Status of weak-scale supersymmetry

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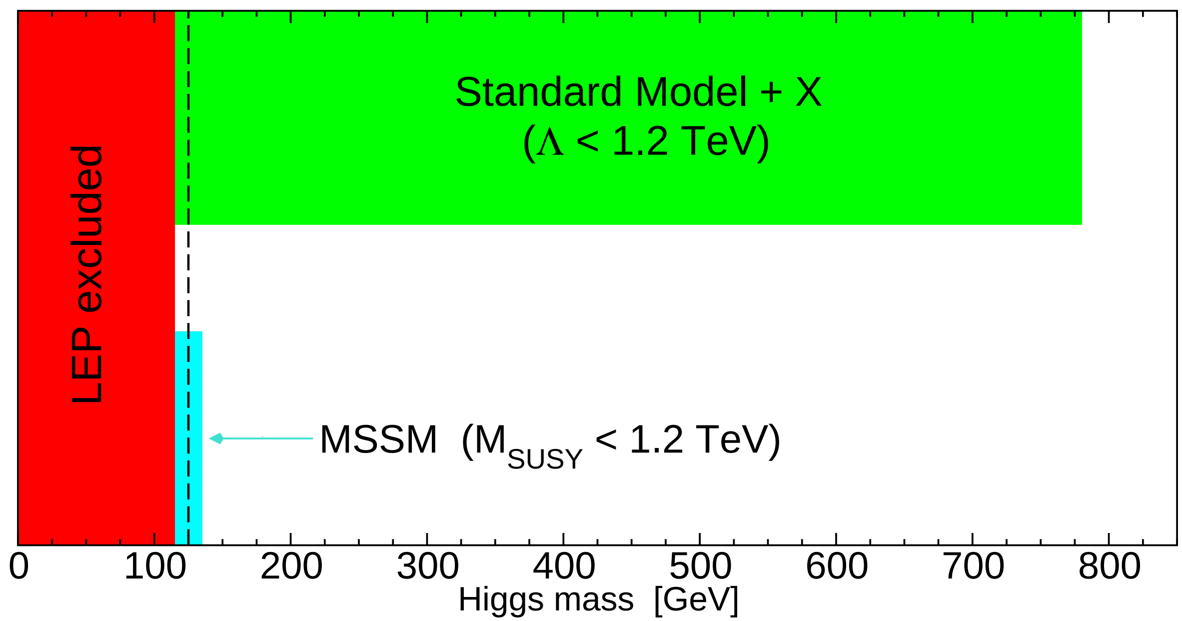
The Higgs boson discovery at the LHC has given us the effective self-interaction at better than 1% accuracy:

$$V_{\rm Higgs} \;=\; m^2|H|^2 + \lambda|H|^4$$

with, at the $\overline{\rm MS}$ renormalization scale $Q = M_{\rm top}$:

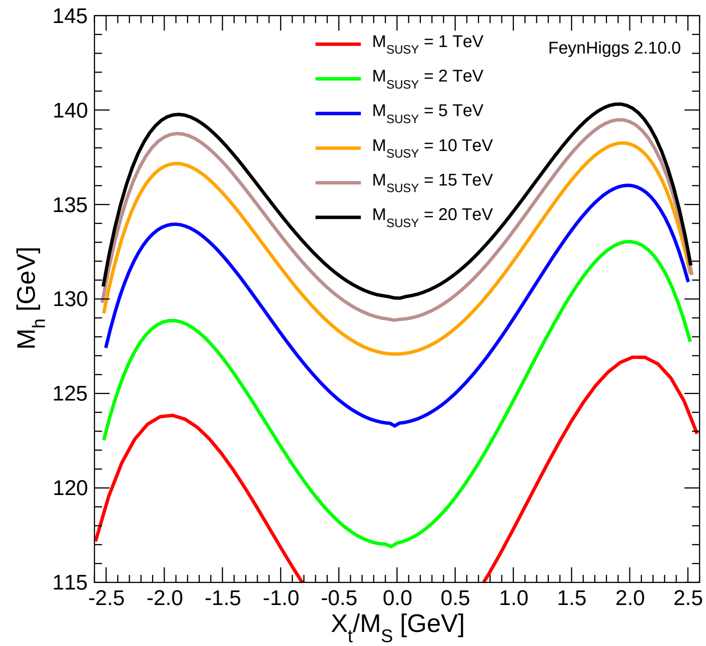
$$\lambda = 0.126 \qquad \text{and} \qquad m^2 = -(93\;{\rm GeV})^2$$

The $\lambda = M_h^2/2v^2$ result is arguably a success for SUSY:



However, in the MSSM $M_h = 125$ GeV needs top-squarks either **heavy** or **highly mixed**.

