Non Standard (Natural) Supersymmetry

Enrico Bertuzzo

IPhT-CEA Saclay

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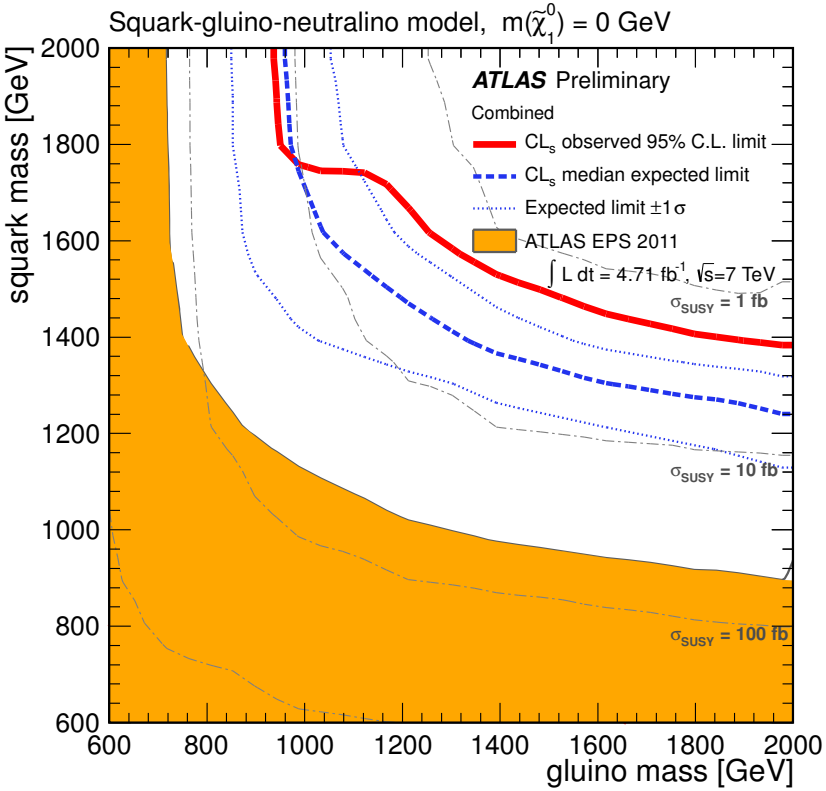
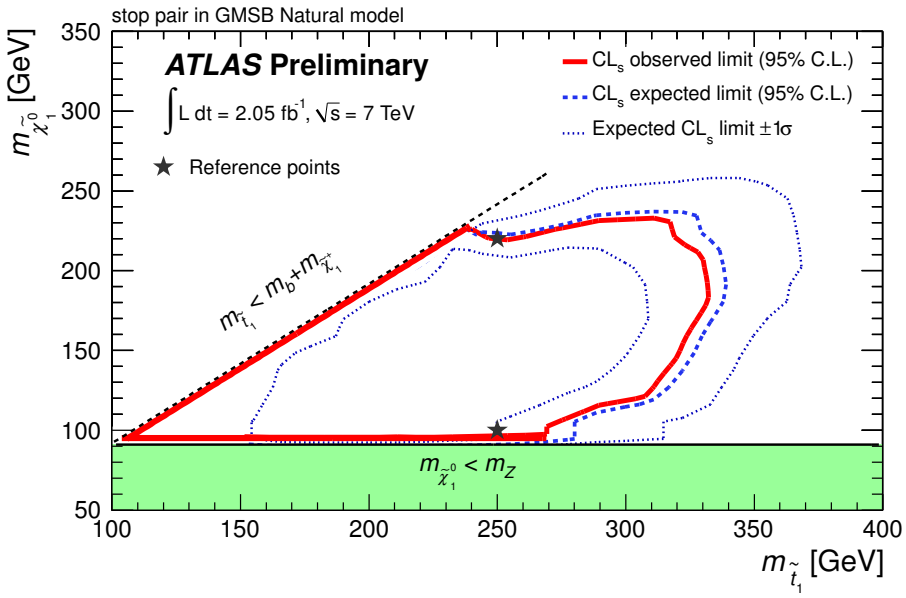
Limits on sparticles from direct searches



ATLAS-CONF-2012-033

$$m_{\tilde{q}_{1,2}} \gtrsim 1 \text{ TeV}$$



ATLAS-CONF-2012-036

[although more model dependent]

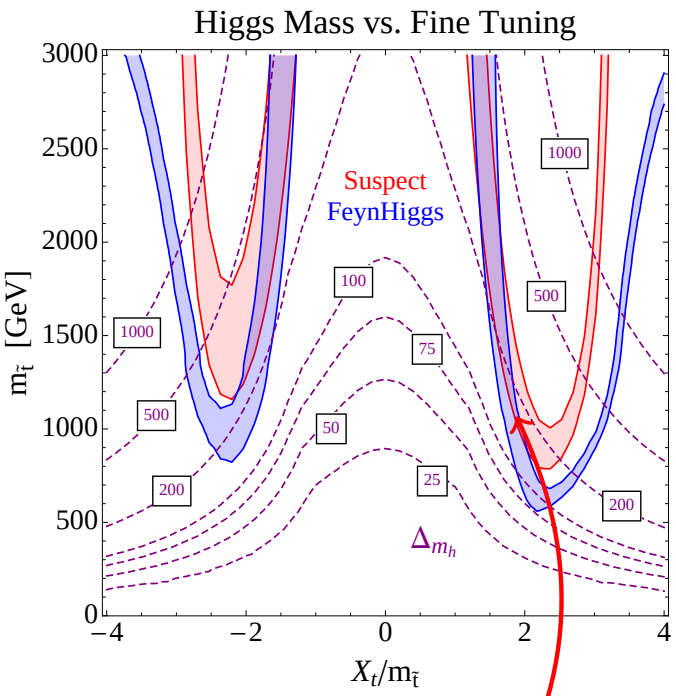
$$m_{\tilde{q}_3} \gtrsim 300 - 400 \text{ GeV}$$

