Alternative theories of Electroweak Symmetry Breaking

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The Standard Model likely suffers from a Naturalness Problem (m_H << M_{pl} – see next lecture)

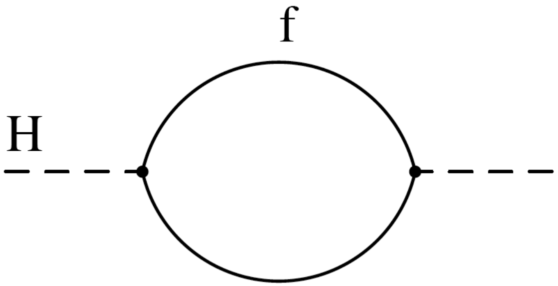
We need to invoke additional principles, and perhaps additional particles and forces to render theory Natural.

This lecture discusses some main ideas for that and their status, as well as the status of Naturalness itself.

Higgs boson unstable to QM

A quantum loop is quadratically divergent. Higgs mass, connected to Higgs vev, is unstable to the highest mass scales in the theory.

Schematically:



$$\Delta\mathcal{L} = m_{bare}^2 H^\dagger H$$

$$m_H^2 = m_{\rm bare}^2 + \frac{y_t^2}{16\pi^2}\Lambda^2 + \delta\mathcal{O}(m_{\rm weak}^2)$$

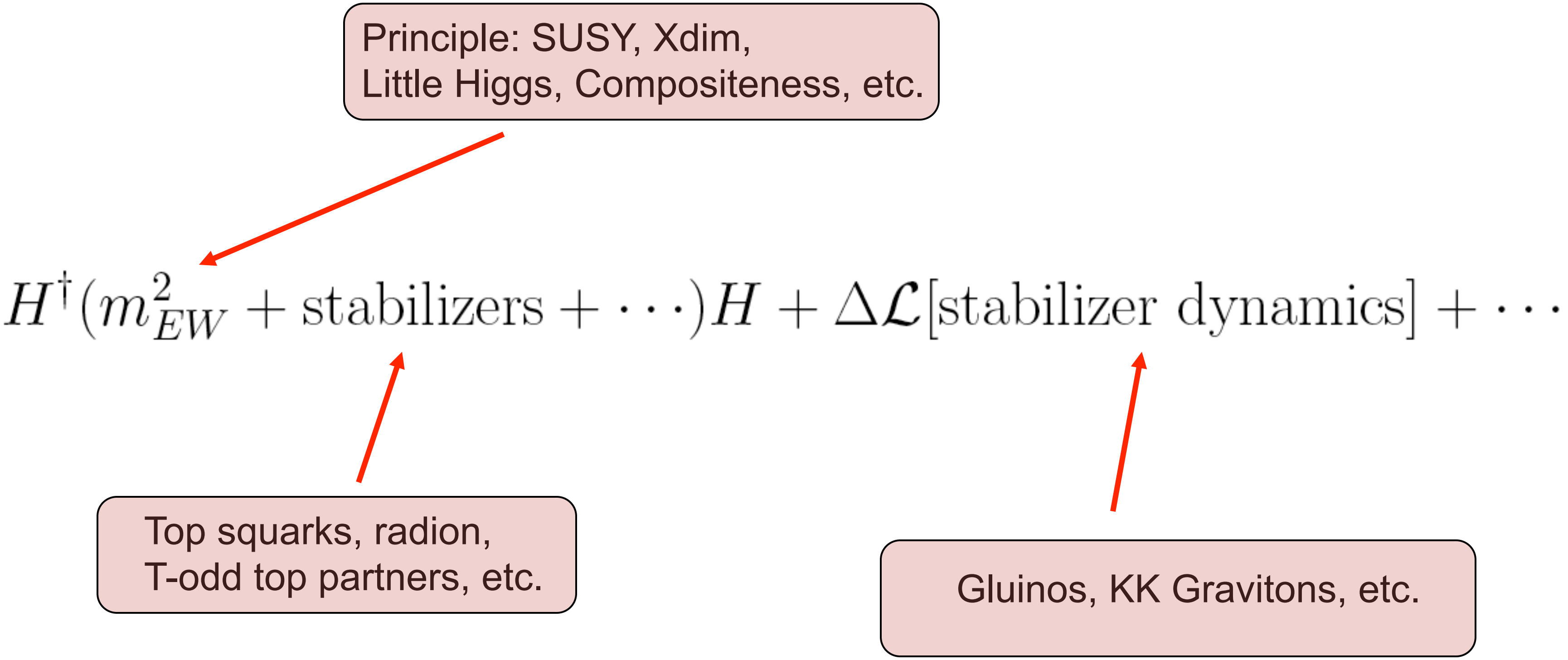
Confusing: M_{Pl} is 10^{16} times more massive than weak scale.

Cures of the Naturalness Problem, and the Resulting Higgs boson Entourage

1. Disallow all scalars in the theory (Technicolor).
2. Symmetry cancels quadratic divergences (supersymmetry)
3. Disallow higher mass scales (extra dimensions).

Implication: “New Physics” needs to be found at LHC.

Statics and Dynamics of Higgs Mass



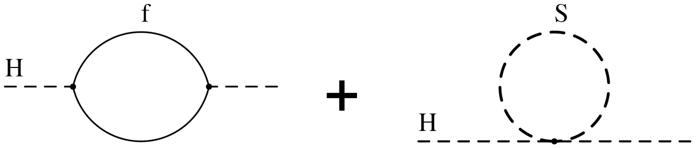
Principle: SUSY, Xdim,
Little Higgs, Compositeness, etc.

$$H^\dagger(m_{EW}^2 + \text{stabilizers} + \cdots)H + \Delta\mathcal{L}[\text{stabilizer dynamics}] + \cdots$$

Top squarks, radion,
T-odd top partners, etc.

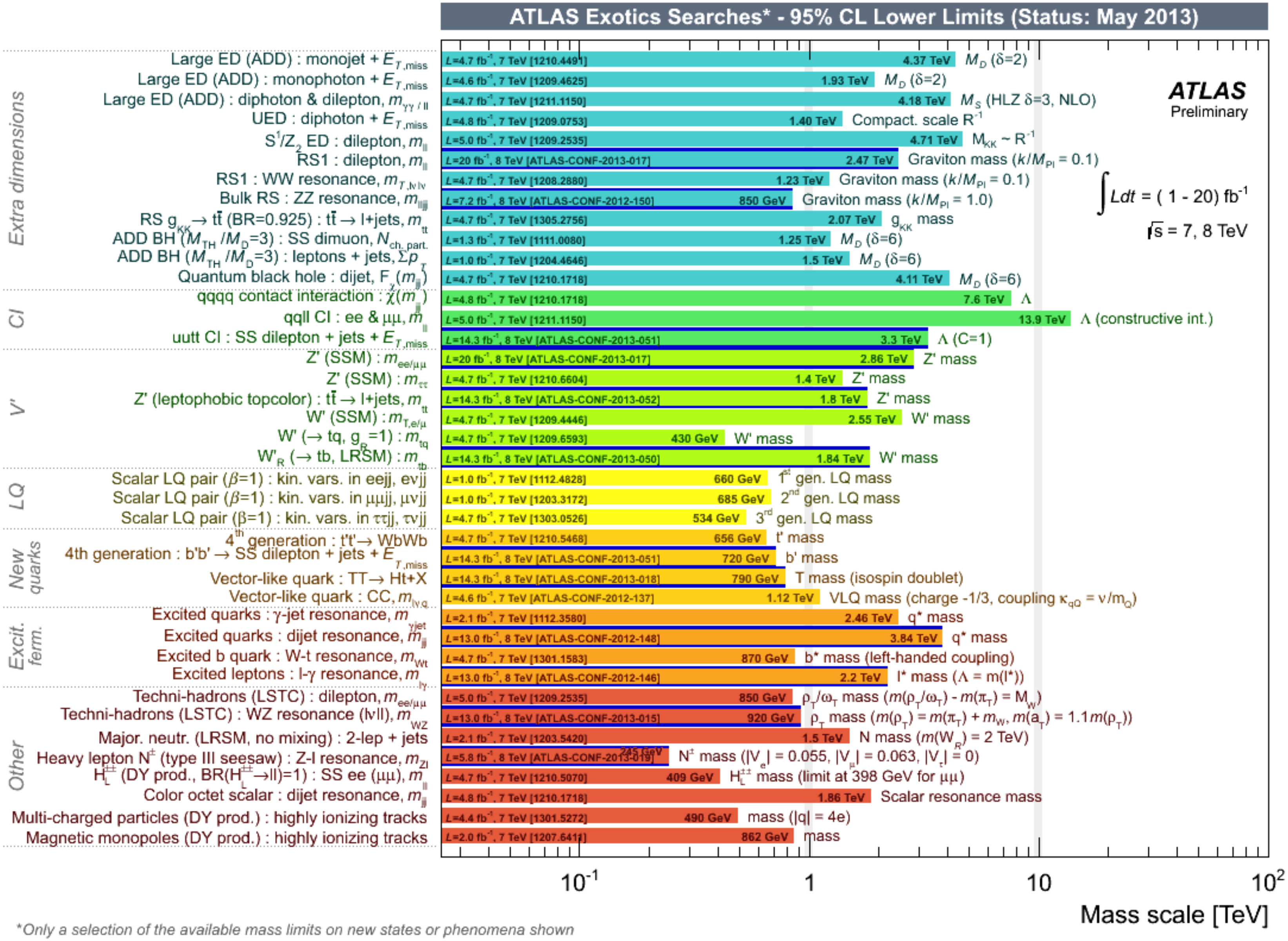
Gluinos, KK Gravitons, etc.

