\dagger t^a \phi_k)^2 \\ &= -\frac{1}{2}\left[2m_{Da} R_a + g_a (\phi_k^\dagger t^a \phi_k)\right]^2 . \end{aligned}$$

Because this is a perfect square, now integrating out the massive field R_a, by solving its equation of motion, leaves no potential for the light fields ϕ_k and I_a.

Supersoft Dirac gauginos: the tachyonic scalar adjoint problem

The imaginary adjoint scalar I_a had no mass in the previous potential.

There is another term, the "lemon-twist" operator, which can give it a mass:

$$\mathcal{L}_{\rm Lemon-Twist} \quad = \quad -m_{LT}^2(R_a^2 - I_a^2)$$

This term (in superfield form; not shown) is not forbidden by any symmetry.

The good: gives a positive $(\text{mass})^2$ to R_a, solving the missing quartic problem, because the potential for R_a is no longer a perfect square.

The bad: then I_a will be tachyonic, breaking $SU(3)_c$ and $SU(2)_L$ and $U(1)_Y$.

The ugly: either I_a or R_a will be a tachyonic, depending on the sign, without fine-tuning or other heroic model-building.

The problem: no symmetry forbids terms like this:

$$\mathcal{L} = -\frac{k}{M^2}\int d^4\theta\, X^* X \Phi_k^* \Phi_k$$

which leads to soft SUSY-breaking masses of the MSSM fields:

$$\mathcal{L} = -\frac{k|\langle F\rangle|^2}{M^2}\phi_k^*\phi_k$$

These are parametrically large compared to the Dirac gaugino masses.

Example: if we want

Dirac gluino mass $= M_{\tilde{g}} \sim \langle F\rangle^2/M^3 \sim 10^3$ GeV

and k is of order 1, and M is of order the Planck mass,

Squark masses $\sim \langle F\rangle/M \sim \sqrt{M m_{\tilde{g}}} \sim 10^{11}$ GeV

This could be a variety of "split SUSY", but I don't want to talk about that.

What about anomaly mediation contributions to gaugino Majorana masses?

Gravitino mass is:

$$m_{3/2} \sim \langle F \rangle / M_{\text{Planck}}.$$

and anomaly mediation gives:

$$M_a = m_{3/2} \beta(g_a)/g_a.$$

So:

- If the mediation scale is the Planck scale $M = M_{\text{Planck}}$, then $m_{3/2} =$ few $\times\ 10^{10}$ GeV, and Majorana gaugino masses will dominate over the Dirac gaugino masses.
- For the Dirac gaugino masses to dominate over the AMSB Majorana masses, need $M \lesssim 10^{13}$ GeV.

If SUSY breaking in the visible sector effective theory is dominated by Dirac gaugino masses, m_{Da}. Then, generate non-holomorphic (scalar)^3 terms through 1-loop RG evolution:

$$\mathcal{L} \quad = \quad -r_a(\phi_a + \phi_a^*)(\tilde{q}_i^* t^a \tilde{q}_i).$$

Normalize the couplings r_a by

$$r_a = \sqrt{2} g_a m_{Da} N_a,$$

so that in the supersoft case, $N_a = 1$.

From Jack+Jones 9909570, can obtain:

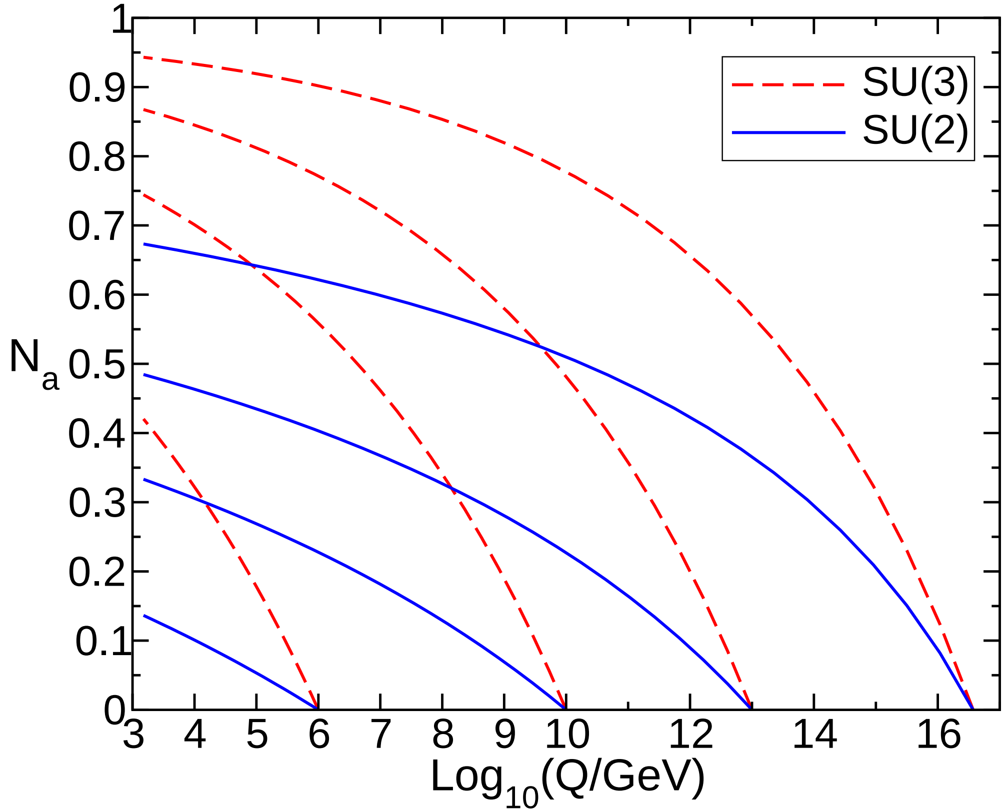
$$16\pi^2 \, \beta(N_a) \quad = \quad 4 g_a^2 C_a (N_a - 1)$$