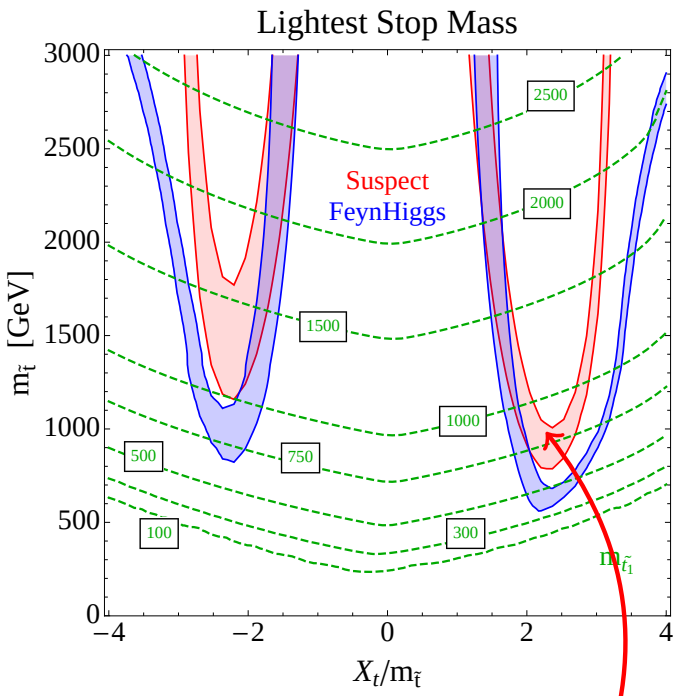
Naturalness, once again

Up to which mass the limits can go while still having a low fine-tuning in the theory?

$$
\begin{aligned}
\mu &\lesssim 200\ \mathrm{GeV}\left(\frac{m_h}{120\ \mathrm{GeV}}\right)\sqrt{\frac{\Delta}{5}} \\
\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} &\lesssim 600\ \mathrm{GeV}\frac{\sin\beta}{(1+x_t^2)^{1/2}}\sqrt{\frac{3}{\log(\Lambda/\mathrm{TeV})}}\left(\frac{m_h}{125\ \mathrm{GeV}}\right)\sqrt{\frac{\Delta}{5}} \\
M_3 &\lesssim 900\ \mathrm{GeV}\sin\beta\left(\frac{3}{\log(\Lambda/\mathrm{TeV})}\right)\left(\frac{m_h}{120\ \mathrm{GeV}}\right)\sqrt{\frac{\Delta}{5}} \\
m_{\tilde{q}_{1,2}} &\lesssim 8\ \mathrm{TeV}\left(\frac{m_h}{120\ \mathrm{GeV}}\right)\left(\frac{3}{\log(\Lambda/\mathrm{TeV})}\right)\sqrt{\frac{\Delta}{5}}
\end{aligned}
$$

A fine tuning issue, again





$m_h = 125$ GeV
fine tuning 1% or
worse

one stop light
the other heavy

Hall, Pinner, Ruderman: 1112.2703

[Improving naturalness] Increasing the tree level Higgs boson mass

Increase the Higgs quartic coupling:

- via D-terms:
  - U(1): $\mathrm{SU}(3) \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}} \times \mathrm{U}(1)_{\mathrm{X}}$

    (Batra, Delgado, Kaplan, Tait: hep-ph/0309149)
  - SU(2): $\mathrm{SU}(3) \times \mathrm{SU}(2)_{\mathrm{I}} \times \mathrm{SU}(2)_{\mathrm{II}} \times \mathrm{U}(1)_{\mathrm{Y}}$

    (Batra, Delgado, Kaplan, Tait: hep-ph/0309149)
- via F-terms: λSUSY, $W = \lambda S H_1 H_2 + f(S)$, $\lambda = 2$

  (Barbieri, Hall, Nomura, Rychkov: hep-ph/0607332)

Two possible cases:

a. What if the 125 GeV hint IS NOT the Higgs? (since only $(2-3)\sigma$s up to now...)

b. What if the 125 GeV hint IS the Higgs?

A decoupled singlet

$$W = (\mu + \lambda S) H_1 H_2 + \frac{M}{2} S^2$$

Almost decoupled Singlet $\longrightarrow$ Higgs boson couplings essentially SM-like (with a mass of $200 - 250$ GeV)