SUSY:



$$m_H^2 \sim \frac{\alpha_f}{4\pi}\Lambda^2 - \frac{\alpha_f}{4\pi}\Lambda^2 \sim 0 + \cdots$$

But nothing else has been found….

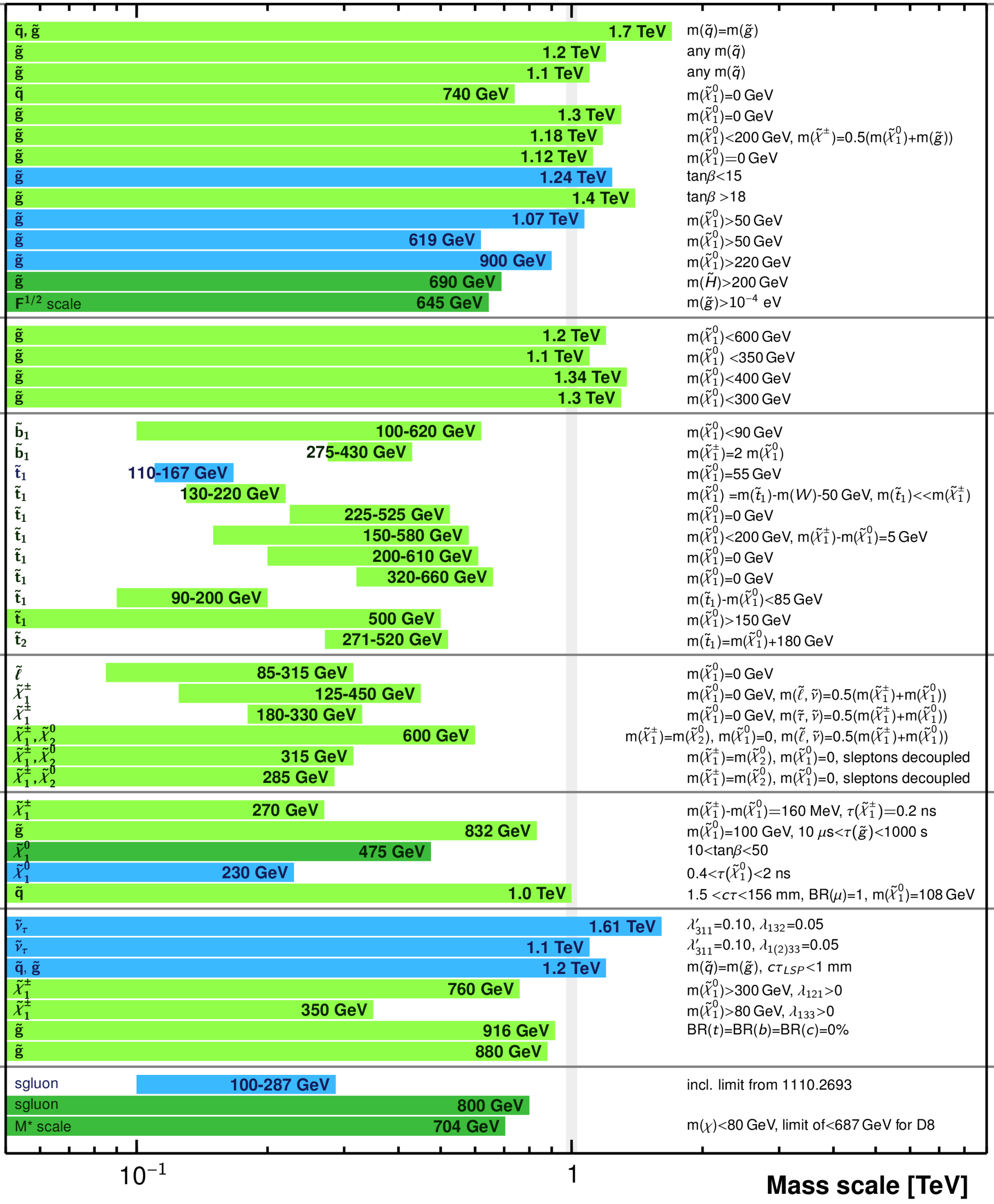


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

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



	Model	**e, μ, τ, γ**	**Jets**	**E_T^{miss}**	**$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$**	**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	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$ >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<$\tan\beta$<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.*

Losing the Naturalness Religion

Starting to hear many more comments like:

“Quadratic divergence Naturalness problem is just philosophical – not really a data-driven concern.”

“Dimensional regularization has no quadratic divergence Naturalness problem, so maybe it doesn’t exist”

Cf. $m_H^2 = m_{\mathrm{bare}}^2 + \frac{y_t^2}{16\pi^2}\Lambda^2 + \delta\mathcal{O}(m_{\mathrm{weak}}^2)$

$$\rightarrow m_W^2\left(\frac{1}{4-n}-\gamma_E+\ln 4\pi+1-\ln\frac{m_W^2}{\mu^2}\right)+\cdots$$

(Note, there is no Λ^2 cutoff funny business – only 1/(4-n))

Gravity and Naturalness

$$m_H^2 = m_{\rm bare}^2 + \frac{y_t^2}{16\pi^2}\Lambda^2 + \delta\mathcal{O}(m_{\rm weak}^2)$$

Common worry: loop momentum cut off by gravity scale

Λ = M_{pl} = $(G_N)^{-1/2}$ ~ 10^{18} GeV which is much higher than M_{weak} = M_H = 10^2 GeV.

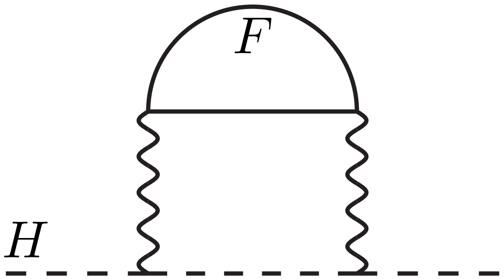
However:

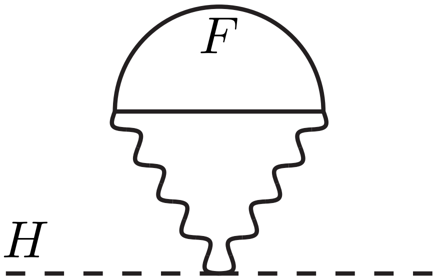
- Gravity is remote
- Gravity is not exactly like our normal gauge theories
- Gravity is mysterious – especially quantum gravity

Criticism: We do not know enough about gravity to use it to criticize the Higgs boson's naturalness. Throw out gravity considerations.

New Charged States

Surely the particles we know of are not everything. For example, nothing prevents us from having a large number of "vectorlike states" at high mass (mass not given by Higgs boson).





A vectorlike fermion feeds into the Higgs mass at two loops through gauge interactions.

$$\Delta m_H^2 = C_H T_F \left(\frac{g^2}{16\pi^2}\right)^2 \left[a\Lambda_{\rm UV}^2 + 24 m_F^2 \ln(\Lambda_{\rm UV}/m_F) + \ldots\right]$$

We see that the Higgs mass is quadratically sensitive to the mass of the “vectorlike fermion”. This is a serious concern.

However:

- It is rather narrow to get worked up about SM charged particles
- Perhaps we know all the particles charged under the SM

Criticism: It is plausibly unfair to criticize the Higgs by invoking speculative new particles that just happen to be charged under the SM.

Where we are at:

Naturalness for a stand-alone Higgs boson has been a concern.

However, perhaps one shouldn’t invoke gravity in the argument.

➔ consider the possibility that gravity induces no Naturalness problems.

And, perhaps one shouldn’t invoke new states charged under the SM in the argument.

➔ Assume that extra SM charged states do not exist.

What does that leave us with:

A question. What about the addition of many extra states not charged under the SM? Is there a naturalness concern?

The answer is mostly no (some subtleties at play), but one generic and serious concern remains:

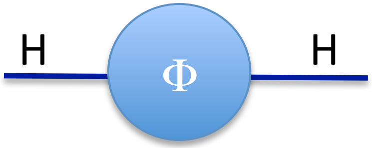
the proliferation of scalar bosons like the Higgs boson.

This can be called the “Higgs boson proliferation instability problem”.

Sensitivity to higher physical scales persists

All it takes is for any massive particle to interact with the Higgs and there is a real physical quantum correction to contend with.

$$\Delta\mathcal{L} = \lambda_\Phi |H|^2 |\Phi|^2$$



$$\Delta m_H^2 \propto \lambda_\Phi \, m_\Phi^2 \ln m_\Phi$$

It is inconceivable to me that there is nothing else between "here" (10^2 GeV) and the Planck scale (10^{18} GeV). And if there is another scalar (even if exotically charged!) there is no simple symmetry to forbid it from coupling to the Higgs boson.

