The Scale-Invariant NMSSM and the 126 GeV Higgs Boson

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in collaboration with
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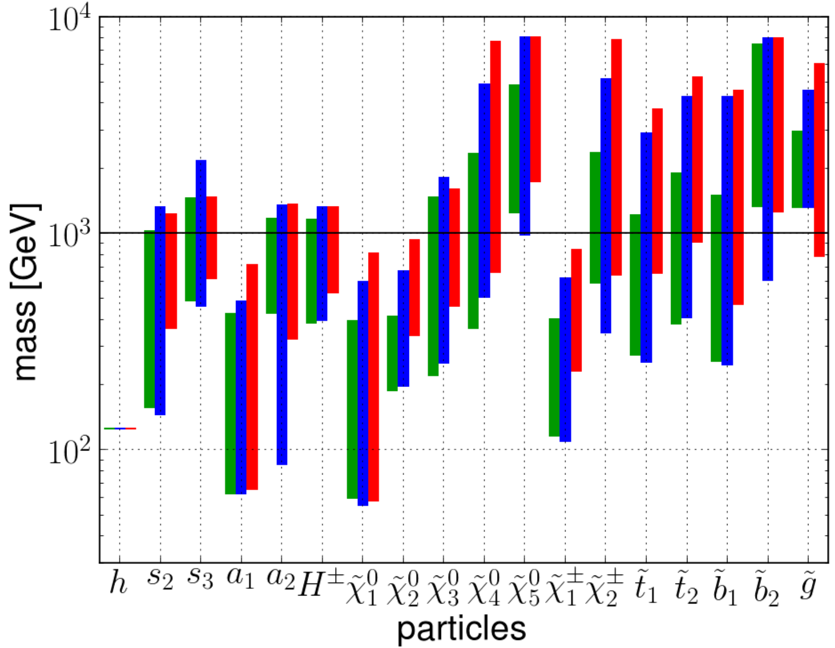


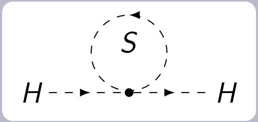
10^4
10^3
10^2
mass [GeV]
h s_2 s_3 a_1 a_2 $H^\pm$ $\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$ $\tilde{\chi}_5^0$ $\tilde{\chi}_1^\pm$ $\tilde{\chi}_2^\pm$ $\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$ $\tilde{g}$
particles

Outline

Outline

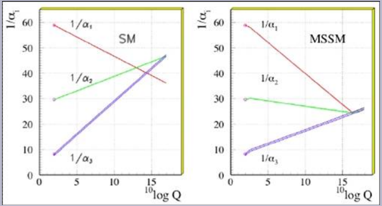
Low-energy Supersymmetry

Solution to hierarchy problem

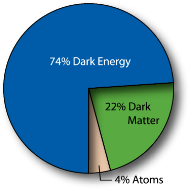


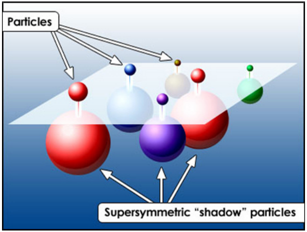
$$\Delta m_H^2 \propto \frac{\lambda_S}{16\pi^2} m_S^2$$