where $C_a = 0, 2, 3$ for $U(1)_Y$, $SU(2)_L$, and $SU(3)_c$.

The supersoft case $N_a = 1$ is an IR fixed point of the RG evolution, for the non-Abelian groups. For $U(1)_Y$, there is no running of N_1. If it vanishes at the input scale, it will remain 0 (at 1-loop order).

Some RG trajectories of $\phi_a \tilde{q}_i^* \tilde{q}_i$ coupling parameter N_a, for $SU(3)_c$ and $SU(2)_L$.

Assuming $N_a = 0$ at input scales 10^6 and 10^{10} and 10^{13} and 3×10^{16} GeV:



$N_a = 1$ is the supersoft special case fixed point.

For the MSSM scalars, the 1-loop RG running is:

$$16\pi^2\,\beta(m_i^2) \quad = \quad 8g_a^2 C_a(i)(N_a^2 - 1)m_{Da}^2 + \text{(usual MSSM Yukawa terms)}$$

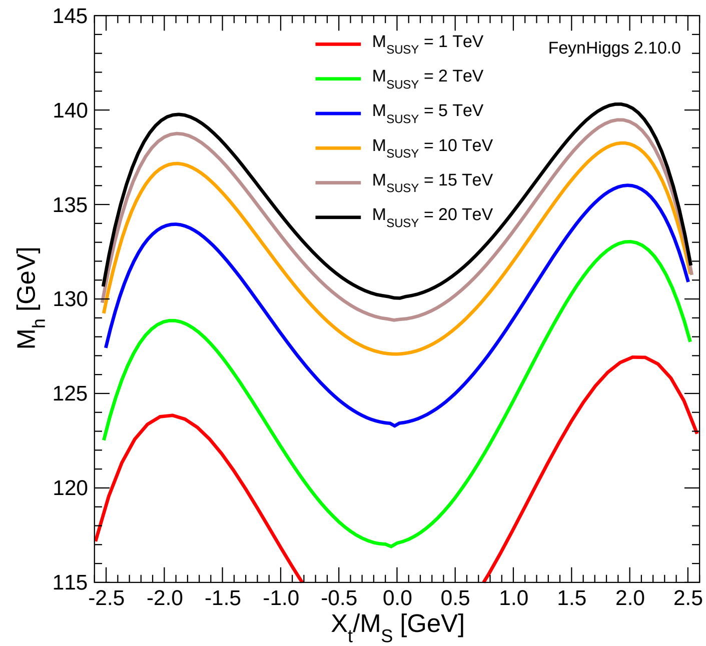
where $C_3(i) = 4/3$ for squarks, $C_2(i) = 3/4$ for doublets, and $C_1(i) = \frac{3}{5}Y_i^2$ for scalars with weak hypercharge Y_i.

For the supersoft case $N_a = 1$, the Dirac gaugino masses do not contribute to MSSM scalar running.

For $|N_a| < 1$, there is a positive RG contribution to MSSM scalar masses.