$\Rightarrow$ Excluded by LHC data

Barbieri, Hall, Nomura, Rychkov: hep-ph/0607332

Cavicchia, Franceschini, Rychkov: 0710.5750

A not so decoupled singlet

$$W = \lambda S H_1 H_2 + \frac{k}{3} S^3$$

Franceschini, Gori: 1005.1070

or again

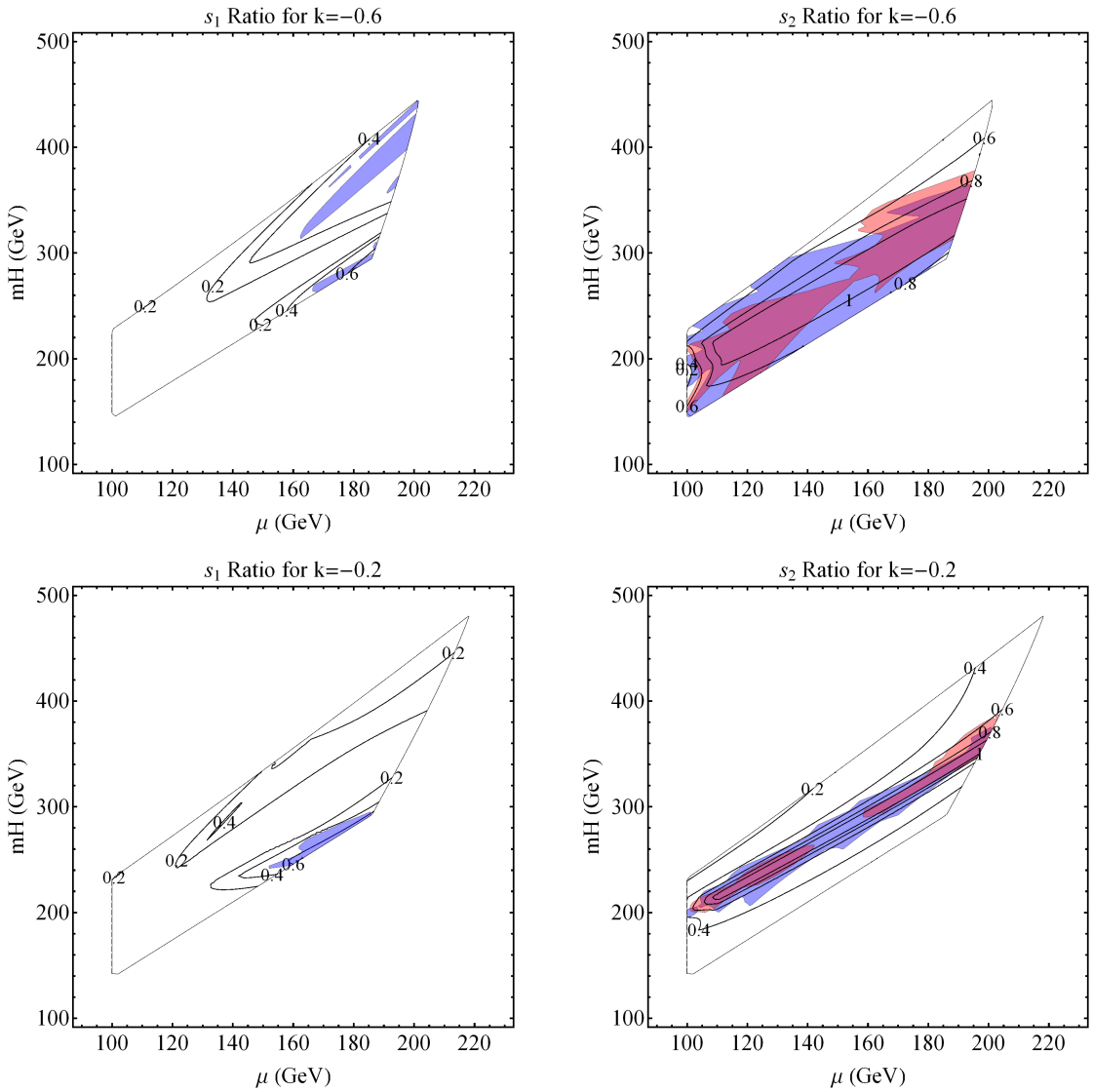
$$W = (\mu + \lambda S) H_1 H_2 + \frac{M}{2} S^2$$

Lodone: 1105.5248

Bertuzzo, Farina: 1105.5389, 1112.2190

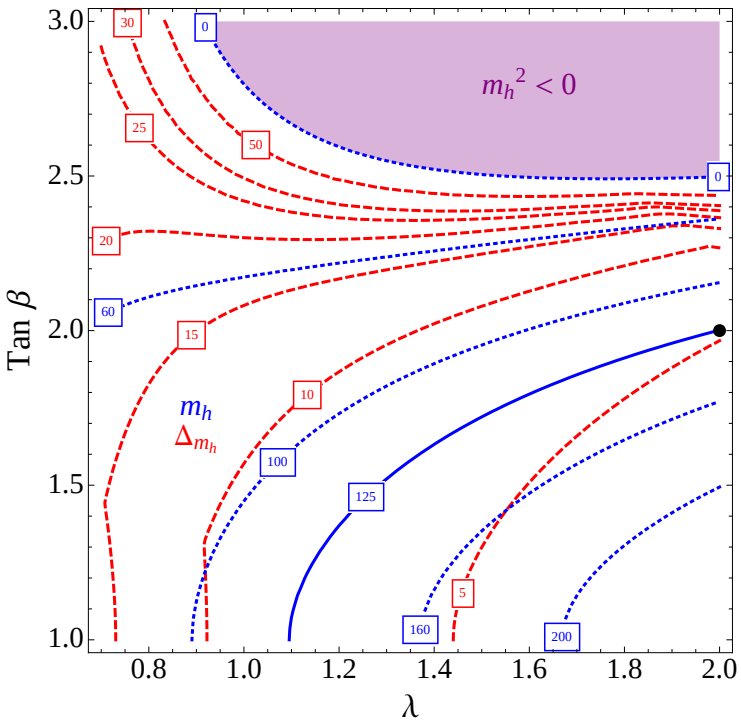
Still a heavy Higgs boson
(with a mass of $200 - 250$ GeV)
BUT
$s_{1,2,3} \to AA,\ \chi\chi$ may be open
$\downarrow$
modified BRs

