Naturalness, SUSY Heavy Higgses and Flavor Constraints

Andrey Katz

work in progress with Matt Reece and Aqil Sajjad

Harvard University

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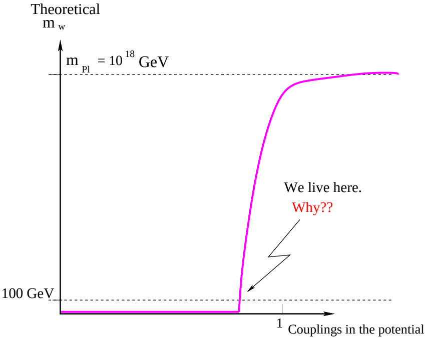
Outline

Naturalness problem of the Standard Model (SM)

The key part of the SM is Electroweak (EW) symmetry breaking via Higgs mechanism. Due to the EW symmetry breaking Z and W get their masses. Assuming no new physics all the way to the Planck scale, what values of m_Z would we expect to get for generic values of the couplings in the Lagrangian?



For completely generic couplings in the potential, we either get $m_Z = 0$ or $m_Z \sim M_{Pl}$.
$m_Z \sim 100$ GeV can be achieved only if the couplings are carefully fine-tuned to cancel one another in the radiative corrections to the m_Z.

Supersymmetry

Supersymmetry (SUSY) is a space time symmetry, extension of the Poincare symmetry which connects the states with different statistics and their couplings

$$Q|b\rangle \propto |f\rangle \qquad Q|f\rangle \propto |b\rangle$$

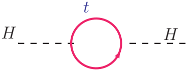
Unbroken SUSY predicts: each fermionic state is accompanied by a bosonic one with exactly the same mass.

SUSY solves the hierarchy problem of the SM by symmetry. Large radiative corrections, induced by the SM are canceled by the superpartners of the SM particles.

SUSY As a Solution to the Hierarchy Problem

$$\begin{aligned} V &= -\frac{m^2}{2}h^2 + \frac{\lambda}{4}h^4 \\ m_Z^2 &\propto v^2 = \frac{m^2}{\lambda} \end{aligned}$$

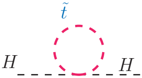
Dominant $\Delta m^2 =$

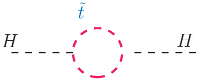


$\Delta m^2 \propto y_t^2 \Lambda^2$

Top has the strongest coupling to the Higgs ⇒ we need top partners to solve the hierarchy problem caused by the top.

In SUSY this diagram, which is sensitive to the cutoff of the theory (namely, very heavy particles that we would naively expect to decouple) is canceled by the top scalar partners.

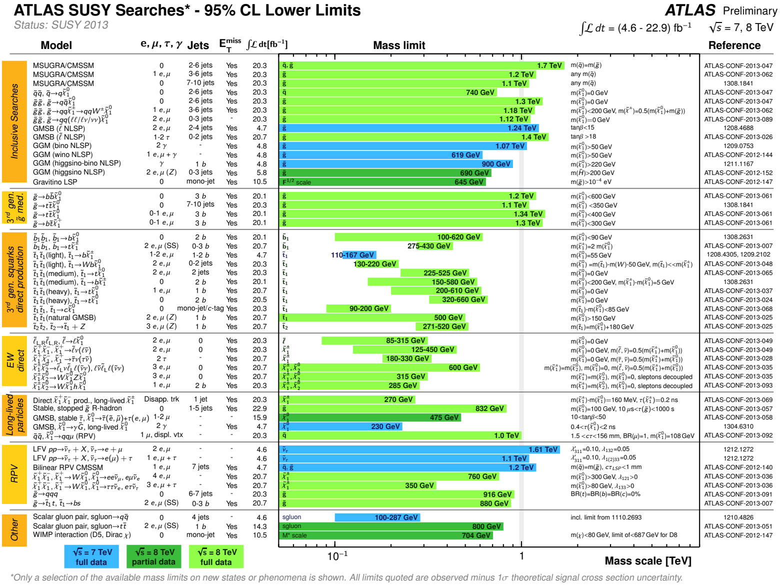




SUSY: the scalar top couples to the Higgs with strength y_t.

SUSY is broken ⇒ $m_{\tilde{t}} \neq m_t$, but this just means that $\Lambda^2 \sim m_{\tilde{t}}^2 \times \log$.

Is There Still Room for SUSY?