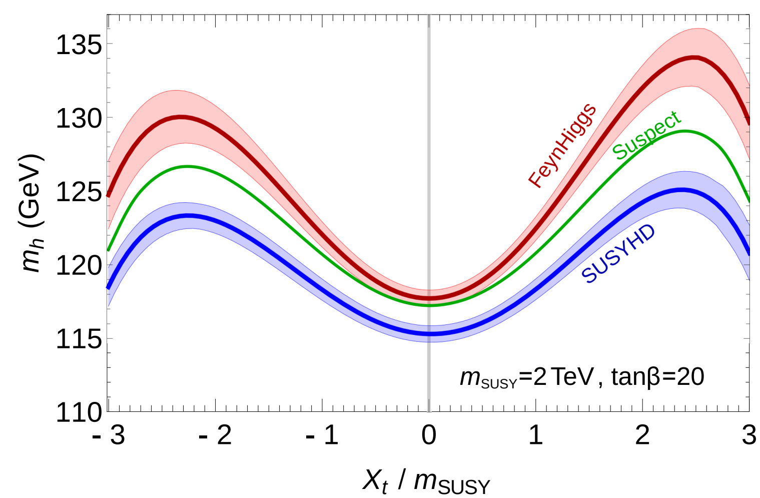
From FeynHiggs 2.10.0, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein:



This is particularly troublesome for e.g. simplest GMSB models.

Theoretical uncertainties remain significant, need more work. Various public codes use different methods and approximations: FeynHiggs, CPsuperH, H3m, SUSYHD, SoftSUSY, SuSpect, SPheno. . .

For example, from 1504.05200, Vega and Villadoro:



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

- Large A_t term, top-squark mixing.
- New F-terms: NMSSM and cousins.

$$W = \lambda S H_u H_d \qquad \rightarrow \qquad \Delta M_h^2 = \lambda^2 v^2 \sin^2(2\beta)$$

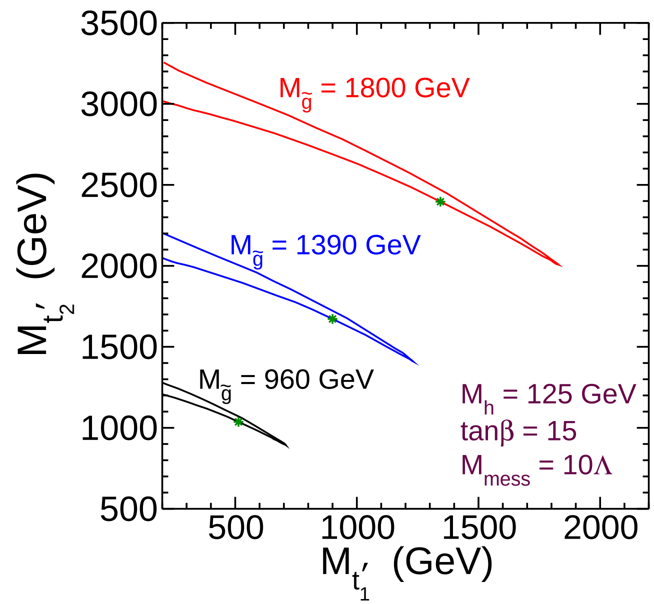
- New D-term contributions to Higgs quartic coupling.
- New vector-like quarks with large Yukawa couplings
  - ⋆ Decoupling for precision EW observables and Higgs production/decay
  - ⋆ **Non**-decoupling contributions to M_h:

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.

From SPM and J.Wells, 1206.2956 $\longrightarrow$

See also Endo, Hamaguchi, Iwamoto, Yokozaki 1108.3071, 1112.5653, 1202.2751, Evans, Ibe, Yanagida 1108.3437, Nakayama, Yokozaki 1204.5420.