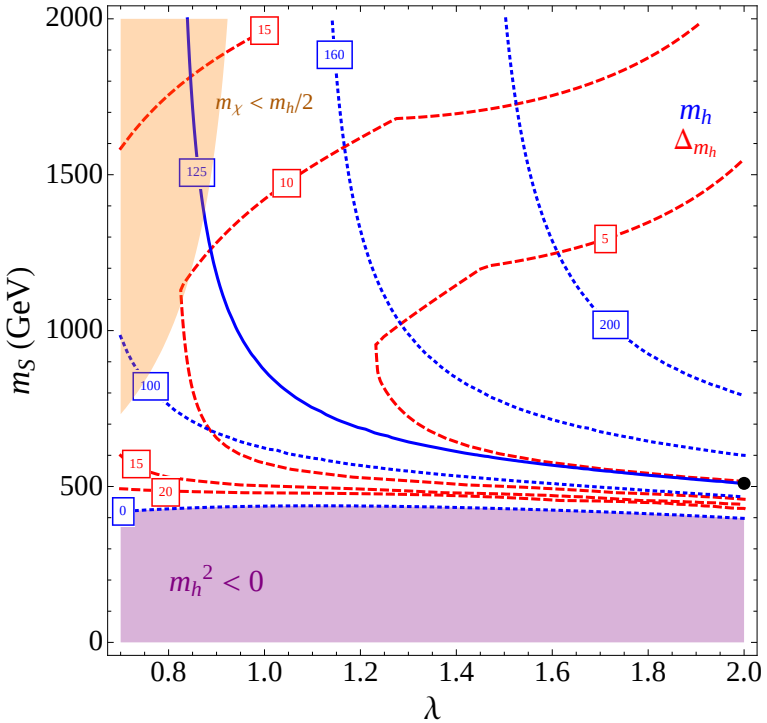
Facing the LHC: $W = \lambda S H_1 H_2 + \frac{k}{3} S^3$



Bertuzzo, Farina: 1112.2190

$$W = (\mu + \lambda S) H_1 H_2 + \frac{M}{2} S^2$$





Hall, Pinner, Ruderman: 1112.2703

$\Delta \simeq 5$ with $m_h \simeq 125$ GeV possible with level splitting.

Alternatives

How to evade limits from $nj + \not{E_T}$?

1. retain only sparticles relevant for EWSB
   $\rightarrow$ *i.e.* natural SUSY
2. most sparticles below the TeV but removing $\not{E_T}$
   $\rightarrow$ *i.e.* RPV-SUSY
3. most sparticles below the TeV but compressed spectrum
   $\rightarrow$ *i.e.* compressed SUSY
4. most sparticles below the TeV but remove $\sigma_{production}$
   $\rightarrow$ *i.e.* Dirac gauginos (Supersoft SUSY, R-symmetric models)

Maybe new "Natural SUSY" in a few months?

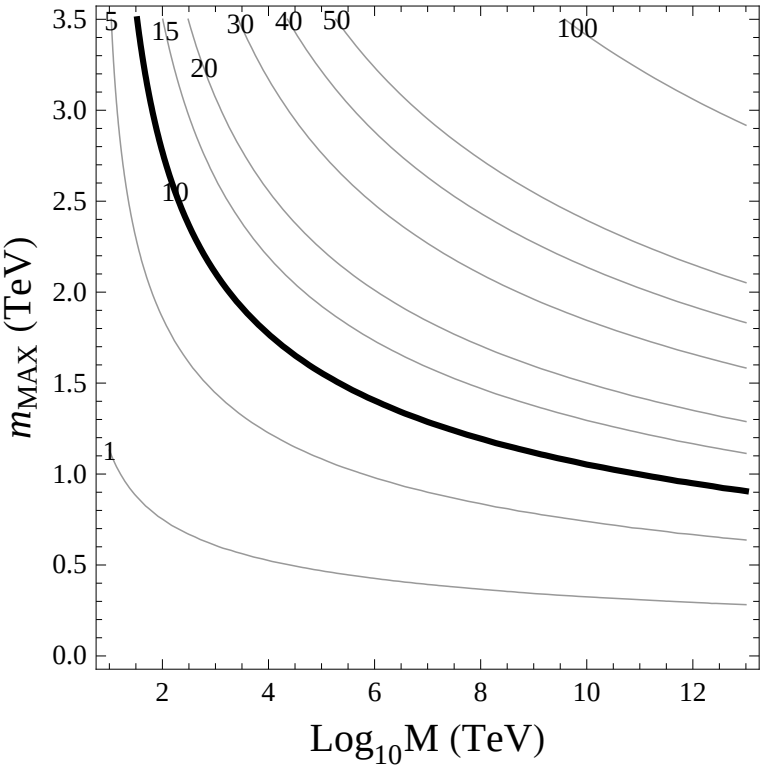
Conclusions

- Current direct limit on sparticle masses still compatible with Natural SUSY
- If we are seeing a 125 GeV Higgs boson, then standard MSSM has at least 1% fine tuning to accommodate such a large mass
- NMSSM-like theories with large Yukawa coupling between the Higgs doublets and the singlet greatly improve the naturalness of the theory
- Phenomenology:
  - IF it's not the Higgs, can explain why we haven't seen anything yet (but probably a signal around the corner)
  - IF it's the Higgs, then we can have a theory with a 20% fine tuning

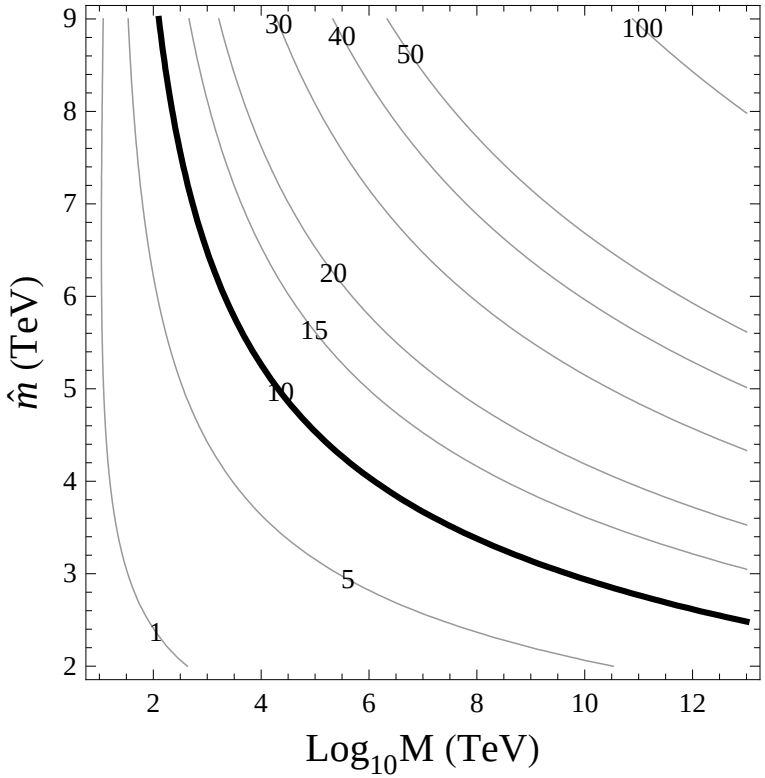
BACK UP

Naturalness bounds on $m_{\tilde{q}_{1,2}}$

Contours $= \Delta$



No condition at M
(1-loop)