Gauge coupling unification



DM candidate



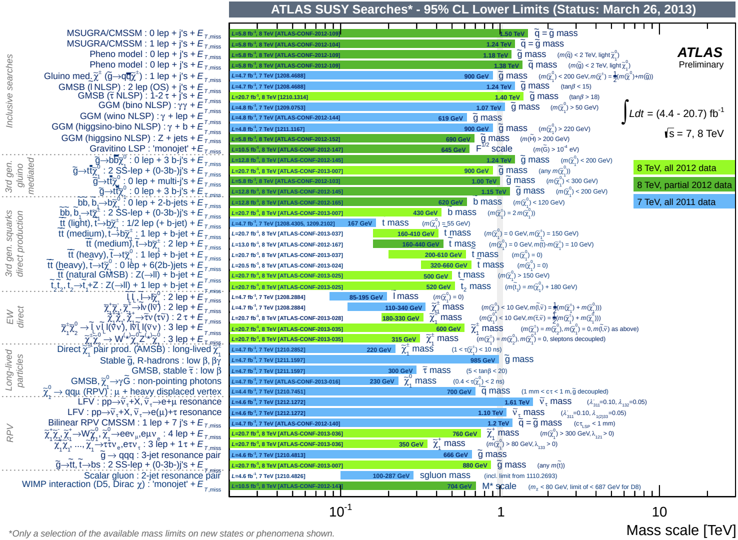


Higgs mass prediction

At tree level

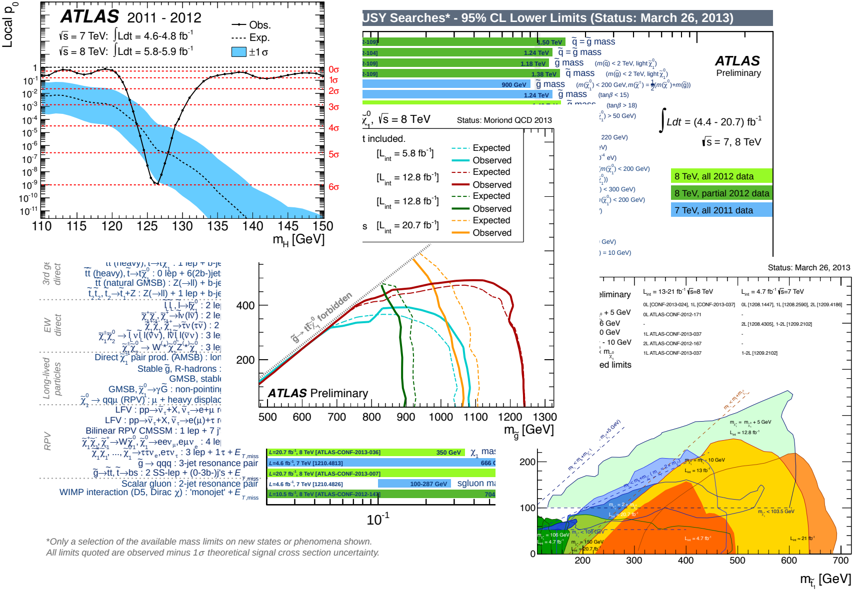
$$m_{h^0} < m_Z |\cos 2\beta|$$

After 8TeV LHC: (C)MSSM and Co.



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

After 8TeV LHC: (C)MSSM and Co.



Fine-tuning in the MSSM

- rely on loop corrections to Higgs mass from (s)top sector

$$m_h^2 = m_Z^2 \cos^2 2\beta \left(1 - \frac{3}{8\pi^2} y_t^2 t\right) + \frac{3}{4\pi^2} y_t^2 \left[\frac{1}{2} X_t + t + \ldots\right]$$

with $t = \ln \frac{m_{\text{soft}}^2}{M_t^2}$, $X_t = \frac{2(A_t - \mu \cot\beta)^2}{m_{soft}^2}\left(1 - \frac{(A_t - \mu\cot\beta)^2}{12 m_{soft}^2}\right)$, $m_{soft} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

- Large contribution to $m_{H_u}^2$ from RG evolution in the supersymmetric theory (finite corrections are small compared to RG effects for $\Lambda \gg m_{\text{soft}}$)

$$m_{H_u}^2(m_{\text{soft}}) = m_{H_u}^2(\Lambda) - \frac{3 y_t^2}{8\pi^2}\left[m_{Q_3}^2(\Lambda) + m_{u_3}^2(\Lambda) + A_t^2(\Lambda)\right] \ln\left[\frac{\Lambda}{m_{\text{soft}}}\right] + \ldots$$