The (mass)^2 scale of the Higgs potential is also problematic for SUSY. This is 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:

"If there are no light Higgsinos, then natural SUSY is dead."

but this is certainly not true; I will comment on important loopholes later.

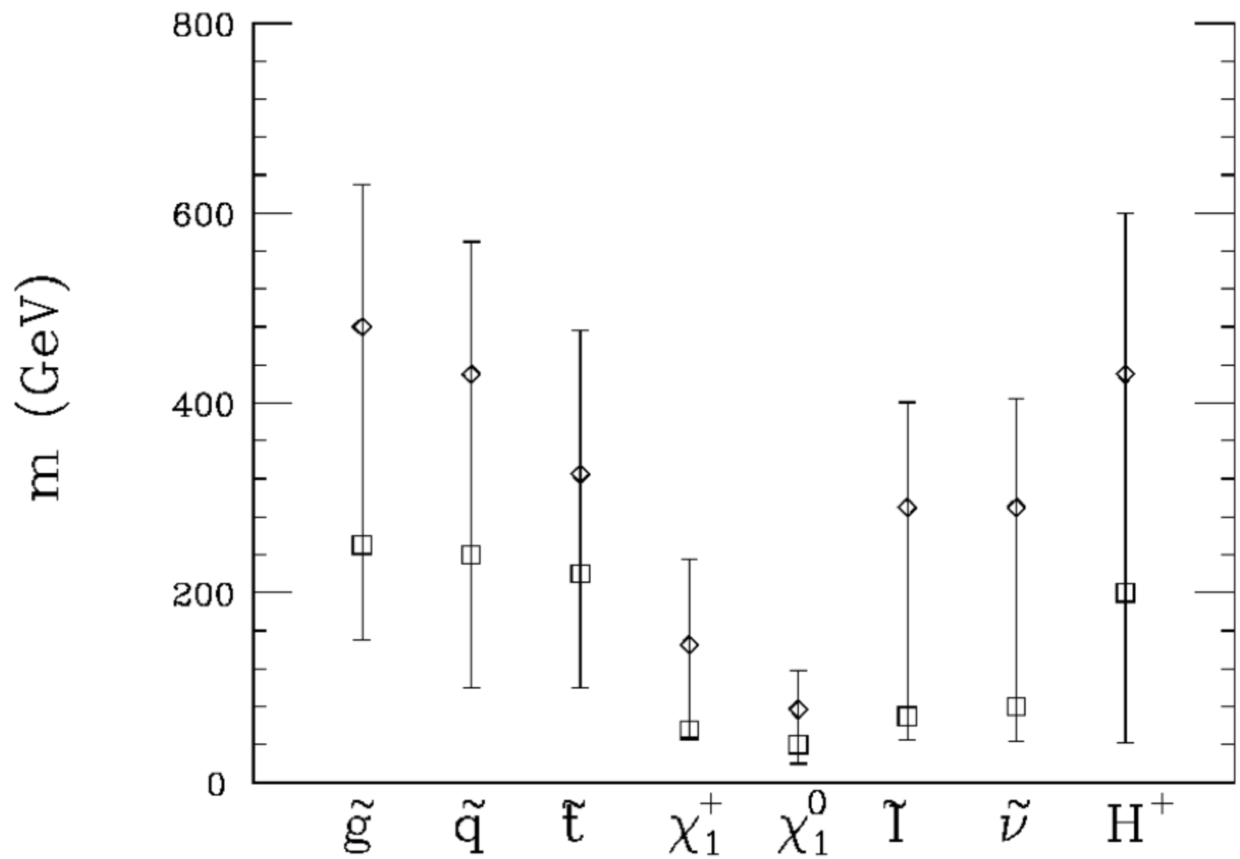
Taken at face value, however, need small $|\mu|^2$ and small:

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

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.

From “Naturalness and superpartner masses or when to give up on weak scale supersymmetry”, Anderson and Castaño, hep-ph/9412322:



So, then, why did we all still come to SUSY 2015?

The answer: regardless of the 1994 “naturalness” of our current situation, in 2015 SUSY is **still** the best known surviving solution to the hierarchy problem of the weak scale.

LHC vs. your favorite SUSY models:

Key point: many of SUSY’s competitors for explaining the hierarchy problem in 1994 are now completely dead (technicolor, Higgsless models, . . .), and the rest are challenged by LHC data as much as, or more than, SUSY is!