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	F$^{1/2}$ scale	645 GeV	$m(\tilde{g})$>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-220 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^{\pm})$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	$m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	285 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

🟦 $\sqrt{s}$ = 7 TeV full data 🟩 $\sqrt{s}$ = 8 TeV partial data 🟩 $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Probing SUSY Naturalness at the LHC

Typical SUSY

As we see, the bounds on generic SUSY spectrum are very severe. The scale of the squarks and gluinos is well above TeV scale ⇒ the cutoff is pushed above the TeV scale. **Unnatural**

Natural SUSY *Papucci, Ruderman, Weiler; Brust, AK, S. Lawrence, Sundrum*

What do we really need for the leading level naturalness? Stops, sbottom, gluino (slghtly heavier), higgsinos, EWikinos (can also be ∼TeV). Most of the versions of this spectrum are already cornered, but RPV stops can be as light as 100 GeV! Gluinos are generically $\geq$ TeV.
Other possibilities are also allowed by current constraints (e.g. "Flavored Naturalness, *Blanke, Giudice, Paradisi, Perez, Zupan*).

LHC has already excluded lots of possibilities, but there is always a question of model-dependence and spectrum dependence.

Model (In)dependent Probe of SUSY Naturalness

SUSY naturalness is already strongly constrained. However, some particular spectra are very hard to exclude.

Given a plethora of variations, spectra, and decay modes, are there any robust probes of SUSY naturalness?

The answer: SUSY higgs sector. SUSY heavy Higgs scalars decay modes are relatively model-independent given one parameter ($\tan\beta$). They provide an important probe of naturalness.

- **−** Heavy Higgses are relatively hard to find – decay modes are not spectacular and cross-sections are small
- **+** It is not easy to significantly modify the decay modes of A, H. Channels $\tau\tau$ ($\tan\beta \gg 1$), $t\bar{t}$($\tan\beta \sim 1$) and hh are generic.

SUSY Predicts the Mass of the Light Higgs

The Standard Model (SM) does not **predict** the higgs mass. The Higgs self-coupling is a free parameter of the theory and

$$m_h^2 \propto \lambda v^2.$$

Depending on λ the higgs mass can acquire **any value** $\lesssim$TeV for given v.

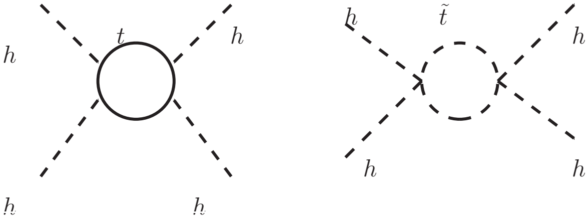
In minimal SUSY extension of the MSSM the quartic is determined by the symmetry: $\lambda \sim g^2$. For known Higgs expectation value we know the mass. More detailed SUSY calculation shows:

$$m_h \leq m_Z |\cos(2\beta)|$$

The measured higgs mass is $m_h \approx 125$ GeV.
What does this tell us about SUSY and how fine tuned it is?

Radiative Corrections to the Higgs Mass in MSSM

In exact SUSY limit the bound $m_h \leq m_Z |\cos 2\beta|$ is exact. SUSY is broken $\Rightarrow$ new radiative quartic is induced



$$+\ldots$$

$$\Delta m_h^2 \propto m_t^2 \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

$m_h \approx 125$ GeV $\Rightarrow m_{\tilde{t}} \gtrsim 10$ TeV $\Rightarrow$ **very unnatural**.

To have natural SUSY we need extra contributions to the Higgs quartic beyond MSSM

SUSY Heavy Higgses

SUSY necessarily has at least two Higgs supermultiplets $H_u,\ H_d \Rightarrow$ three additional (heavy) Higgs (pseudo)scalars compared to the SM: $A, H^0, H^\pm$. SUSY constrains possible mass splitting between the heavy Higgses. In non-minimal SUSY we might get slightly different splittings than in MSSM, but since we will need $\delta\lambda \sim \mathcal{O}(1)$ at most, $m_A,\ m_H,\ m_{H^+}$ will still be $\approx$ at the same scale. We will denote this scale as m_A.

As we will later see, this scale cannot be arbitrarily heavy, unless severe fine tuning is involved.

Extra Quartics, Heavy Higgses and Naturalness

Assume that we have extra Higgs quartic contributions from the new physics, that we integrate out at several TeV scale. Our considerations will be insensitive to the exact mechanism which produces the extra quartics.

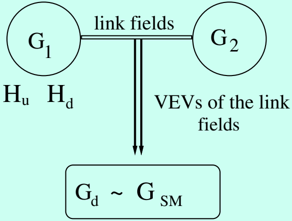
- How big are the quartics that we need?
- **What is the bound on the mass of heavy higgses from naturalness considerations? Where does this bound come from?**
- Most of natural parameter space will require large $\tan\beta$. **What constraints do we have there from flavor physics?**.
- What is the natural parameter space which is left?