Finetuning of Mass Scales

Another example : scalar potential for the SM Higgs boson H and the condensing exotic boson Φ.

$$V = -\mu_H^2|H|^2 - \mu_\Phi^2|\Phi|^2 + \eta|H|^2|\Phi|^2 + \lambda_H|H|^4 + \lambda_\Phi|\Phi|^4$$

The Minimization conditions from dV/dH = 0 and dV/dΦ = 0 yield.

$$-\mu_H^2 + \frac{\eta}{2}\xi^2 + \lambda_H v^2 = 0$$
$$-\mu_\Phi^2 + \frac{\eta}{2}v^2 + \lambda_\Phi \xi^2 = 0$$

where

$$\langle H\rangle = v \text{ and } \langle \Phi\rangle = \xi$$

If we assume all dimensionless couplings are $\mathcal{O}(1)$ and $\mu_\Phi^2 \sim \xi^2 \gg v^2$, we have a serious problem with eq. (~10 TeV exotic masses)

-(10,000.787 GeV)^2 + (10,000 GeV)^2 + 0.26*(246 GeV)^2 = 0
Or,
- 100,015,734 + 100,000,000 + 15,734 = 0

$$-\mu_H^2 + \frac{\eta}{2}\xi^2 + \lambda_H v^2 = 0$$

$$-\mu_\Phi^2 + \frac{\eta}{2}v^2 + \lambda_\Phi \xi^2 = 0$$

The extraordinary finetuning to make these conditions work out constitutes a naturalness problem.

The addition of more scalars makes the problem even worse.

This is the proliferation problem, and it only goes away if you believe

1) there are no other scalars in nature ("unlikely"), or
2) there is a principle that generically keeps $|H|^2|\Phi|^2$ type of terms in check (new physics!!)

Solutions to the Proliferation Problem

Not surprisingly, they are similar to the solutions of the general Naturalness problem.

1) No fundamental scalars in the spectrum (technicolor/ composite Higgs)

2) Extra dimensions: this is actually not as pleasant since a slew of scalars at a few TeV can be very destabilizing

3) Supersymmetry: this theory elegantly solves the problem.

Composite Higgs Theories

First, a few words on composite Higgs theories.

Higgs boson as pNGB of G→H breaking at scale f.

Resonances at scale f: $m_\rho \sim g_\rho f$ where $1 \lesssim g_\rho \lesssim 4\pi$

Higgs potential generated

where,

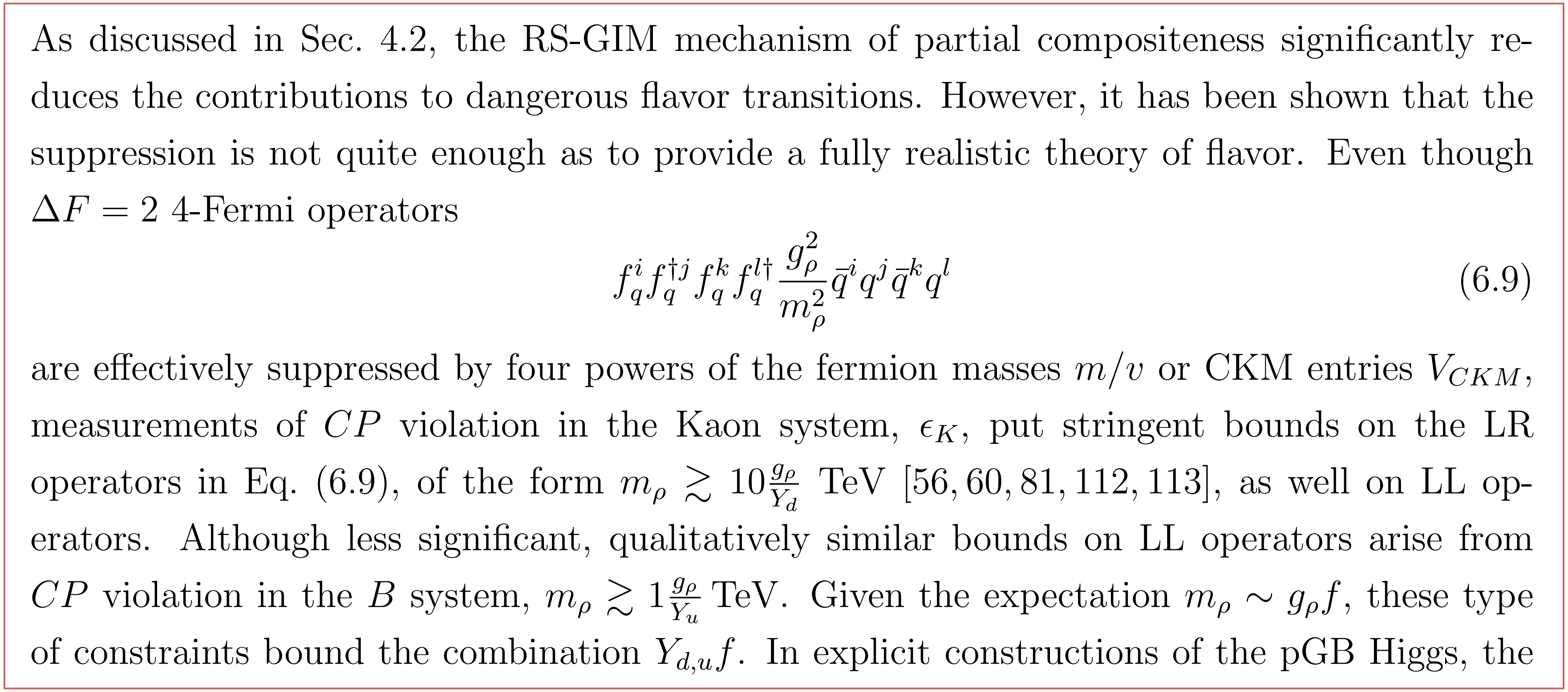
$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

$$\mu^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2 \qquad \lambda \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 \qquad \Rightarrow \qquad \langle H \rangle = v = \sqrt{\frac{\mu^2}{\lambda}} \sim f$$

This is the challenge with composite theories:

Although v ~ f is the naïve expectation, we need f >> v.

Why? FCNC issues.



As discussed in Sec. 4.2, the RS-GIM mechanism of partial compositeness significantly reduces the contributions to dangerous flavor transitions. However, it has been shown that the suppression is not quite enough as to provide a fully realistic theory of flavor. Even though $\Delta F = 2$ 4-Fermi operators

$$f_q^i f_q^{\dagger j} f_q^k f_q^{l\dagger} \frac{g_\rho^2}{m_\rho^2} \bar{q}^i q^j \bar{q}^k q^l \tag{6.9}$$

are effectively suppressed by four powers of the fermion masses m/v or CKM entries V_{CKM}, measurements of CP violation in the Kaon system, ϵ_K, put stringent bounds on the LR operators in Eq. (6.9), of the form $m_\rho \gtrsim 10 \frac{g_\rho}{Y_d}$ TeV $[56, 60, 81, 112, 113]$, as well on LL operators. Although less significant, qualitatively similar bounds on LL operators arise from CP violation in the B system, $m_\rho \gtrsim 1 \frac{g_\rho}{Y_u}$ TeV. Given the expectation $m_\rho \sim g_\rho f$, these type of constraints bound the combination $Y_{d,u} f$. In explicit constructions of the pGB Higgs, the

Bellazzini, Csaki, Serra, `14

f greater than ~ 10 TeV probably needed ➔ $\dfrac{v^2}{f^2} \lesssim 10^{-3}$

Significant interesting model building in composite Higgs theories.

The theories are still viable.

Tuning requirements to achieve $v^2 << f^2$ are analogous to susy's $v^2 <<$ $msusy^2$ (if indeed that is required).

Compositeness affects Higgs couplings to vector bosons and fermions with shifts of order v^2/f^2, which can be O(few %).

Many alternative EWSB ideas allow or even require more Higgs bosons.

1) Either extra singlets under the SM symmetries.

2) Or, extra scalars charged under the SM – in particular extra doublets.

Supersymmetry example of this 2nd type.

First: How SUSY Solves the Higgs/scalar Proliferation Problem

Supersymmetry is symmetry between bosons (even spin particles, such as W, Z, H) and fermions (half-integer spin particles, such as electron, muon and top quark).

Supersymmetry invariance manifest when theory construction with "superpotential" and "Kahler potential".