Tree-level minimization conditions

$$m_Z^2 = \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\mu^2$$

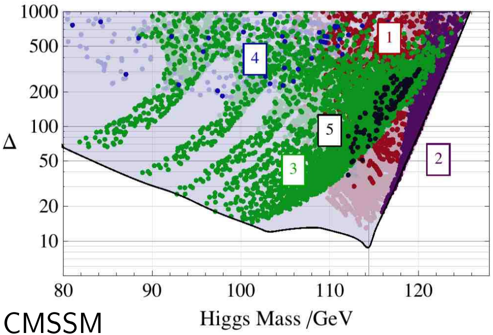
$$0 = \frac{2b}{\sin 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\mu^2$$

Fine-tuning in the MSSM 2

Finetuning measure [Barbieri, Giudice (1988)]

$$\Sigma^v = \Delta \equiv \max_{\xi} \left| \frac{\partial \ln v^2}{\partial \ln \xi(\Lambda)} \right|$$

with $\xi = (m^2_{H_u}, m^2_{H_d}, m^2_{Q_3}, m^2_{u_3}, m^2_{d_3}, A_t, A_b, M_1, M_2, M_3)$



CMSSM

[Cassel et al. 1101.4664 [hep-ph]]

- after LEP: $\Sigma^v \gtrsim 10$, i.e. 10% fine tuning
- after 8TeV LHC: $\Sigma^v \gtrsim 100$, i.e. worse than 1% fine tuning

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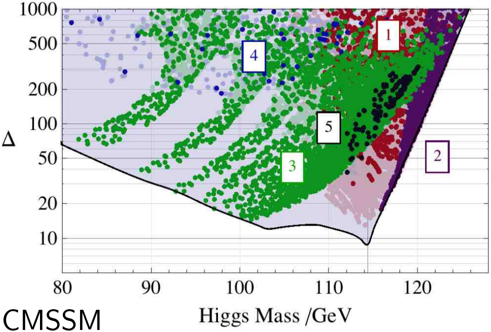

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NEVER, NEVER,
NEVER GIVE UP!

New tree-level contributions to the Higgs mass

- additional D-term contributions
- additional F-term contributions

$\rightarrow$ e.g. in the NMSSM: additional gauge singlet S

Outline

NMSSM

Superpotential

$$W_{NMSSM} = \lambda S H_d H_u + \frac{\kappa}{3} S^3$$

Soft breaking terms

$$V_{soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_s^2 |S|^2 - (a_\lambda S H_d H_u + \frac{a_\kappa}{3} S^3 + h.c.)$$

Bound on lightest Higgs mass m_h

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \rightarrow \begin{cases} m_Z^2 \cos^2 2\beta & \text{large } \tan\beta \\ \lambda^2 v^2 \sin^2 2\beta & \text{small } \tan\beta \end{cases}$$

- No gain for large $\tan\beta$ compared to MSSM $\rightarrow$ small $\tan\beta$

$\rightarrow$ relatively large $\lambda \gtrsim 0.7$ or additional stop loop contribution

$\rightarrow$ Landau pole below GUT scale

Large λ: Landau pole below GUT scale

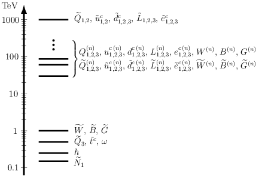
- Additional vector-like $5 + \bar{5}$ SU(5) multiplets delay Landau pole

  [Mazip, Munoz-Tapia, Pomarol (1998); Barbieri et al. (2007); Barbieri et al. (2013)]
- Strong-coupling effects might even correct for 3% discrepancy in unification [Hardy, March-Russell, Unwin (1207.1435)]
- New physics at $\Lambda \sim 10$ TeV (λSUSY [Barbieri, Hall, Nomura, Rychkov (2006)])

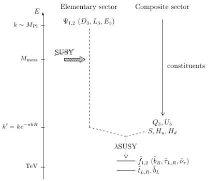
→ e.g. Fat Higgs [Harnik, Kribs, Larson, Murayama (2003)]