Sources of Extra Higgs Quartic

Mostly during this talk we will be agnostic about the precise origin of the new Higgs quartic. Here we just review the most important possibilities

New D-terms

The SM gauge group emerges from a bigger symmetry.



New quartics - D-terms of the heavy W', Z'. Most important term: $\Delta V \sim |H_u|^4$.

NMMSM

By integrating out the singlet field we get an effective term $\Delta V \sim |H_u \cdot H_d|^2$.

$SU(2)$ triplets which couple to the SUSY Higgses

Depending on the hypercharge can induce either $\Delta V \sim |H_u|^4$ coupling or $\Delta V \sim |H_u \cdot H_d|^2$ coupling

Why Do We Have Naturalness Bound from the Heavy Higgses?

Let us consider first MSSM and $\tan\beta \gg 1$. For $\tan\beta \sim 1$ we will always need very big correction to the quartic. From equations of motion we have:

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \mu^2 - (m_{H_u}^2 + \mu^2)\tan^2\beta}{\tan^2\beta - 1}$$

No fine tuning $=$ no unnatural cancellations

- $\mu \approx m_Z^2$ – Higgsinos should not be much heavier than the EW scale
- $|m_{H_u}^2| \approx m_Z^2$ – to get a mass near the weak scale, Higgs should have a mass parameter near the weak scale
- $m_{H_d}^2 \approx m_Z^2 \tan^2\beta$. **This is a constraint on the masses of heavy Higgses. They cannot be much heavier than $m_Z \tan\beta$.** In non-minimal SUSY we will see very similar constraint, even though it will be numerically modified.

What are more precise bounds on m_A in MSSM extensions?

Non-minimal SUSY

A priori 2HDM has seven different types of quartic couplings one can write down. Most of them are very hard to get in any SUSY model, and they are naturally very small. In the MSSM only 4 types are present at the tree level

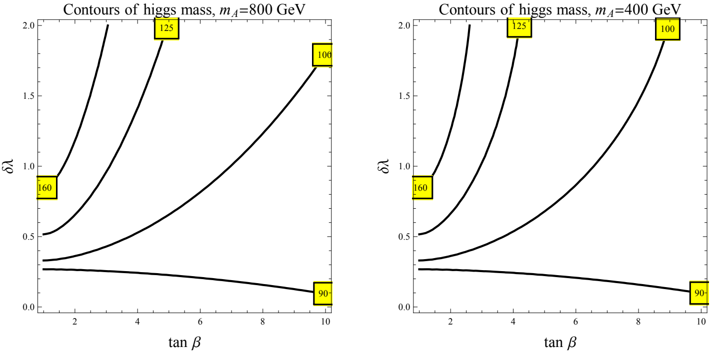
- $V \sim |H_u|^4$
- $V \sim |H_u|^2 |H_d|^2$
- $V \sim |H_u \cdot H_d|^2$
- $V \sim |H_d|^4$ – very suppressed in $\tan\beta \gg 1$ limit

To illustrate the point that heavy Higgses can exacerbate the fine tuning, we will concentrate on beyond-MSSM contributions to two different types of quartics: $|H_u|^4$ and $|H_u \cdot H_d|^2$.

$|H_u \cdot H_d|^2$ Extension

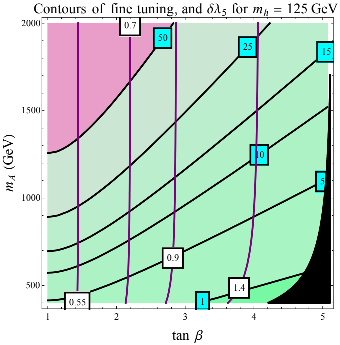
This extension arises in models with a singlet, which couples to the Higgses. The correction term involves $v_d \Rightarrow$ will be small in the limit of $\tan\beta \gg 1$. On the other hand, the MSSM term becomes small in $\tan\beta \sim 1$ limit.

The effect is maximized for moderate $\tan\beta$.