Degeneracy at M
(2-loops)

$(\mathrm{tr}(Ym^2) = 0)$

Minimal Flavor Violation

- $SU(3)^3 \to$ almost degenerate squarks
  direct searches: $m_{\tilde{q}} \gtrsim 1\ \mathrm{TeV}$

  D'Ambrosio, Giudice, Isidori, Strumia (2002)

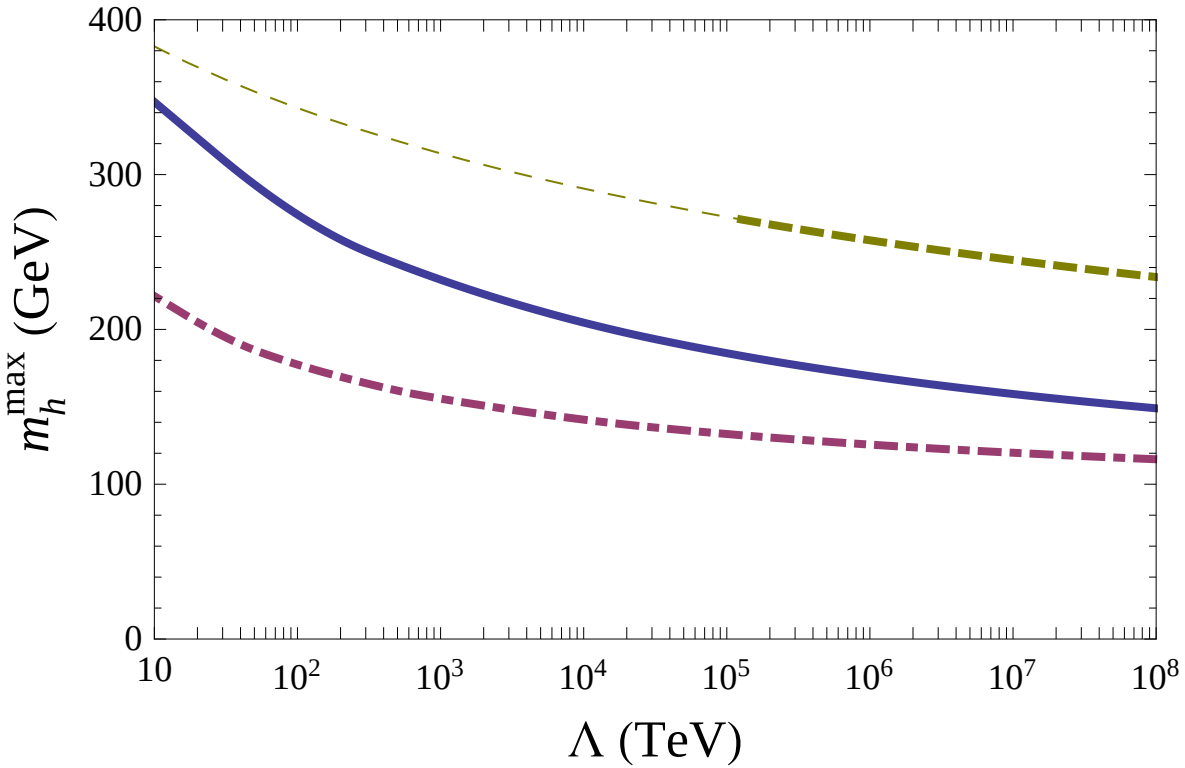
- $U(1)_{\tilde{B}_1} \times U(1)_{\tilde{B}_2} \times U(1)_{\tilde{B}_3} \times U(3)_{d_R} \to$ hierarchical spectrum
  flavor: $m_{\tilde{q}_{1,2}} \gtrsim 10\ \mathrm{TeV}$

  Barbieri, Bertuzzo, Farina, Lodone, Zhuridov (2010)

- $U(2)^3 \to$ almost degenerate $1^{st}, 2^{nd}$ generations
  flavor: $m_{\tilde{q}_{1,2}} \sim \text{few TeV}$

  Barbieri, Isidori, Jones-Perez, Lodone, Straub (2011)