[Chang, Kilic, Mahbubani (2004); Delgado, Tait; Birkedal, Chacko, Nomura (2004)]

→ e.g. within extra dimensional models



[Gherghetta, v.Harling, Setzer (2011)]



[Larsen, Nomura, Roberts (2012)]

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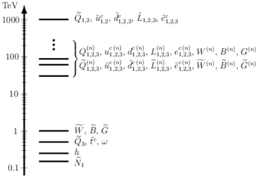

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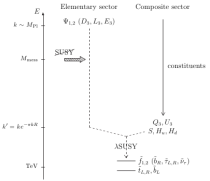

[Larsen, Nomura, Roberts (2012)]

$\rightarrow$ Our assumptions: decouple first two generations of sparticles as well as third generation of sleptons

EW symmetry breaking

MSSM minimization conditions

$$m_Z^2 = \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\mu^2$$

$$0 = m_A^2 - m_{H_u}^2 - m_{H_d}^2 - 2\mu^2$$

We obtain the following minimization conditions in the NMSSM [$\mu \equiv \lambda v_S$ and $m_A^2 \equiv \frac{2(a_\lambda + \lambda\kappa v_S)v_S}{\sin 2\beta}$]

$$m_Z^2 = \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\lambda^2 v_S^2$$

$$\lambda^2 v^2 = \frac{2(a_\lambda + \lambda\kappa v_S)v_S}{\sin 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\lambda^2 v_S^2$$

$$m_S^2 = \lambda\kappa v^2 \sin 2\beta - 2\kappa^2 v_S^2 - \lambda^2 v^2 - \frac{a_\lambda v^2}{2v_S} \sin 2\beta - a_\kappa v_S$$

Beyond tree-level

$$\mathcal{S}_{eff} = \int d^4x \left\{ \sum_{n=0}^{\infty} Z_i^n \partial_\mu \phi_i^\dagger \partial^\mu \phi_i - \sum_{n=0}^{\infty} V_n \right\}$$

The NLO corrections to the potential are given by the Coleman-Weinberg potential

$$V_1 = \frac{1}{64\pi^2} \mathrm{STr}\, M^4 \left[\ln\left(\frac{M^2}{\mu_r^2} \right) - \frac{3}{2} \right]$$

Defining

$$\widehat{m}_{H_u}^2 \equiv m_{H_u}^2 + \frac{d}{dv_u^2} V_1, \qquad \widehat{m}_{H_d}^2 \equiv m_{H_d}^2 + \frac{d}{dv_d^2} V_1, \qquad \widehat{m}_S^2 \equiv m_S^2 + \frac{d}{dv_S^2} V_1$$

the minimization conditions at NLO can be written as

$$m_Z^2 = \frac{\widehat{m}_{H_u}^2 - \widehat{m}_{H_d}^2}{\cos 2\beta} - \widehat{m}_{H_u}^2 - \widehat{m}_{H_d}^2 - 2\lambda^2 v_S^2.$$

$$\lambda^2 v^2 = 2\frac{(a_\lambda v_S + \lambda\kappa v_S^2)}{\sin 2\beta} - \widehat{m}_{H_u}^2 - \widehat{m}_{H_d}^2 - 2\lambda^2 v_S^2$$

$$\widehat{m}_S^2 = \lambda\kappa v^2 \sin 2\beta - 2\kappa^2 v_S^2 - \lambda^2 v^2 - \frac{a_\lambda v^2}{2v_S} \sin 2\beta - a_\kappa v_S$$

Fine-tuning in the NMSSM

Finetuning measure [Barbieri, Giudice (1988)]

$$\Sigma^v = \max_i \left| \frac{\partial \ln v^2}{\partial \ln \xi_i(\Lambda)} \right|$$

with $\xi_i = (m^2_{H_u}, m^2_{H_d}, m^2_S, \lambda, \kappa, a_\lambda, a_\kappa, m^2_{Q_3}, m^2_{u_3}, m^2_{d_3}, A_t, A_b, M_1, M_2, M_3)$