Fine Tuning in $|H_u \cdot H_d|^2$ Extension

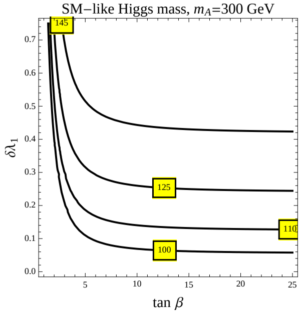
We quantify the fine tuning as variation of the Higgs VEV with respect to the input parameter $m^2_{H_d}$: $\Delta = \frac{\partial \ln v^2}{\partial \ln m^2_{H_d}}$

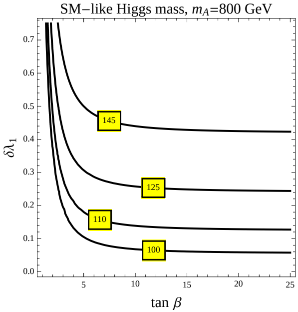


- Purple lines - required values of $\delta\lambda$ to get $m_h = 125$ GeV.
- Non fine tuned region is very small and requires large $\delta\lambda$
- Black - contours of fine tuning Δ, in very big regions of parameter space the fine tuning is worse than 4%.

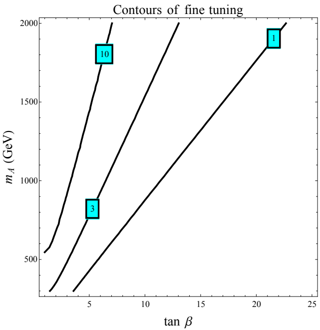
$|H_u|^4$ Extension

This term does not involve v_d and therefore the contribution to the Higgs mass is maximized and the fine tuning is minimized for $\tan\beta \gg 1$. Values of $\delta\lambda$ that we need to accommodate $m_h = 125$ GeV are modest.


SM−like Higgs mass, m_A=300 GeV


SM−like Higgs mass, m_A=800 GeV

Fine tuning in $|H_u|^4$ Extension

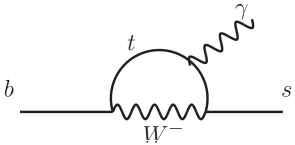


- Large regions of parameter space are completely not fine tuned, for $\tan\beta \gg 1$ one get appreciable fine tuning at $m_A \sim 6\ldots7$ TeV.
- Here it looks like most of the parameter space is not fine tuned. However, it is subject to $b \to s\gamma$ constraints. In practice $\tan\beta > 10$ will be difficult to get.

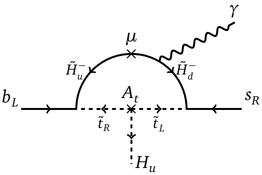
$b \to s\gamma$ in the SM and MSSM

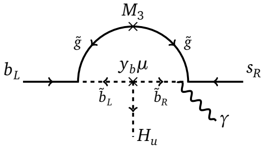
This constraint is important only for $\tan\beta \gg 1$. If we discover, that there are no heavy Higgses in the LHC range, we will be pushed to $\tan\beta \gg 1$ limit. This would be immediately in tension with $b \to s\gamma$.

In the SM this process is mediated only by W-loop:



In the MSSM we get three new contributions: Higgsino, gluino and wino loops.





In the natural regime the Higgsino diagram is the most important one.

$b \to s\gamma$ in Natural SUSY

Correction to the matrix element is

$$\mathcal{M}(b \to s\gamma)_{\tilde{H},\tilde{t}} \sim \frac{A_t \mu}{m_{\tilde{t}}^4}$$

- $m_{\tilde{t}}$ cannot be too large (needed for 1-loop naturalness)
- μ is constrained by direct searches for Higgsinos at LEP
- A_t cannot be too small, since it receives loop corrections proportional to the gluino mass

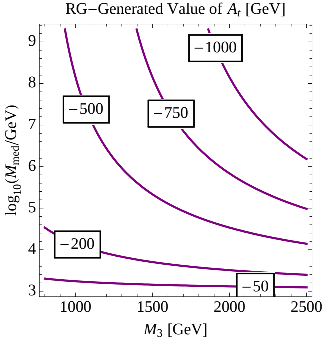
Experimentally measured:

$$0.9 < \frac{BR(B_s \to X_S\gamma)_{exp}}{BR(B_S \to X_s\gamma)_{SM}} < 1.32$$

What Are the Natural Values for A_t?

Running of A_t from a high scale Λ is dominated by gluino loop:

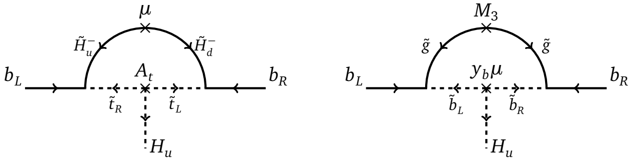
$$A_t \approx -190\ GeV \left(\frac{M_3}{TeV}\right) \log_{10} \frac{\Lambda}{M_3}$$



Even for low mediation scale, the natural value for A_t is around -200 GeV, and it can naturally as high as 0.7 TeV for higher scales. Getting A_t much smaller than that (preferred by $b \to s\gamma$) involves fine tuning against the tree level parameter.