Suppose we awaken from a long sleep, and read in the 2040 Review of Particle Properties that:

$$\begin{aligned} M_{\text{Higgsinos}} &= 1200\ \text{GeV} \\ M_{\text{stops}} &= 2000,\ 2500\ \text{GeV} \\ M_{\text{gluino}} &= 3000\ \text{GeV} \\ \ldots \end{aligned}$$

Which will we then say?

- This must be a mistake! It violates Professor Baye Z. Ian's famous Standard of Acceptable Naturalness, established back in 2015.

OR

- SUSY does successfully address the hierarchy problem of $M_W^2/M_{\text{Planck}}^2 = 10^{-32}$.

My opinion: there is not, and cannot be, any such thing as an objective measure of fine-tuning.

This is not to say that naturalness is not a useful concept. There **are** fine-tuning problems, and we should worry about them!

Instead, naturalness and fine-tuning are useful, but personal and subjective, criteria for answering such important questions as

- What ideas and models should I (not) work on this week?
- Where should finite resources be directed?

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

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

- ...

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

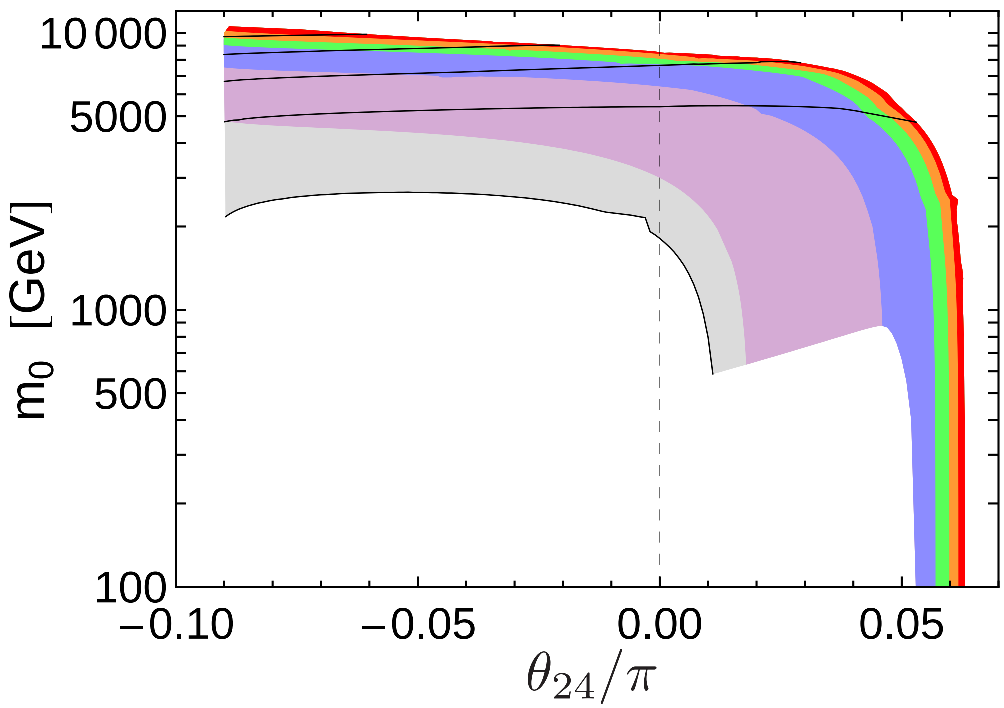
Note $\theta_{24} = 0$ corresponds to mSUGRA, while $\theta_{24} = \pm\pi/2$ is a pure adjoint F-term.

GUT models will generically have non-zero θ_{24}, the only question is how big.

Map μ for models compatible with $M_h =$ 125 GeV:

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

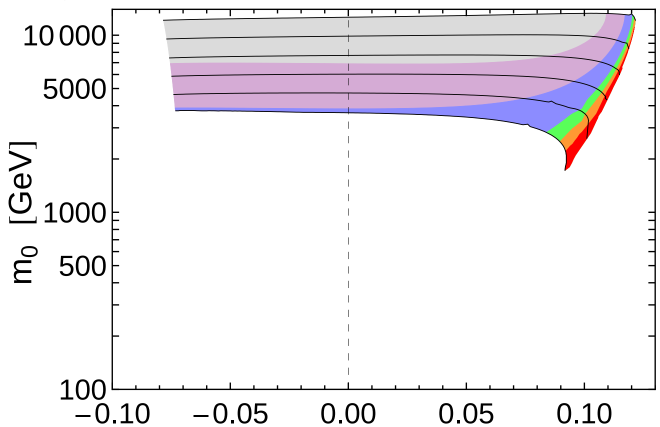
The Focus Point region is continuously connected to a semi-natural region with small μ and the rest of the SUSY spectrum compressed and heavy.