Finite one-loop corrections alleviate tuning by 10-20% compared to tree-level (cf. [Cassel, Ghilencia, Ross (2010)])

$$\Sigma^v = \max_i \left| \sum_j \frac{d \ln v^2}{d \ln \xi_j(m_{\text{soft}})} \frac{d \ln \xi_j(m_{\text{soft}})}{d \ln \xi_i(\Lambda)} \right|$$

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For example in the case of $m_{Q_3}^2$ neglecting finite one-loop correction:

$$\left| \frac{d \ln v^2}{d \ln m_{Q_3}^2(\Lambda)} \right| \approx \left| \frac{3 y_t^2}{8\pi^2} \frac{m_{Q_3}^2(\Lambda)}{v^2} \ln \left[\frac{\Lambda}{m_{\text{soft}}} \right] \times \frac{dv^2}{dm_{H_u}^2(m_{\text{soft}})} \right| \lesssim \Sigma^v$$

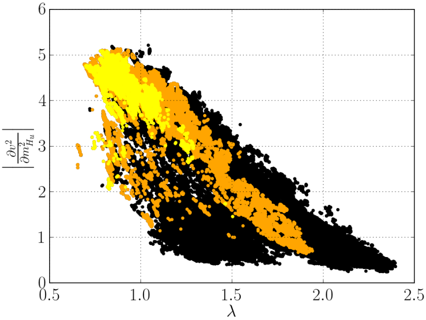
MSSM

$$\frac{dv^2}{dm_{H_u}^2(m_{\text{soft}})} = -2 \frac{v^2}{m_Z^2} + \mathcal{O}\left(\frac{1}{\tan\beta}\right)$$

NMSSM

$$\frac{dv^2}{dm_{H_u}^2(m_{\text{soft}})} = \frac{\kappa}{\lambda^3} \cot 2\beta + \mathcal{O}\left(\frac{1}{\lambda^4}\right)$$

Large λ helps



- $\frac{dv^2}{dm^2_{H_u}(m_{\text{soft}})} \sim \frac{\kappa}{\lambda^3} \cot 2\beta$

$\rightarrow$ large λ reduces finetuning

- black $\Lambda = 20$ TeV, orange $\Lambda = 100$ TeV, yellow $\Lambda = 1000$ TeV

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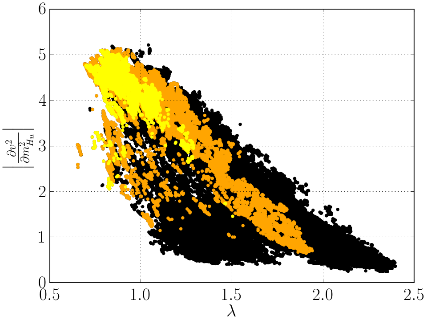

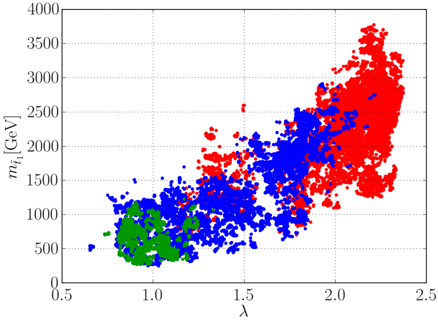

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- right: $\Sigma^v < 20$: better than 5% VEV tuning
- large λ allows larger stop masses

Large λ hurts

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta m^2_{h,\mathrm{stop}} + \delta m^2_{h,\mathrm{S}}$$

- For large λ: $\lambda v \sin 2\beta > m_h$: cancellation required
- generally $\delta m^2_{h,stop} > 0$
- partly cancelled by mixing with singlet (cf. [Agashe, Cui, Franceschini (2012)])
- In our scan, it amounts to at most 40% of $m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$