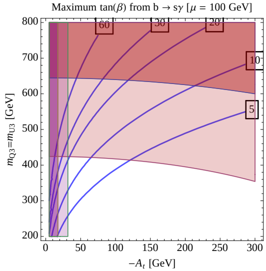
$b \to s\gamma$ for $\tan\beta > 50$

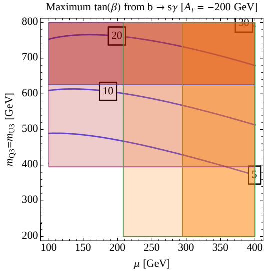
For very large $\tan\beta$ the standard expressions for the $b \to s\gamma$ are corrected by “wrong Yukawa terms”, which are formed radiatively: $\mathcal{L} \sim \epsilon_b H_u^\dagger Q b^c$:



These corrections can become important only if $\epsilon_b \tan\beta \sim \mathcal{O}(1)$.
Both gluino and higgsino loop must be proportional to μ. For large values of μ this can give sizable contributions to the observed Yukawas, however $\mu \gg 100$ GeV are disfavored by naturalness considerations. Practically, for $\mu \sim 100$ GeV we always get $\epsilon_b \lesssim 10^{-2}$, which gives less than 10% correction in $b \to s\gamma$ rate.

Interpretation of $b \to s\gamma$ results


Maximum tan(β) from b $\to$ sγ [μ = 100 GeV]

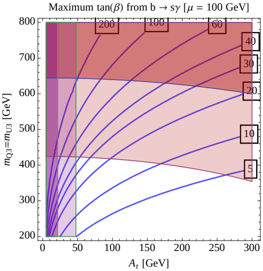

Maximum tan(β) from b $\to$ sγ [A_t = −200 GeV]

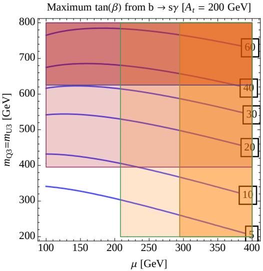
Contours of maximal allowed $\tan\beta$ for $\mu A_t < 0$. The shaded regions are fine-tuned:

- Purple - fine tuning in A_t (assuming $M_3 = 1$ TeV)
- Red - fine tuning in $m^2_{H_u}$ from the large stop mass
- Orange - fine tuning of tree level EWSB due to large μ

Very little room in not fine tuned regime even for $\tan\beta = 10$.

Interpretation of constraints



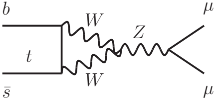


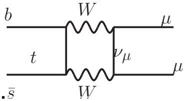
Contours of maximal allowed $\tan\beta$ for $\mu A_t > 0$. The shaded regions are fine-tuned. The constraints are slightly weaker for μA_t because the new physics interferes constructively with the SM contribution, and the data prefers slightly higher values than the SM.

Not fine tuned region of parameter space is still very limited for $\tan\beta > 10$.

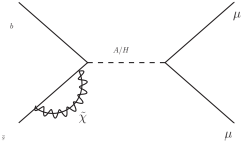
Comment on $B_s \to \mu^+\mu^-$

This extremely rare process, mediated in the SM by W-diagrams, can be hugely enhanced in SUSY $\tan\beta \gg 1$ limit.





Additional SUSY contribution:



Naively should be a strong constraint, SUSY contribution $\propto \tan^3\beta$. However, it is suppressed by m_A. From our preliminary estimates this bound is sub-dominant to $b \to s\gamma$.

Conclusions

1. In SUSY theories heavy higgses can be a very clear diagnostic of naturalness or fine tuning. Natural theory requires either SUSY Higgses not too heavy or large tan β.
2. Natural SUSY theory needs extra Higgs quartic beyond MSSM. The exact naturalness bound on the masses of heavy Higgses depends on the details of the MSSM extension.
3. The demand of large tan β (for the heavy A) is already in clear tension with flavor measurements, predominantly $b \to s\gamma$. There is still some room for "natural theories", but most of the parameter space demand fine tuning to reduce A_t to have heavy stops.
4. Given the importance of the heavy Higgses for SUSY naturalness, it is crucial to understand, how one can improve the LHC searches for the heavy Higgses.