Note: SUSY flavor problem solved by gaugino mass domination.

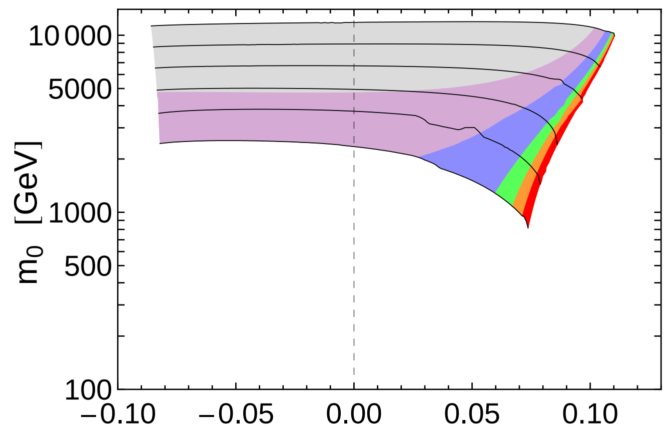
[Here: $m_0^2 \ll M_1^2, M_2^2, M_3^2$, but more generally $m^2_{\text{scalars}} \ll M_1^2, M_2^2, M_3^2$]

For larger stop mixing ($A_0/M_3 = -1$), can have $M_h = 125.5$ GeV with lighter sparticles. Focus Point disappears, but semi-natural region with small M_3/M_2 lives on:

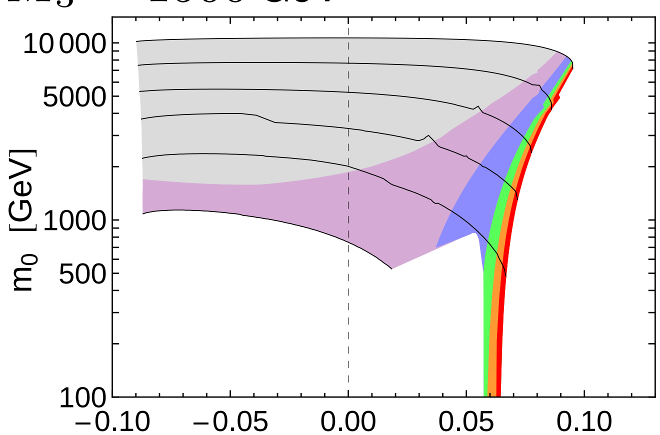
$M_3 = 600$ GeV



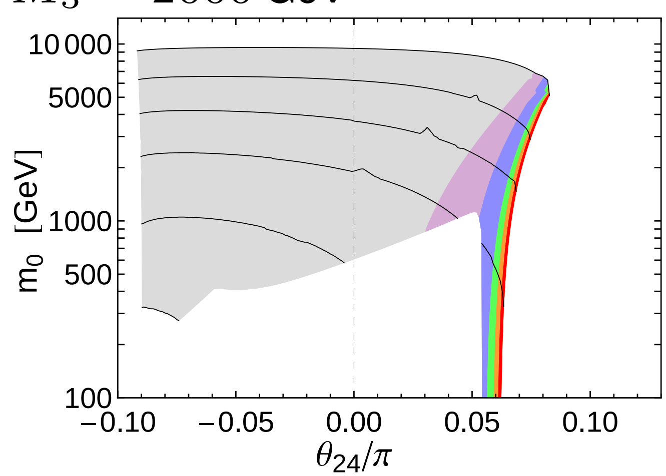
$M_3 = 1000$ GeV



$M_3 = 1500$ GeV

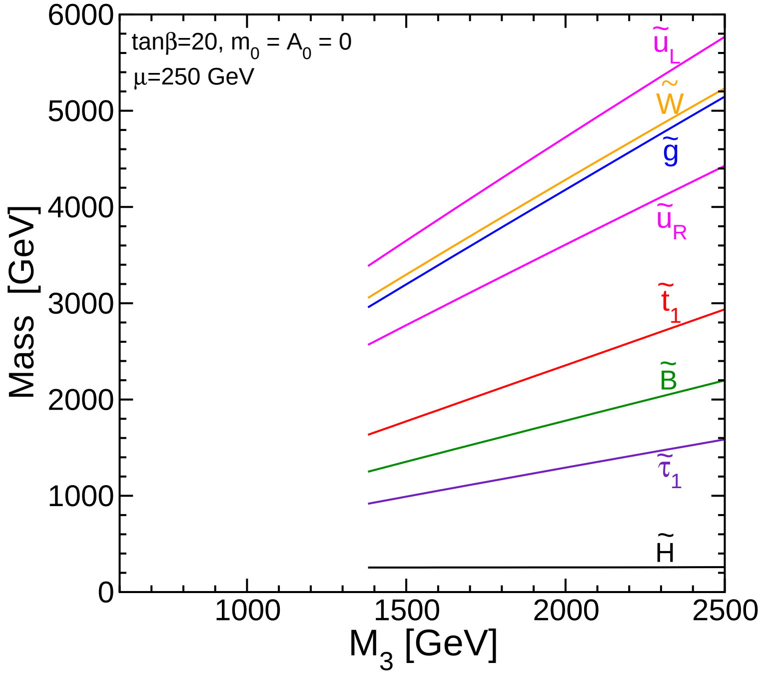


$M_3 = 2000$ GeV

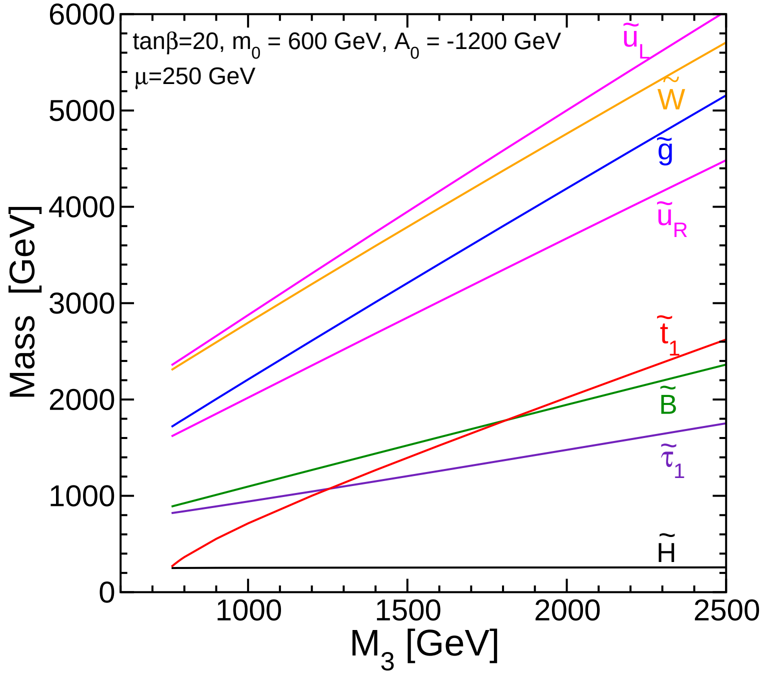


Sample mass spectra for semi-natural SUSY

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).

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 1401.1255
- 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

Usually, gaugino masses are taken to be Majorana:

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

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

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

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:

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

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

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

Supersoft SUSY breaking has many interesting properties. . .

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. (Fixed point, 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 interaction $\lambda = (g^2 + g'^2)/8$ in the low-energy effective MSSM Lagrangian. Integrating out the scalar adjoints removes it. 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

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

Note there are no accompanying supersoft scalar interactions here.

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.

Confession: I do not know how to make a UV completion to a complete SUSY-breaking model where this type of Dirac gaugino mass can generically dominate.

A set of model-building criteria:

- 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 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.