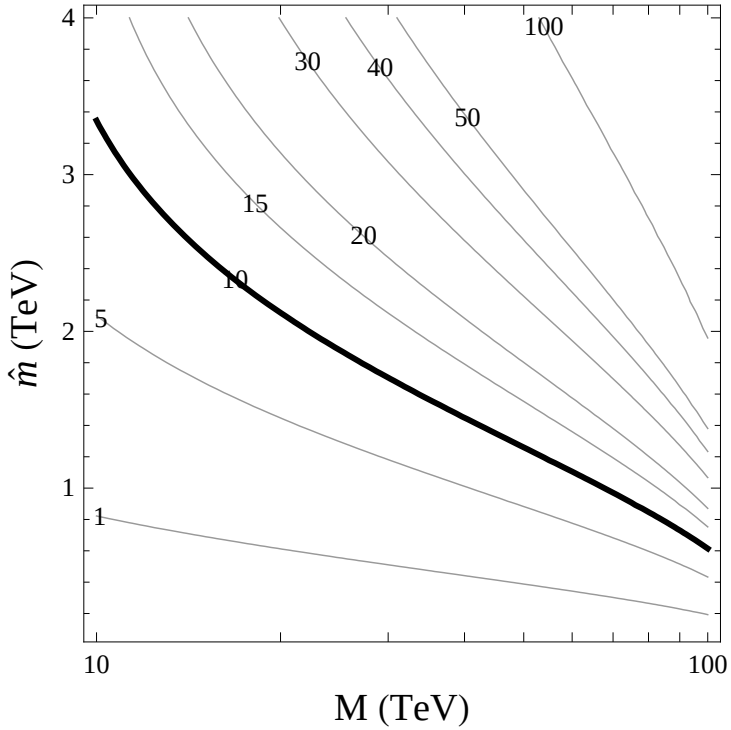
Mass of the Higgs boson



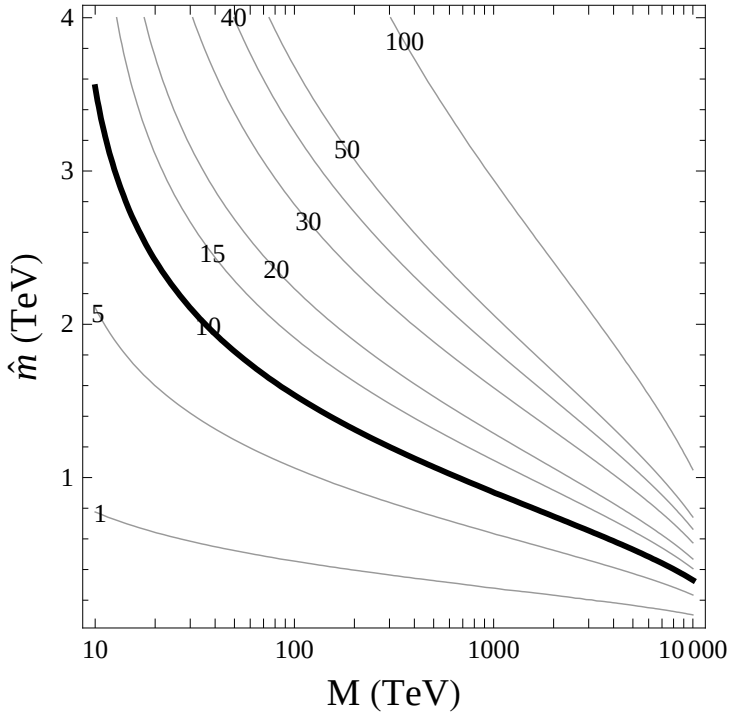
dotdashed = U(1)
solid = λSUSY
dashed = SU(2)

Λ = scale at which some coupling becomes semiperturbative

Naturalness bounds on $\tilde{q}_{1,2}$: gauge models



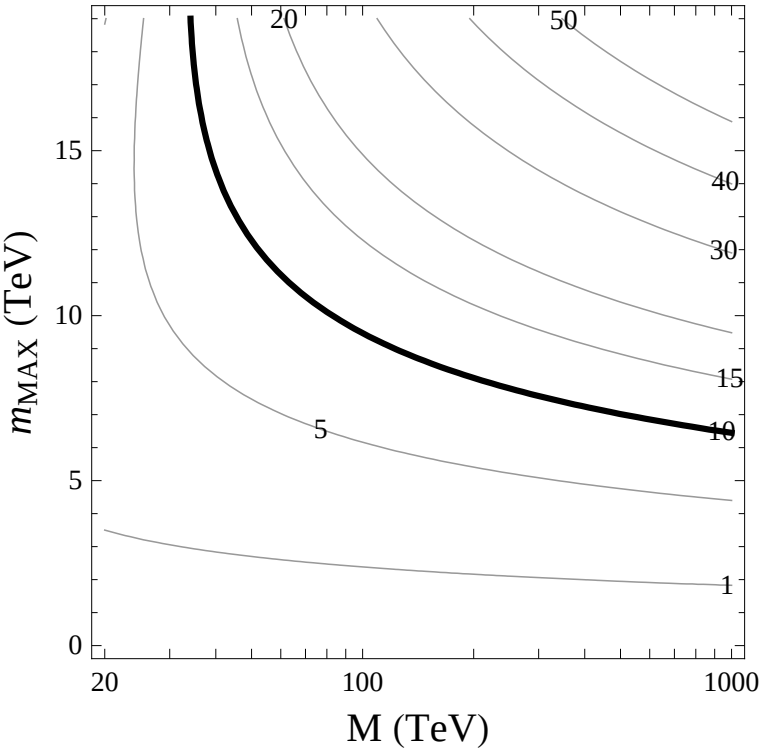
U(1) ($m_h = 180\,\mathrm{GeV}$)

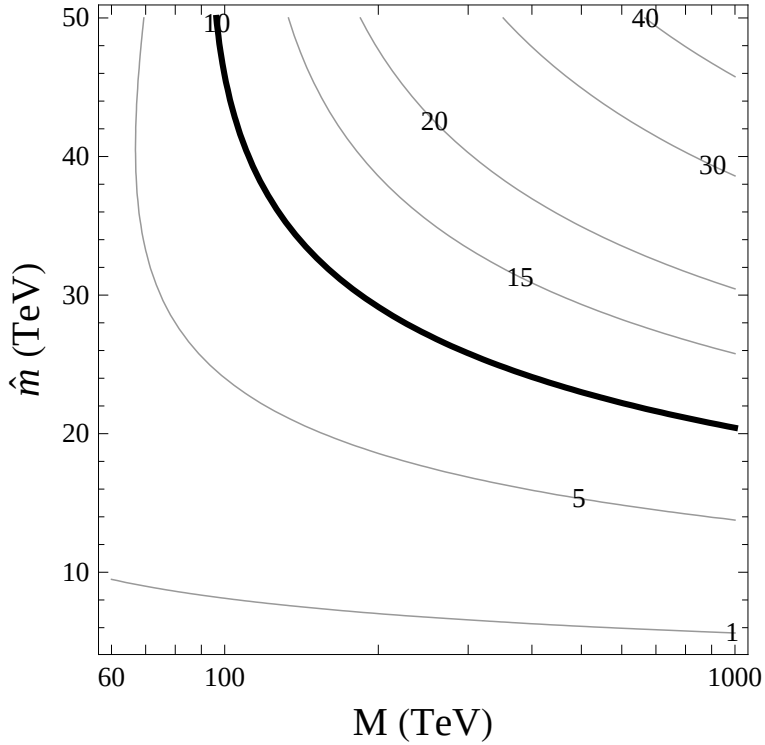


SU(2) ($m_h = 250\,\mathrm{GeV}$)