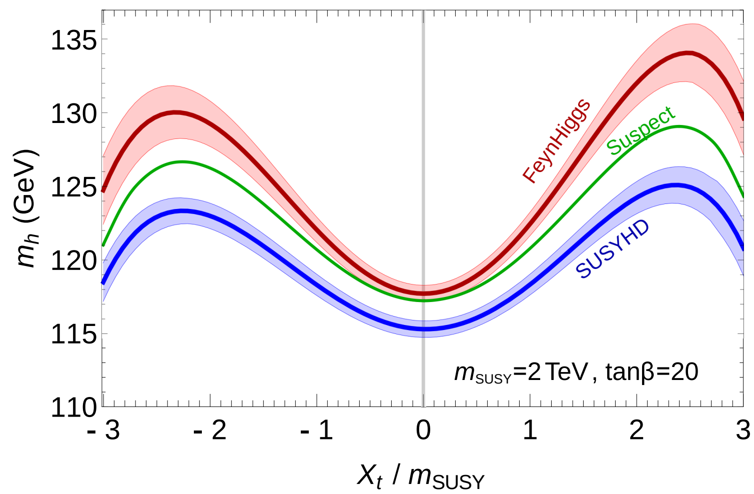
To get $M_h = 125$ GeV, MSSM typically needs top-squarks either **heavy** or **highly mixed**.

From FeynHiggs 2.10.0, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein:



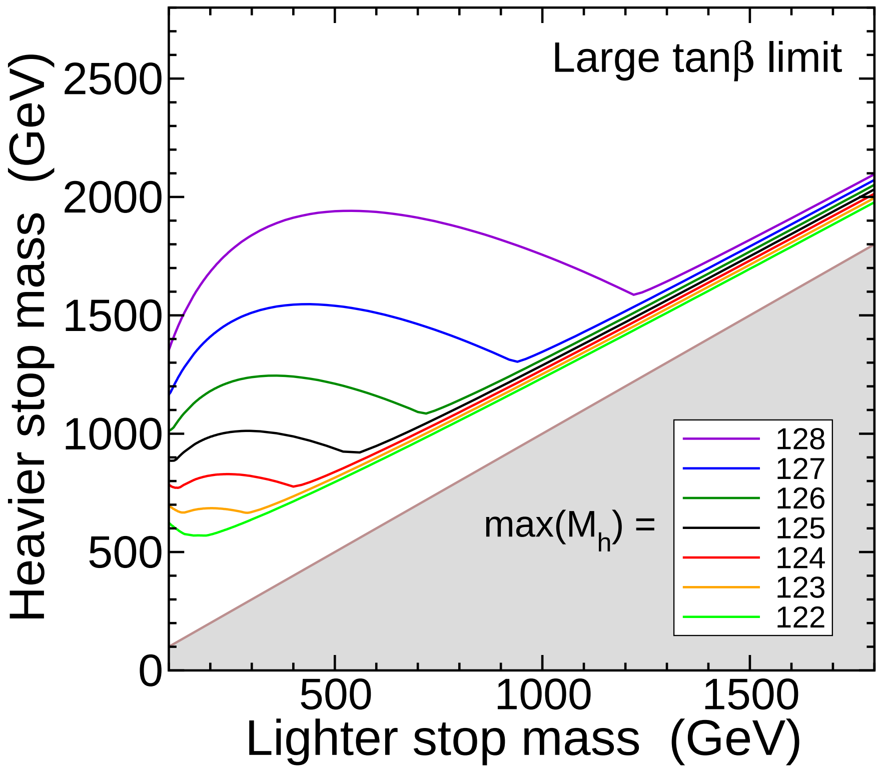
This is particularly troublesome for GMSB (Gauge-mediated SUSY breaking).

Theoretical uncertainties remain significant. Various public codes use different methods and approximations: FeynHiggs, CPsuperH, H3m, SUSYHD, SoftSUSY, SuSpect, SPheno, ISASUSY. . . For example, from 1504.05200, Vega and Villadoro:



How heavy do top squarks really need to be?

Consider general MSSM, no mSUGRA or other assumptions. Top squark masses uncorrelated with other superpartner masses, mixing can be large.



For each $\tilde{t}_1$, $\tilde{t}_2$ masses, scan over other parameters, find maximum M_h compatible with precision electroweak constraints and $\sigma \cdot BR(h \to \gamma\gamma)$.

Depends strongly on theoretical uncertainty in the M_h calculation.

"When to give up on supersymmetry" is not a quantifiable scientific thing, and for me does not depend just on supersymmetry, but on its viable alternatives.

Odds of winning North Grove Elementary School Fun Fair Cake Walk twice in a row:

$$\left(\frac{1}{20}\right)^2 = \frac{1}{400}$$

Odds of winning the Powerball lottery four times in a row:

$$\left(\frac{1}{175223510}\right)^4 \approx 10^{-31}$$

The first thing actually happened. The second thing never happens.