Then the complete set of SUSY-breaking terms are the $\frac{1}{M^3}\int d^4\theta$ integrals of:

$XX^*\,\mathcal{W}^{\alpha a}\,\nabla_\alpha A^a$ = Dirac gaugino mass,

$XX^*\,A^a\,\nabla_\alpha \mathcal{W}^{\alpha a}$ = supersoft scalar interactions,

$XX^*\,\mathcal{W}^{\alpha a}\,\mathcal{W}^a_\alpha$ = Majorana gaugino mass,

$XX^*\,\nabla^\alpha A^a\,\nabla_\alpha A^a,\qquad XX^*\,A^a\,\nabla^\alpha\nabla_\alpha A^a,$

$XX^*\,\nabla^\alpha H_u\,\nabla_\alpha H_d,\qquad XX^*\,H_u\,\nabla^\alpha\nabla_\alpha H_d,\qquad XX^*\,H_d\,\nabla^\alpha\nabla_\alpha H_u.$

The μ problem is solved by the terms involving Higgses:

$$\frac{c_1}{2M^3} \int d^4\theta \, X X^* \, \nabla^\alpha H_u \, \nabla_\alpha H_d \quad = \quad -\tilde{\mu} \tilde{H}_u \tilde{H}_d$$

is a mass term for the Higgsinos **only**, with $\tilde{\mu} = c_1 \langle F \rangle^2 / M^3$.

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

$$\frac{c_2}{4M^3} \int d^4\theta \, X X^* H_u \, \nabla^\alpha \nabla_\alpha H_d \quad = \quad \mu_u H_u F_{H_d} \; \rightarrow \; -|\mu_u|^2 |H_u|^2 + \ldots$$

$$\frac{c_3}{4M^3} \int d^4\theta \, X X^* H_d \, \nabla^\alpha \nabla_\alpha H_u \quad = \quad \mu_d H_d F_{H_u} \; \rightarrow \; -|\mu_d|^2 |H_d|^2 + \ldots$$

where $\mu_u = c_2 \langle F \rangle^2 / M^3$ and $\mu_d = c_3 \langle F \rangle^2 / M^3$.

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

Nelson and Roy 1501.03251 already did an analogous thing in the Supersoft case. Decouples the Higgsino mass from the MSSM Higgs naturalness problem!

Other recent proposals for decoupling the Higgsino mass from the MSSM Higgs naturalness problem: Cohen, Kearney, Luty “Natural Supersymmetry without Light Higgsinos”, 1501.01962, and Dimopoulos, Howe, March-Russell “Maximally Natural Supersymmetry”, 1404.7554.

The usual supersymmetric μ can be obtained by taking the particular combination $c_1 = c_2 = c_3$, 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 this particular combination is not special, in the present context.

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:

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

gives the same **positive** (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.

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 **Adam** 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

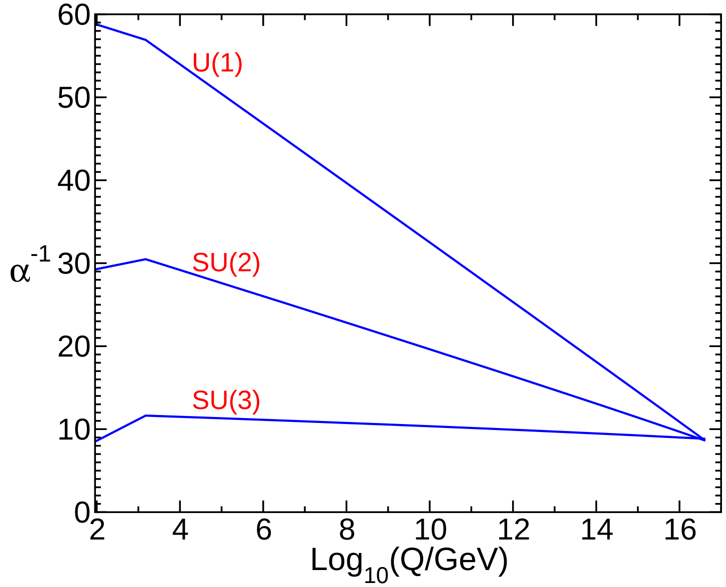
and the Dirac gaugino masses run as:

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

Dirac wino, bino masses shrink in IR

Dirac gluino mass grows fast in IR

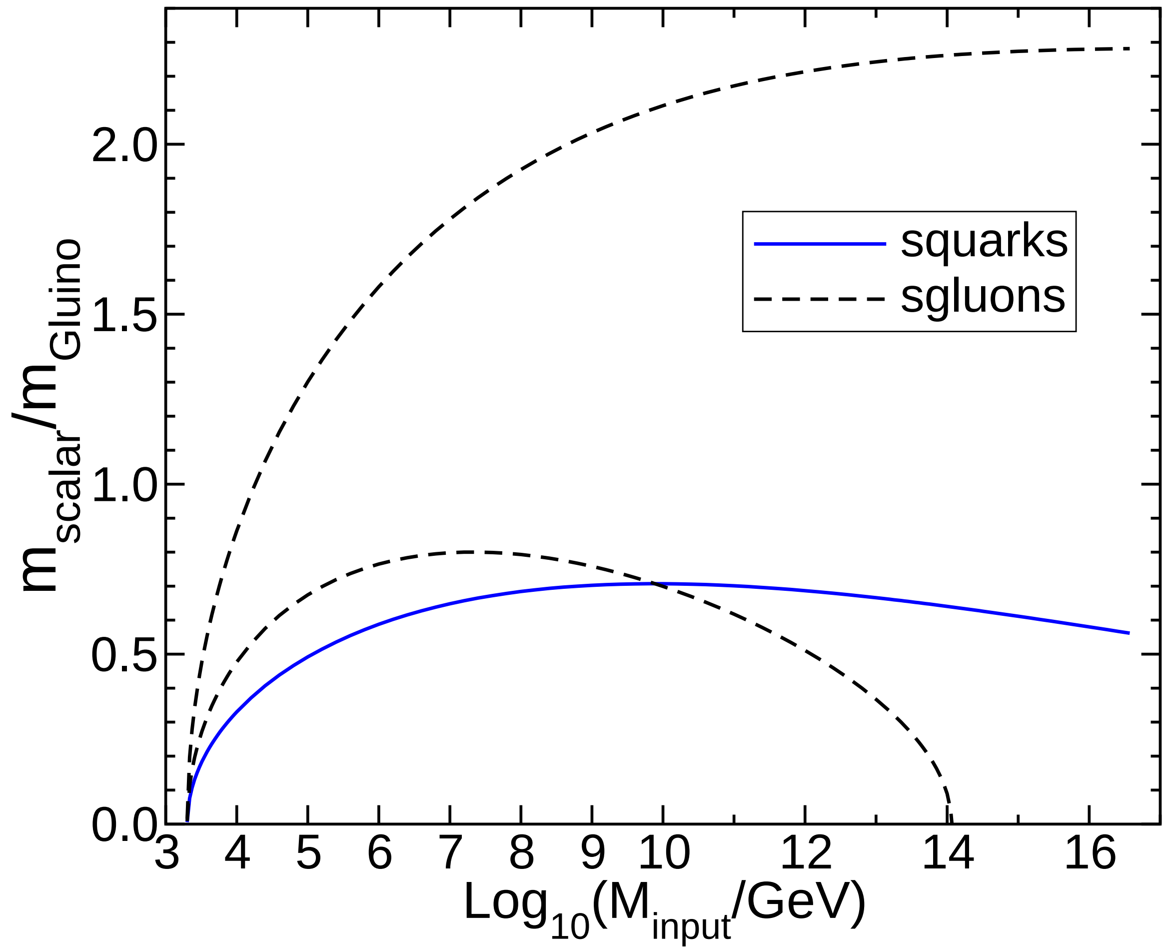
Running of gauge couplings with MSSM + Dirac gauginos and vector-like $L + \overline{L}$ and $2 \times (e + \overline{e})$ at the weak scale:



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_{squark} and m_{sgluon} to m_{gluino}, as a function of the input scale M_{input}:



Summary

Using F-term VEV for SUSY breaking, coupling to MSSM sector with assumed $1/M^3$ suppression, can have:

- SUSY breaking Dirac gaugino mass, 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
- 3 distinct μ parameters for Higgsinos and Higgs scalars H_u, H_d

All mass scales proportional to $\langle F \rangle^2/M^3$.

Can this be realized in some reasonable UV completion?

Backup slides

What about anomaly mediation contributions to gaugino Majorana masses?

Gravitino mass is:

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

and anomaly mediation gives:

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

So:

- If the mediation scale is the Planck scale $M = M_{\rm Planck}$, 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.