Naturalness bounds on $\tilde{q}_{1,2}$: λSUSY

$$m_h = 250 \text{ GeV}$$



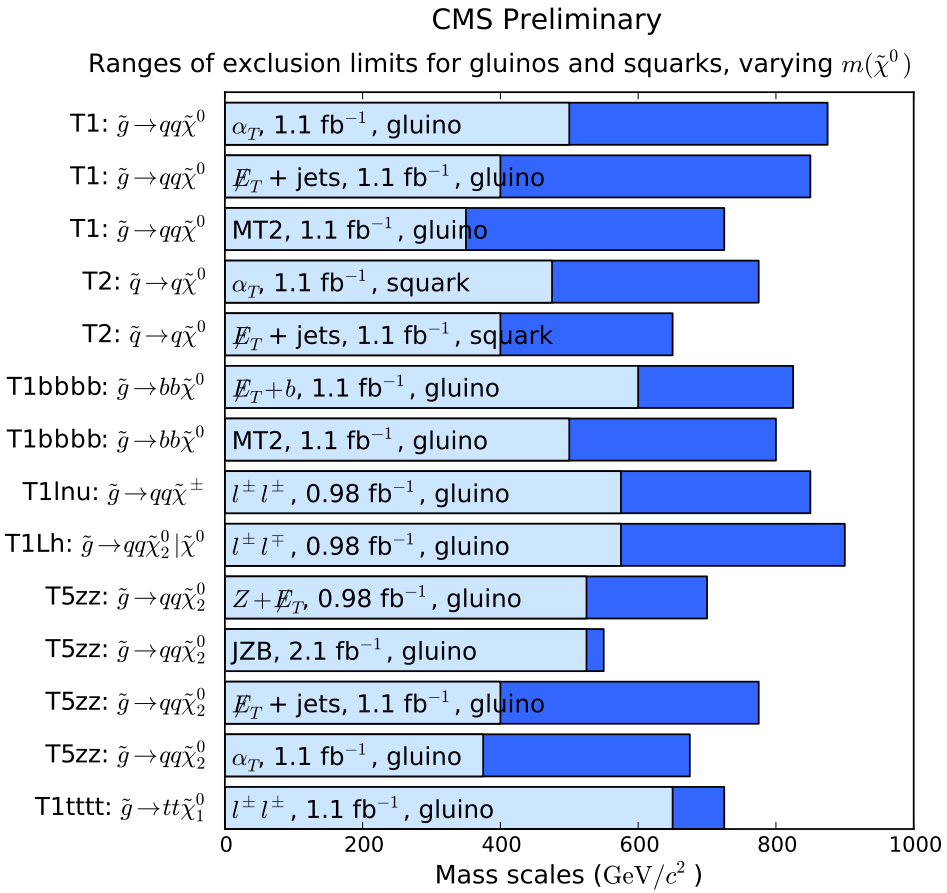


No conditions at M (1-loop)

Degeneracy at M (2-loops)

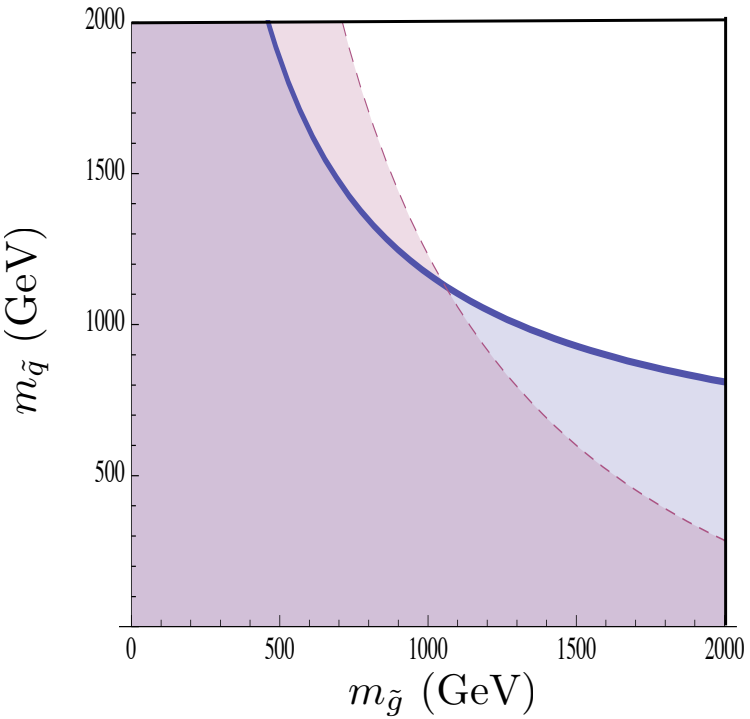
Similar bounds from color conservation

Compressed spectrum case



For limits on $m(\tilde{g})$,$m(\tilde{q})>>m(\tilde{g})$ (and vice versa). $\sigma^{\text{prod}}=\sigma^{\text{NLO-QCD}}$.
$m(\tilde{\chi}^\pm)$,$m(\tilde{\chi}_2^0)\equiv\frac{m(\tilde{g})+m(\tilde{\chi}^0)}{2}$.
$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})-200$ GeV/c^2 (light blue).