No superpotential term can give rise to $|H|^2|S|^2$ interaction at all under our considerations. (the "mu term" with a singlet has this, but there are solutions…)

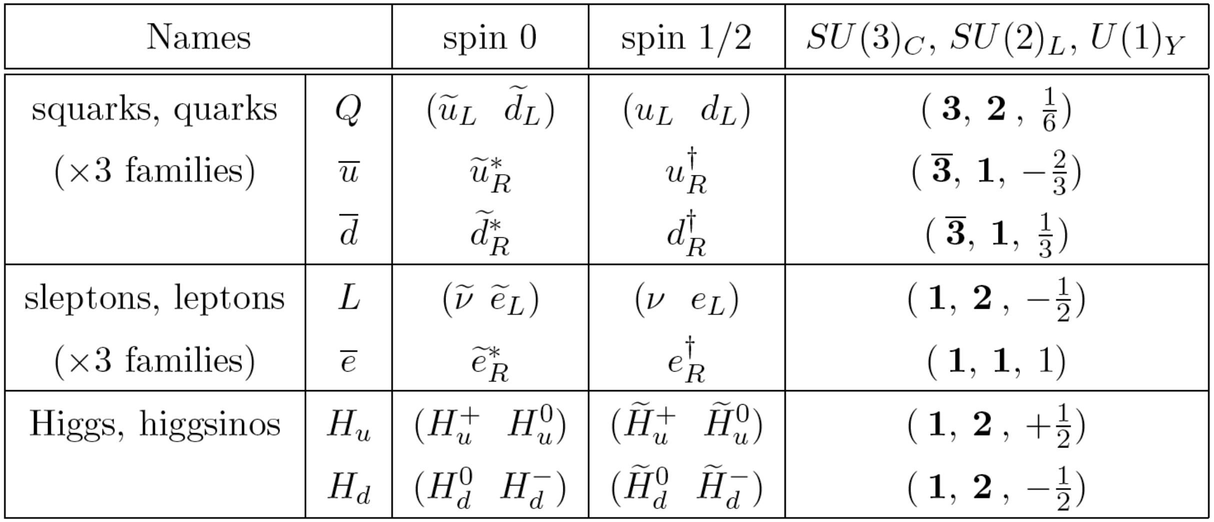
Kahler potential terms can have this interaction, but they are suppressed by $(m_{weak}/M_{pl})^2 = 10^{-32}$. In other words, lagrangian can have $\lambda|H|^2|S|^2$, but $\lambda \sim 10^{-32}$.

$$\begin{aligned} \Delta\mathcal{L} &= \int d^4\theta X^\dagger X \frac{\hat{\Phi}_i^\dagger \hat{\Phi}_i}{M_{Pl}^4} \hat{H}_u \cdot \hat{H}_d \sim \frac{F^\dagger F}{M_{Pl}^4} \Phi_i^\dagger \Phi_i H_u \cdot H_d \\ &\sim \left(\frac{M_{weak}}{M_{Pl}}\right)^2 \Phi_i^\dagger \Phi_i H_u \cdot H_d \end{aligned}$$

(tiny and safe coefficient)

More discussion on SUSY:
Minimal Supersymmetric Standard Model

Martin, hep-ph/9709356



Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\ \mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

If supersymmetry masses heavy (greater than all the SM masses), 4 Higgses $\{H^+, H^-, A, H\}$ form a heavy, decoupled doublet, and h remains a light field, which behaves almost just as the Standard Model Higgs boson.

Supersymmetry predicts mass of h field to be less than About 135 GeV. I.e., compatible with the 126 GeV discovery.

Thoughts on Implications for SUSY

First, I am slightly more encouraged about Supersymmetry than I was a few years ago….

Why?

Although supersymmetry particles have not been directly observed, its prediction that a Standard Model-like Higgs boson with mass

$m_H < 135$ GeV (a priori, m_H in SM could have been up to ~1000 GeV)

is satisfied ($m_H = 125$ GeV).

In a relative sense it seems "better" than other ideas now (including compositeness, strongly coupled, Extra dimensions, etc.).

Judgment on absolute terms is of course less clear.

Let us explore how susy might be compatible with what we know now

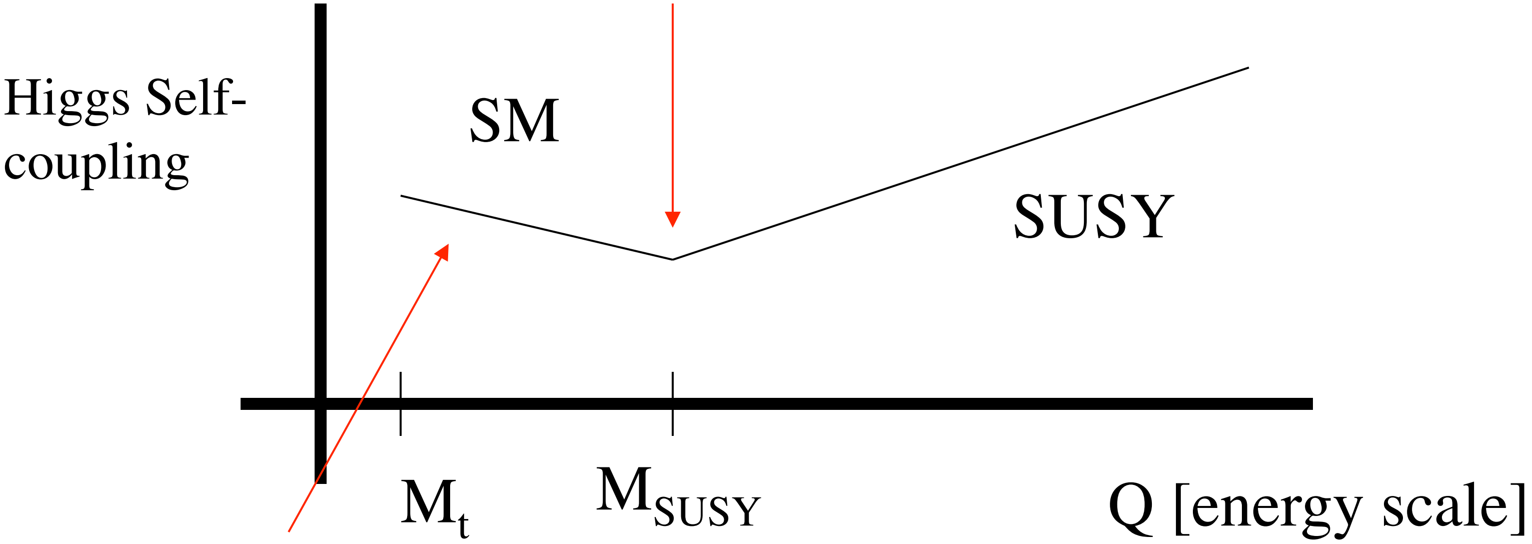
It is useful to consider how susy might manifest itself if it is indeed behind the 125 GeV Higgs mass.

Many ideas abound. I will tell you about one of my favorites.

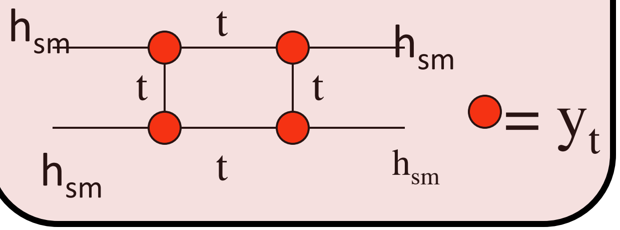
But first, let me remind you about the light Higgs boson mass in Supersymmetry, since that's really where all the stress is.

Understanding Lightest Higgs Mass Computation

$$\lambda(M_{SUSY}) = \frac{1}{8}(g^2 + g'^2)\cos^2 2\beta$$



$$\frac{d\lambda}{d\log Q} = -\frac{3}{4\pi^2}y_t^4 + \cdots$$



$$\begin{aligned} m_h^2 &= 2\lambda v^2 = 2\left(\lambda(M_{SUSY}) + \frac{3}{4\pi^2}y_t^4 \log\frac{M_{SUSY}}{M_t}\right)v^2 \\ &= M_Z^2\cos^2 2\beta + \frac{3M_t^4}{\pi^2 v^2}\log\frac{M_{SUSY}}{M_t} \end{aligned}$$

Naturalness

Naturalness is strained if M_{SUSY} becomes too large.

From the EW scalar potential of supersymmetry, the minimization conditions yield

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

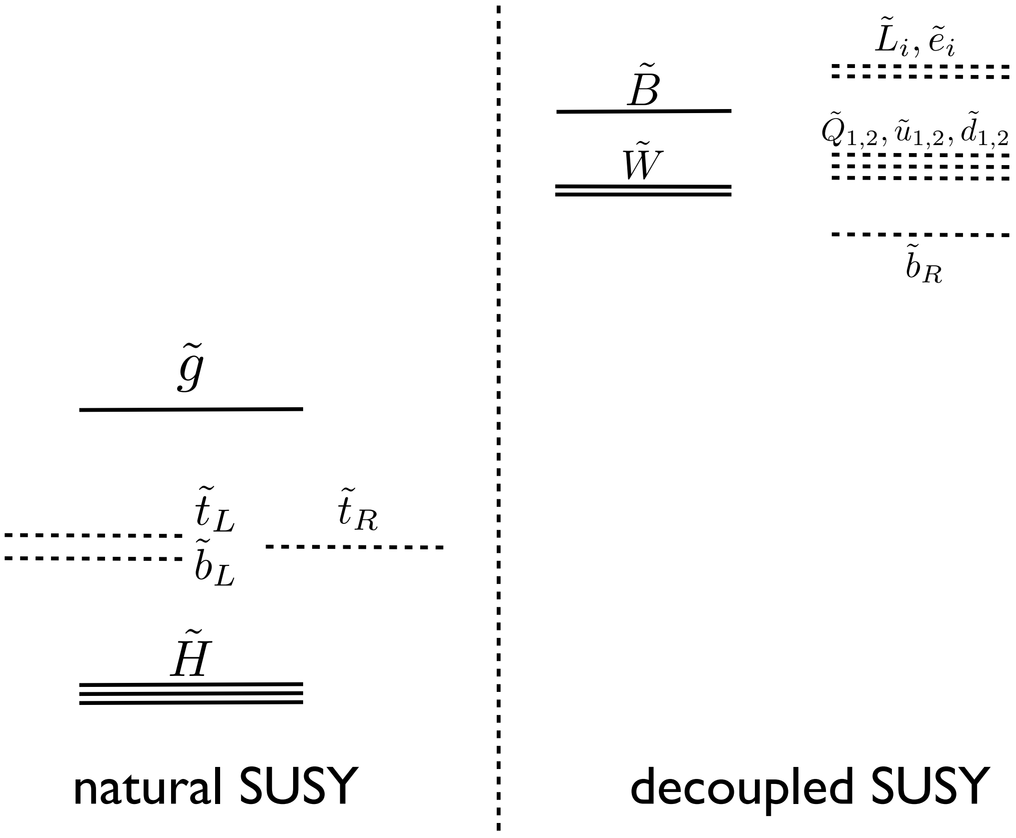
🟩 = weak scale (10^2 GeV)

🟥 = supersymmetry scale (> 10^3 GeV?)