Dirac gluino



Heikinheimo, Kellerstein, Sanz (2011)

Solid $\rightarrow$ Majorana gluino

Dashed $\rightarrow$ Dirac gluino (improved naturalness)

Increased Higgs boson mass:

Upper bounds on the Higgs boson mass:

- U(1): $\mathrm{SU}(3) \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}} \times \mathrm{U}(1)_{\mathrm{X}}$

$$m_h^2 \leq (m_Z^2 + \frac{g_x^2 v^2}{2(1 + M_X^2/2M_\phi^2)}) \cos^2 2\beta$$

- SU(2): $\mathrm{SU}(3) \times \mathrm{SU}(2)_{\mathrm{I}} \times \mathrm{SU}(2)_{\mathrm{II}} \times \mathrm{U}(1)_{\mathrm{Y}}$

$$m_h^2 \leq m_Z^2 \frac{g'^2 + \eta g^2}{g'^2 + g^2} \cos^2 2\beta, \qquad \eta = \left(1 + \frac{g_l^2 M_\Sigma^2}{g^2 M_X^2}\right) / \left(1 + \frac{M_\Sigma^2}{M_X^2}\right)$$

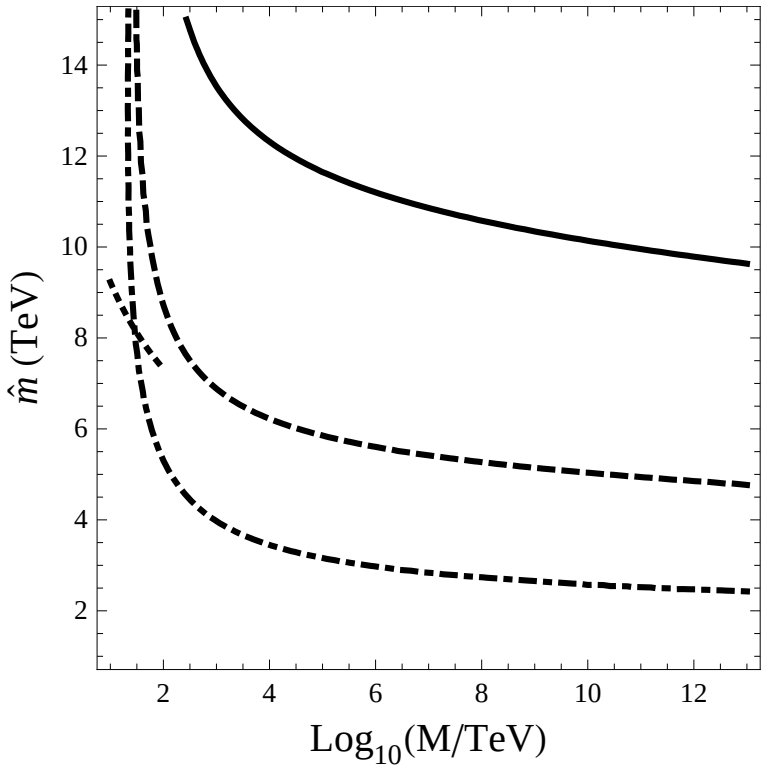
- λSUSY: $W = \lambda S H_1 H_2 + f(S)$

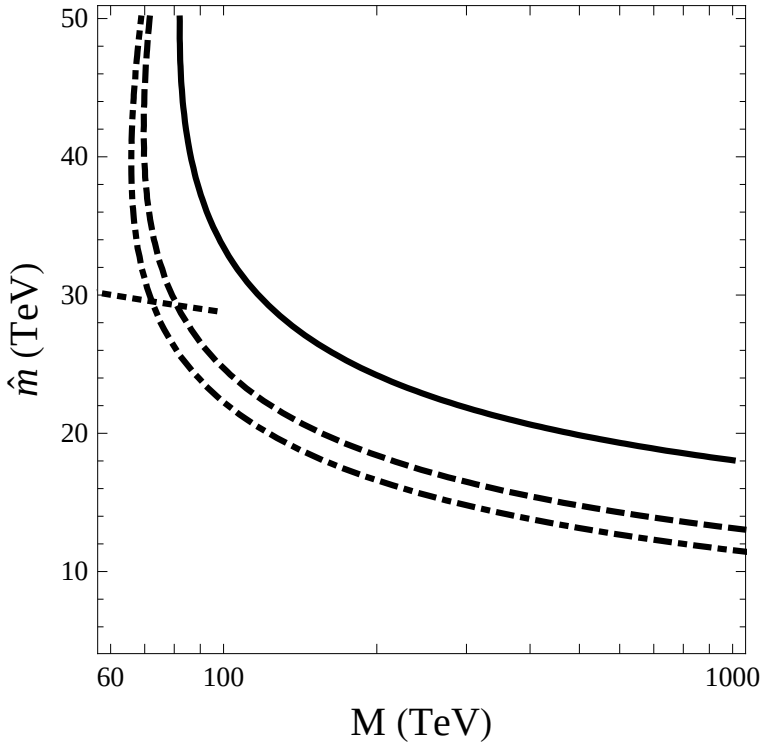
$$m_h^2 \leq m_Z^2 (\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta)$$

Color conservation

1^{st}, 2^{nd} generation of squarks $\longrightarrow$ affects evolution of $m^2_{\widetilde{u}_3}$, $m^2_{\widetilde{Q}_3}$

Colour conservation $\longrightarrow$ $m^2_{\widetilde{u}_3}$, $m^2_{\widetilde{Q}_3} \geq 0$





$m_h = m_Z$ $\qquad$ $m_h = 250$ GeV

(Solid $= m_{\widetilde{g}} = 2$ TeV, dashed $= m_{\widetilde{g}} = 1$ TeV, dotdashed $= m_{\widetilde{g}} = 500$ GeV)