This is of the generic form of one large number subtracting another and getting a small number:

$$\boxed{\tilde{m}_1^2}-\boxed{\tilde{m}_2^2}=\boxed{m_Z^2}$$

Two generic approaches to SUSY with right Higgs mass

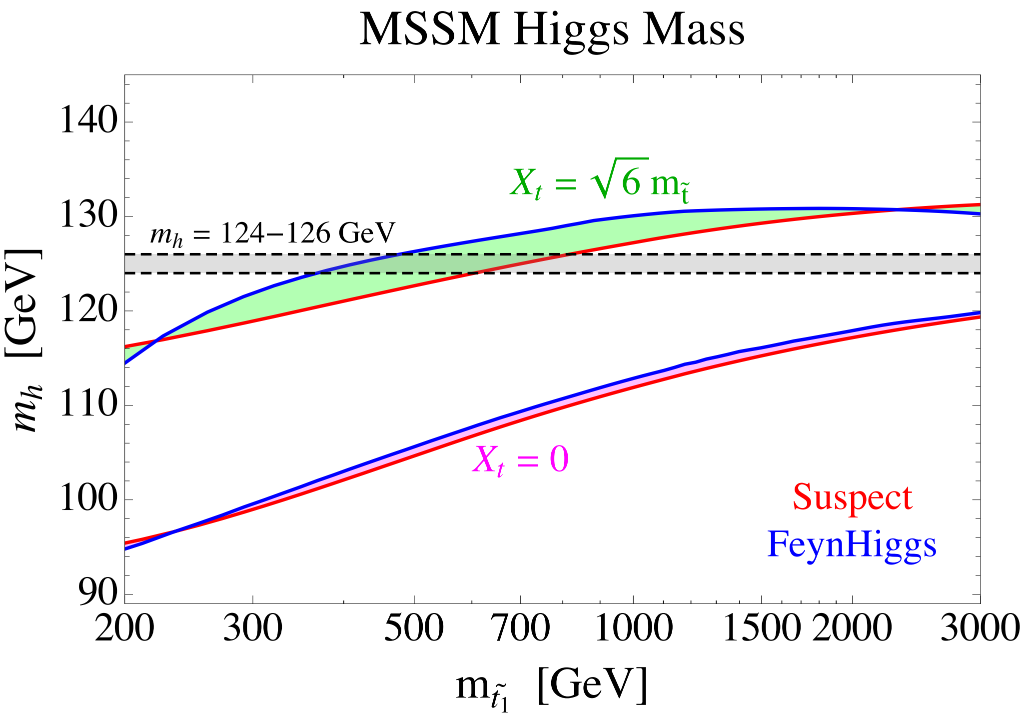


Papucci, Ruderman, Weiler, `12

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log\left(\frac{\overline{m}_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{\overline{m}_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12\overline{m}_{\tilde{t}}^2}\right)\right)$$

Large stop mixing
X_t may be required

Large stop mixing
not required



$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

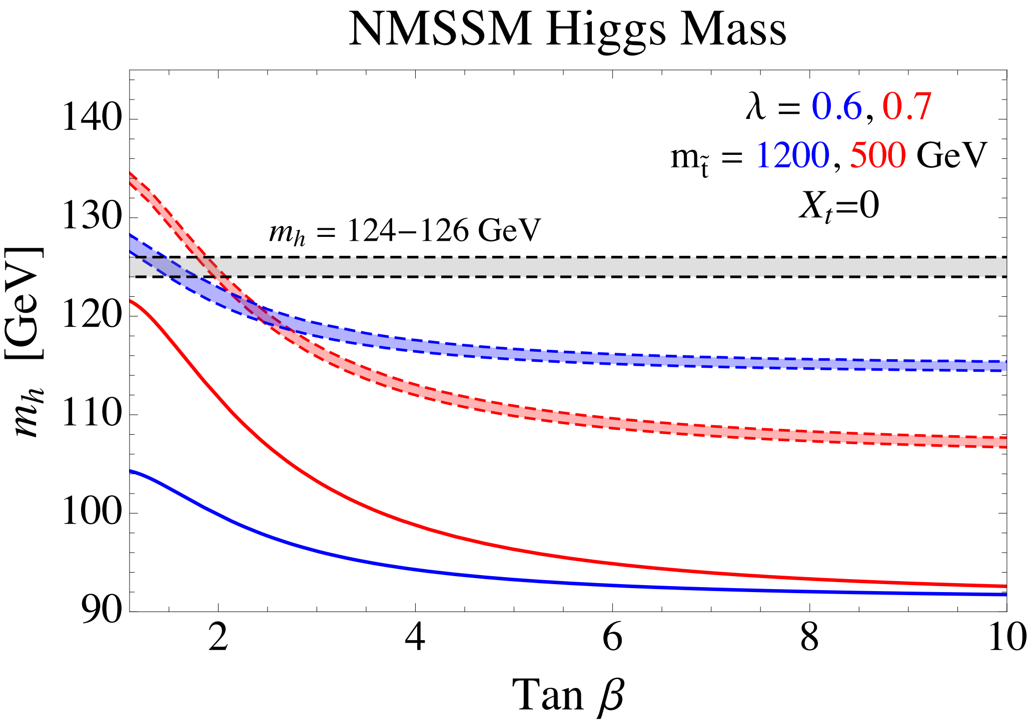
Figure 1: The Higgs mass in the MSSM as a function of the lightest top squark mass, $m_{\tilde{t}_1}$, with red/blue solid lines computed using Suspect/FeynHiggs. The two upper lines are for maximal top squark mixing assuming degenerate stop soft masses and yield a 124 (126) GeV Higgs mass for $m_{\tilde{t}_1}$ in the range of 350–600 (500–800) GeV, while the two lower lines are for zero top squark mixing and do not yield a 124 GeV Higgs mass for $m_{\tilde{t}_1}$ below 3 TeV. Here we have taken $\tan\beta = 20$. The shaded regions highlight the difference between the Suspect and FeynHiggs results, and may be taken as an estimate of the uncertainties in the two-loop calculation.

Hall, Pinner, Ruderman, `12

COMMENT:

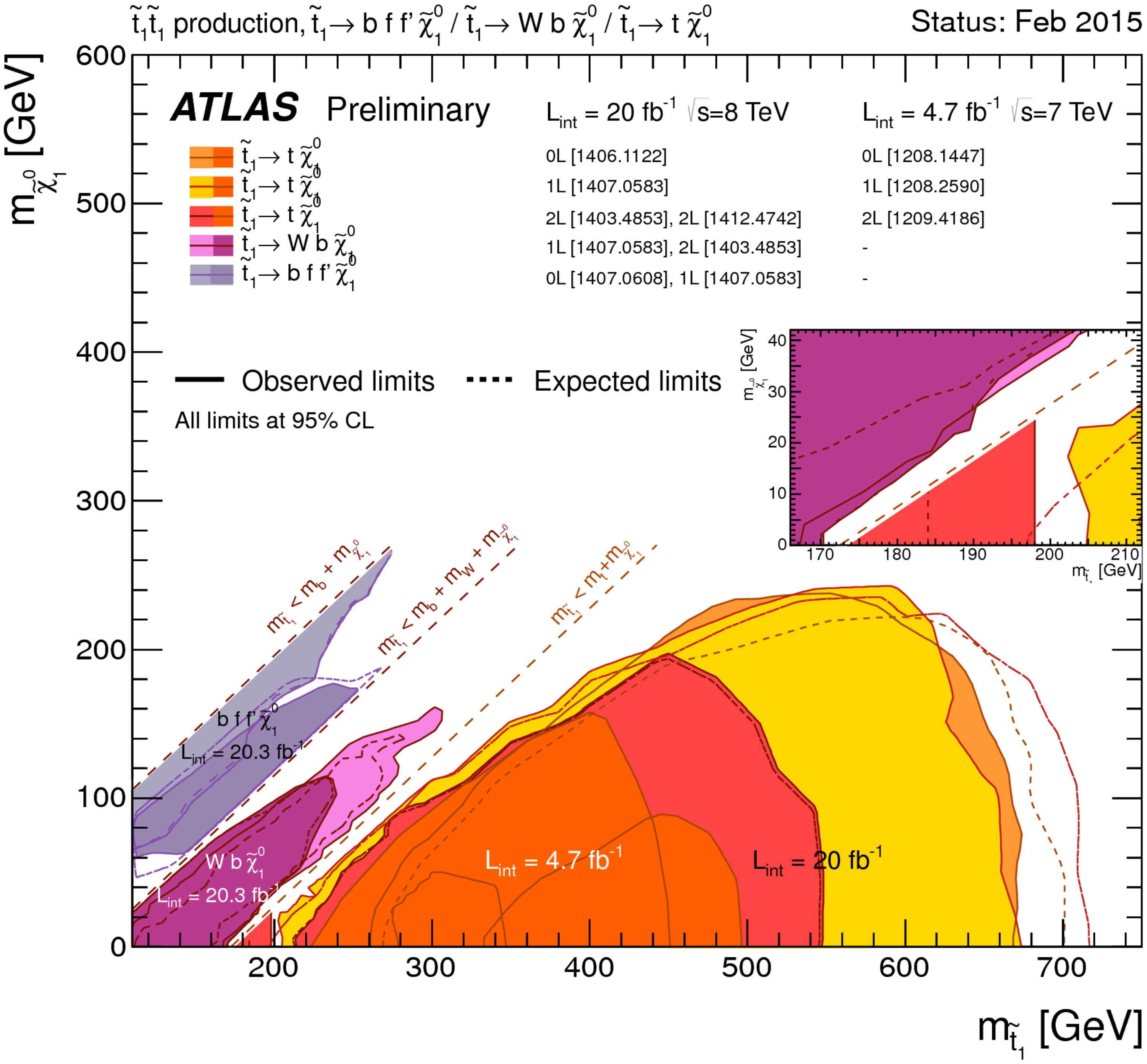
NMSSM can raise Higgs mass at tree level

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$



$\Delta W = \lambda\, S\, H_u\, H_d$

Figure 2: The Higgs mass in the NMSSM as a function of tan β. The solid lines show the tree-level result of equation 2 while the shaded bands bounded by dashed lines result from adding the $\lambda^2 v^2 \sin^2 2\beta$ contribution of equation 2 to the two-loop Suspect/FeynHiggs MSSM result, with degenerate stop soft masses and no stop mixing. The top contribution δ_t is sufficient to raise the Higgs mass to 125 GeV for $\lambda = 0.7$ for a top squark mass of 500 GeV; but as λ is decreased to 0.6 a larger value of the top squark mass is needed.



<u>Stops are not so easy to find</u>

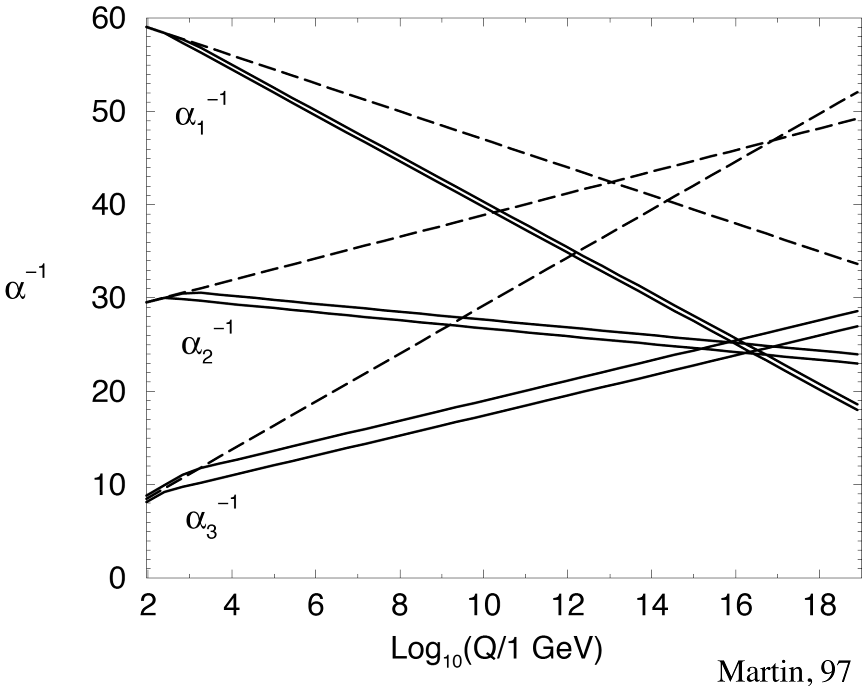
Arbitrary heavy SUSY?

If allowed to strain naturalness, we should
not conclude that SUSY is at some arbitrarily large
scale.

We wish to retain good things about SUSY:

•Gauge Coupling unification
•Light Higgs boson mass prediction (severely constrains)
•Cold Dark Matter

Gauge Coupling Unification



Martin, 97

“Proximity Factor” for gauge coupling unification is defined to be the factor A needed such that

Generic quantum correction

$$g_U = g_1(M_U) = g_2(M_U) = g_3(M_U) + A\frac{g_U^3}{16\pi^2}$$

In weak-scale MSSM $M_U \simeq 2\times 10^{16}\,\text{GeV}$ and $A\simeq 1$.

Unification success sensitive to -inos, but not scalars.

CDM Limits and SUSY Mass

Experiment tells us

$$0.09 < \Omega_{CDM} h^2 < 0.13$$

Leads to upper bound constraint on lightest susy mass (neutralino), but others can be much heavier (squarks and sleptons).

$$\Omega h^2 = \frac{A}{\langle\sigma v\rangle} = \frac{A\tilde{m}^2}{\alpha}, \quad \text{where } \langle\sigma v\rangle = \frac{\alpha}{\tilde{m}^2}$$

$$\frac{A\tilde{m}^2}{\alpha} < 0.13 \quad \rightarrow \quad \tilde{m} < \sqrt{0.13\alpha/A} < \text{ few TeV}$$

E.g., Wino or Higgsino

Heavier but bounded SUSY Advantages

Stretching Naturalness …

Eliminates bad things:

1. FCNC
2. Proton decay strains
3. CP Violation
4. Too light Higgs mass

Preserves good things:

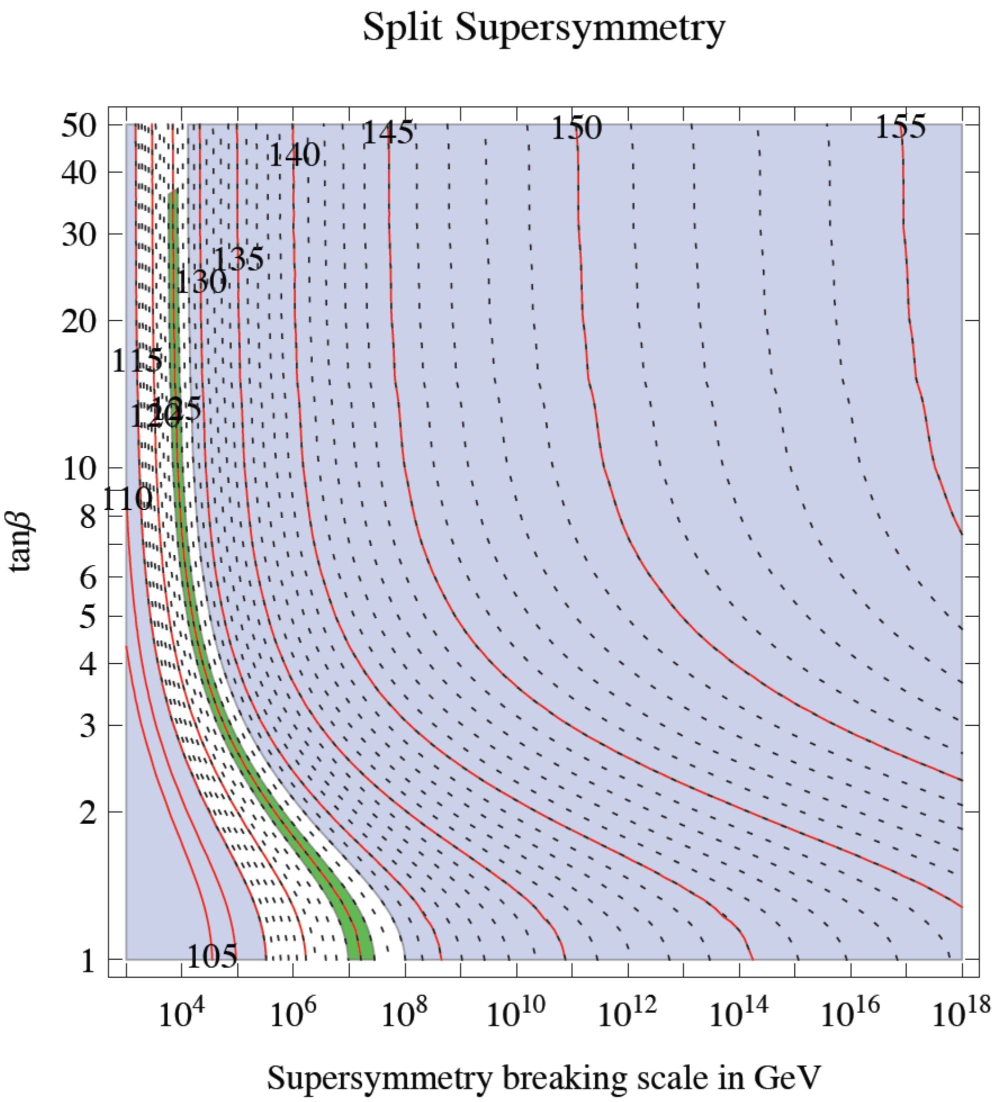
- SUSY
- Light Higgs prediction
- Gauge Coupling Unification
- Dark Matter

Accomplished by large scalar susy masses, but light fermion susy masses (gauginos, higgsinos)

Good theory for this? Yes. The -ino masses charged under symmetries (R and PQ) whereas scalars are not.

[See, Split SUSY literature.]

Higgs Boson Mass Implication



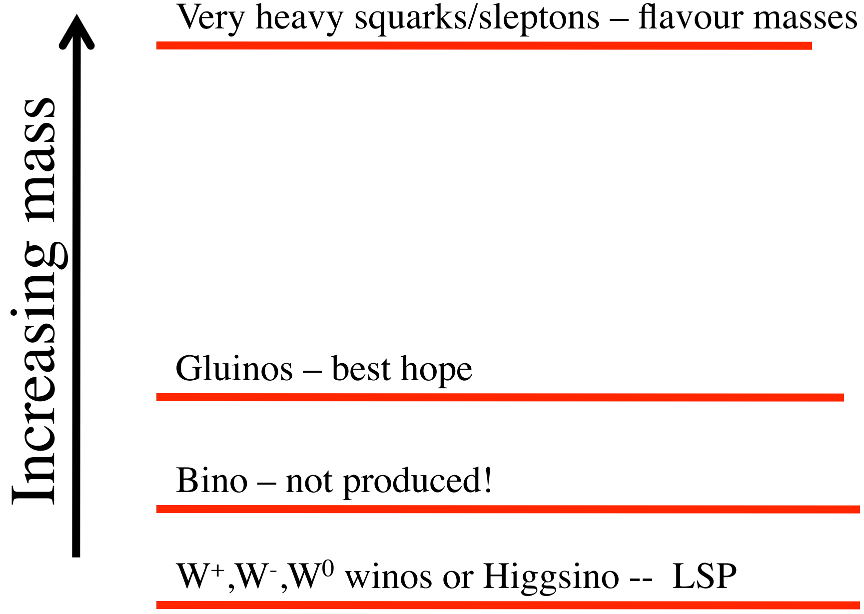
There is no trouble for split supersymmetry to accommodate a 125 GeV Higgs boson mass.

Also, note that data is not compatible with SUSY at arbitrarily high mass. (related to SM triviality bound.)

Giudice, Strumia, '11

Collider Implications of Heavy Flavor Supersymmetry

Example order of
the spectrum:



Increasing mass

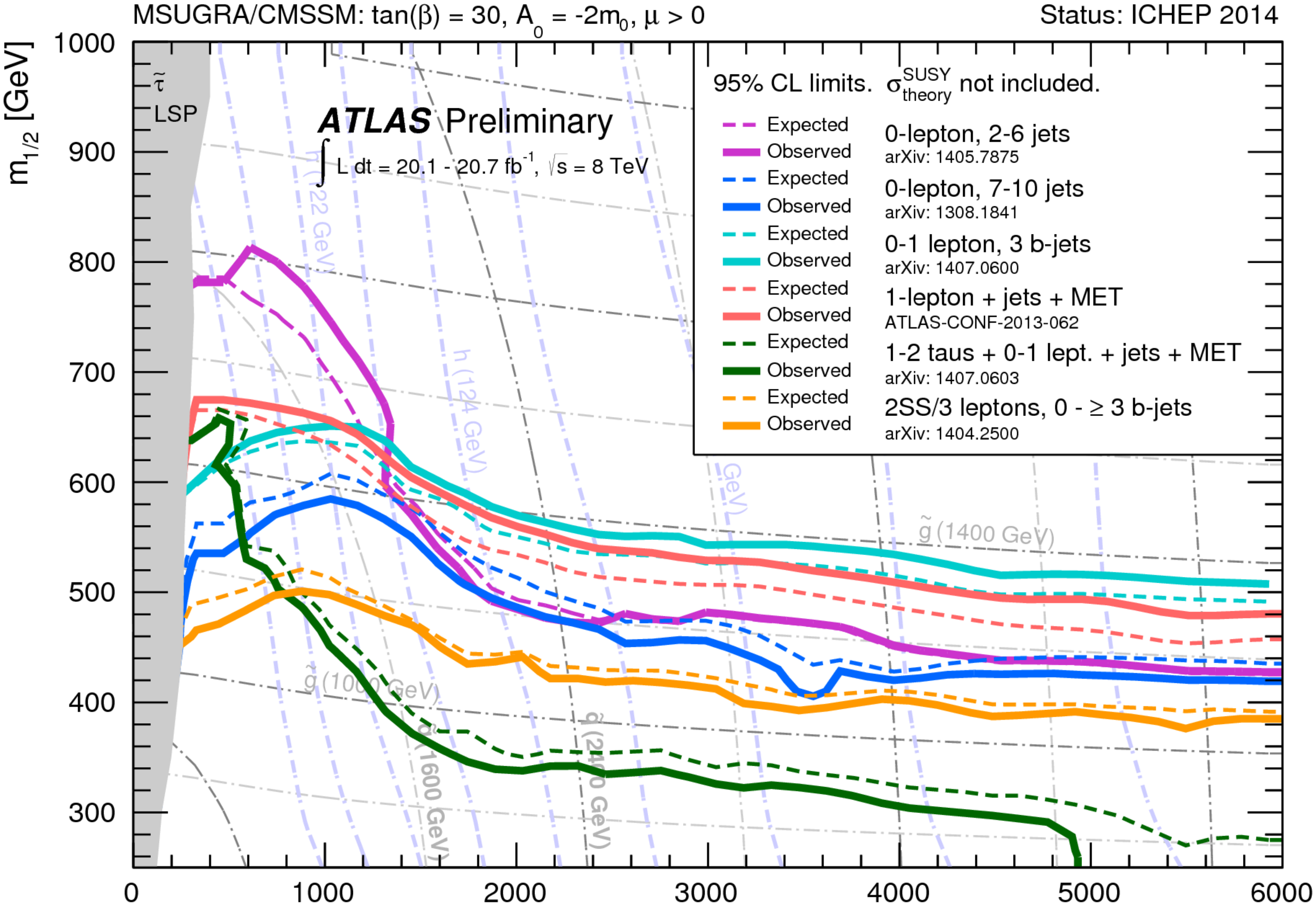
Very heavy squarks/sleptons – flavour masses

Gluinos – best hope

Bino – not produced!

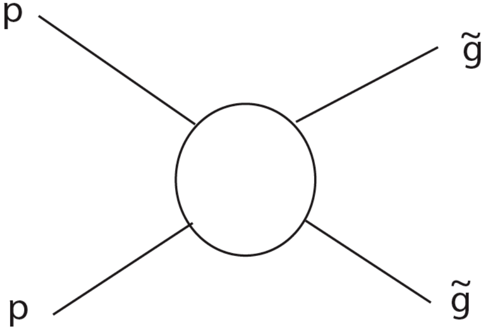
W^+,W^-,W^0 winos or Higgsino -- LSP

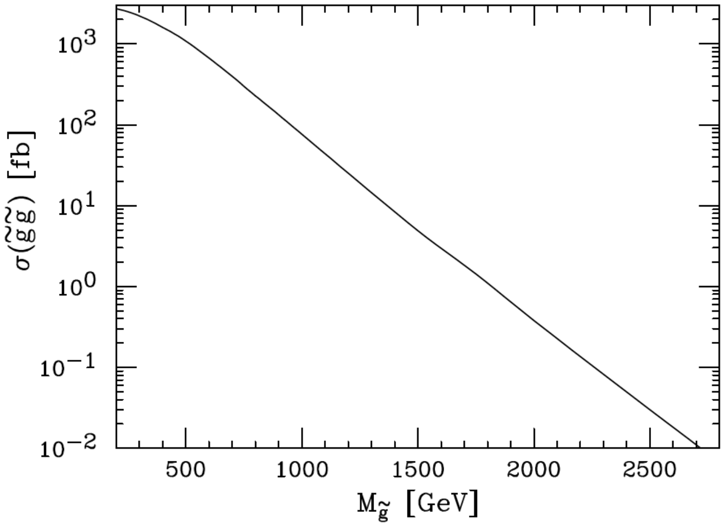
- Scalars are out of reach
- Binos are not produced
- Higgs mass of 125 GeV can be accommodated
- Wino and gluino production give colliders hope



Gluino limits (mgluino ~ $3m_{1/2}$) similar to the $m_0 >> m_{1/2}$ limit.

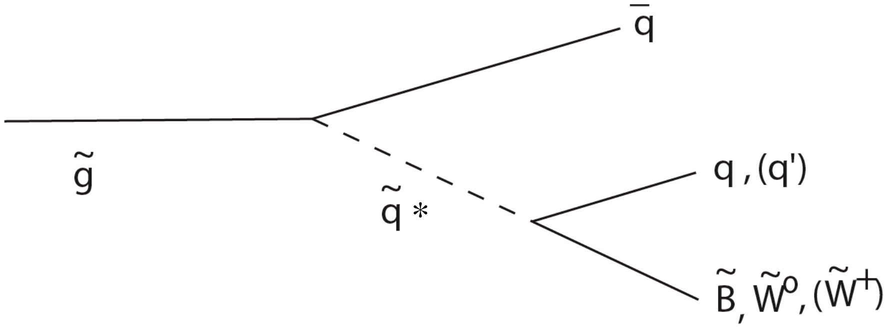
Gluino Production and Decays





Pythia output

Main decay is three-body through off-shell squark

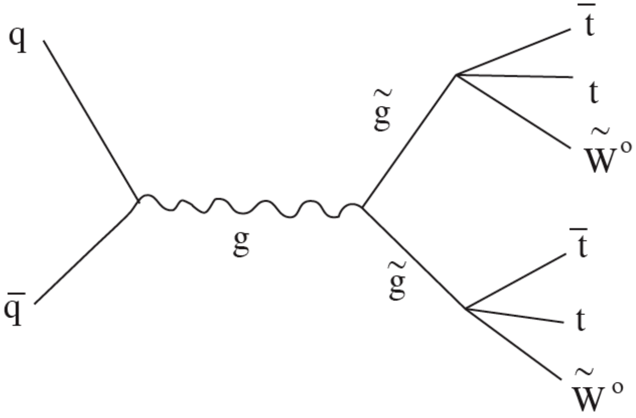


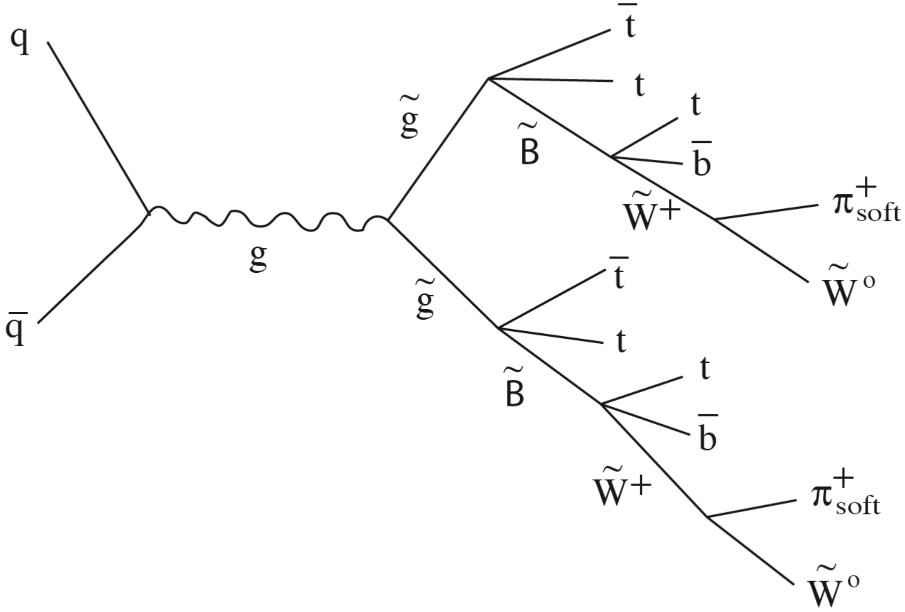
(Toharia, JW for more details on gluino decays)

S. Jung, JDW, 2014: gluino production at 100 TeV collidr

High multiplicity tops+MET events

Simplest event type: 4 top quarks plus missing energy. Can the missing energy be measured?



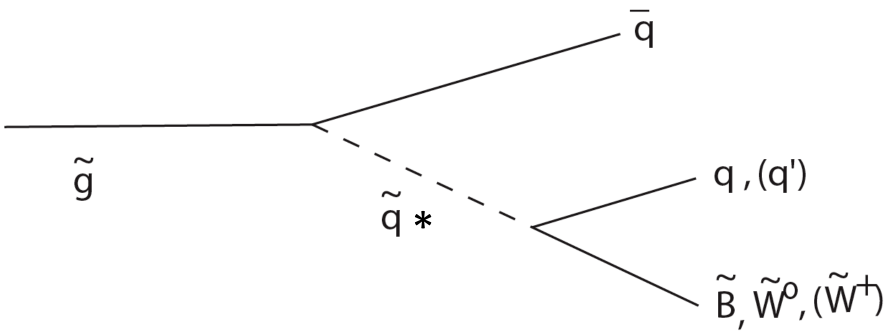


Combinatoric/experimental Challenge.

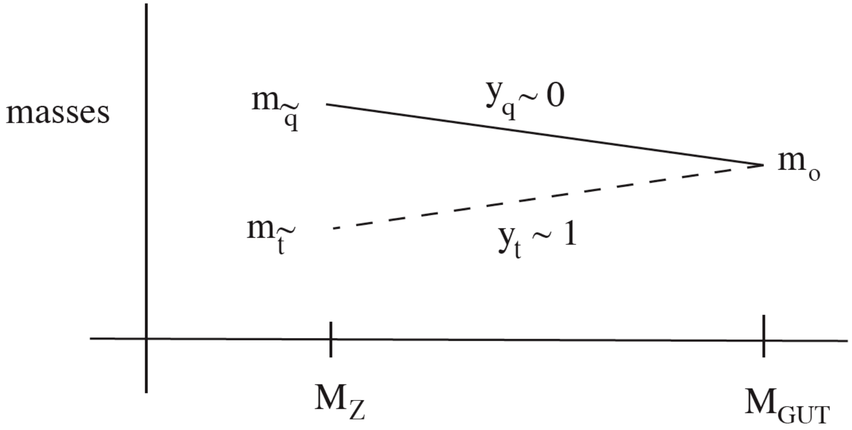
6 tops + 2 b’s + 2 pions + MET

Preference for 3rd generation

The lighter the squark
the higher the BR to
its corresponding quark



$$\frac{d\tilde{m}^2_{q_i}}{d\log Q} = -\frac{32}{3}M_3^2 + a_i y^2_{q_i}\tilde{m}^2_{q_i} + \cdots \quad (a_i \text{ is positive})$$



There is a generic
preference for decays
into 3rd generation
quarks.

Electroweakinos at future Hadron Colliders

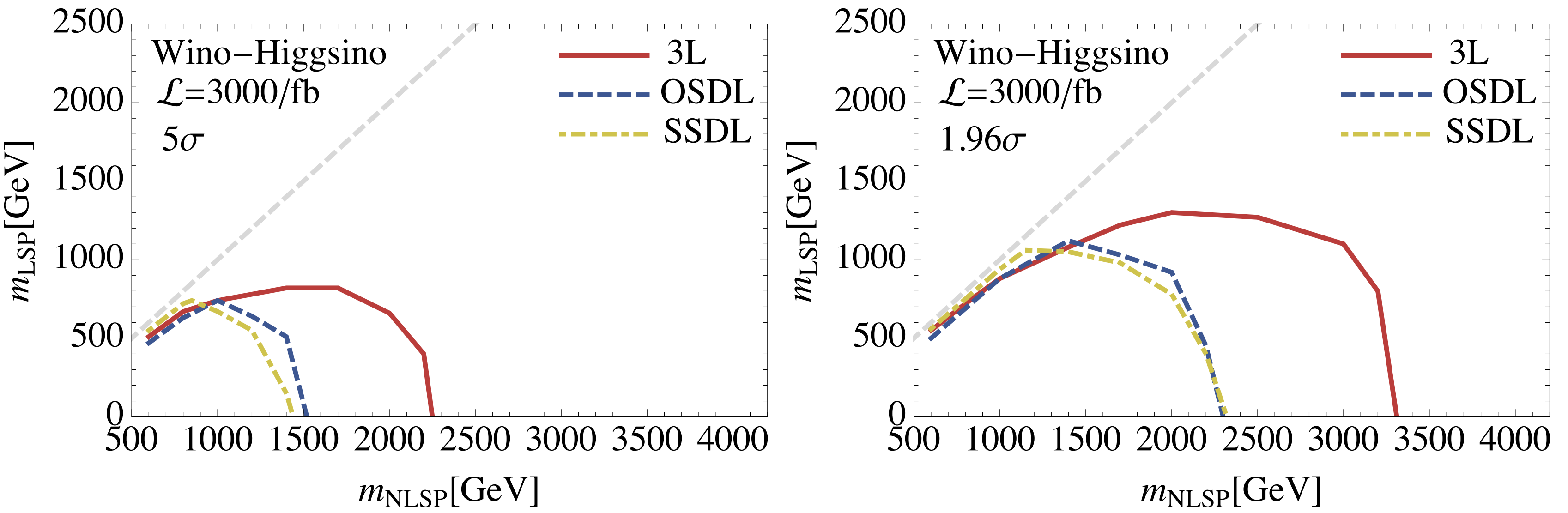


FIG. 5: 5σ discovery reaches (left panel) and 1.96σ CL exclusion limits (right panel) of the Wino-NLSP and Higgsino-LSP model from the 3ℓ (red solid), OSDL (blue dashed) and SSDL (green dot-dashed) searches.

Gori, Jung, Wang, JW, `15

Mgluino/Mwino ~ 8 in AMSB-like scenarios.

Gluino discovery/limits of ~ 20 TeV possible at 100 TeV pp collider –
This would be nearly definitive for the scenario.

Conclusions

Naturalness concerns are correlated with what else you think has in its storehouse.

Extra scalars with heavy masses are particularly lethal to stability of the electroweak theory.

Several ideas solve this problem by principles.

SUSY is a key and elegant example. Current limits not nearly significant enough to draw strong conclusions.

All principled ideas will continue to be strongly constrained or discovered by new experiment.