$\rightarrow$ loop corrections from Higgs-singlet sector lead to required cancellation

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Higgs mass tuning

$$\Sigma^h \equiv \max_{\xi_i} \left| \frac{d \ln m_h^2}{d \ln \xi_i} \right| \approx \max_{\xi_i} \left| \frac{\xi_i}{m_h^2} \frac{dm_{h,\mathrm{tree}}^2}{d\xi_i} \right|$$

with $\xi_i = (\lambda, \kappa, a_\lambda, a_\kappa, m_{Q_3}^2, m_{u_3}^2, m_{d_3}^2, A_t, A_b, M_1, M_2, M_3)$ and fix $v_{u,d,S}$

Large λ hurts 2

Higgs mass tuning

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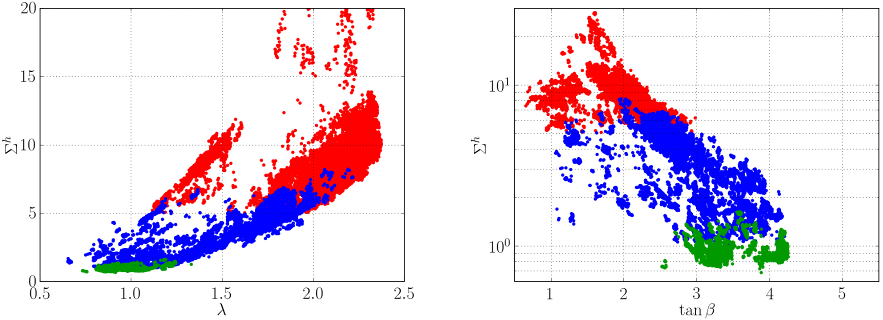
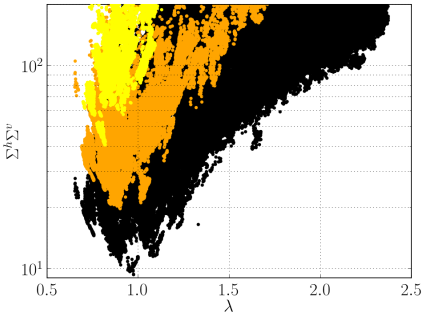


Combined fine-tuning



- In a statistical sense, if two quantities are not correlated, the probability involving both is $P(A \cap B) = P(A) * P(B)$.
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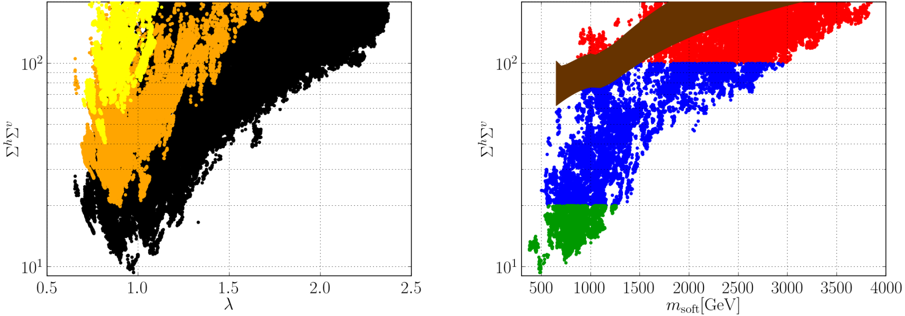

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- right: $\Sigma^v < 20$: better than 5% VEV tuning
- green $\Sigma^h\Sigma^v < 20$, blue $20 < \Sigma^h\Sigma^v < 100$, red $\Sigma^h\Sigma^v > 100$
- brown band: MSSM with $\mu = 200$ GeV, $\tan\beta = 20$ and $m_A = 1$ TeV

  [generated using FeynHiggs]

Outline

Numerical Scan

- Markov Chain Monte Carlo
- We used a modified version of NMHDECAY, which is part of NMSSMTools 3.2.1, as well as MicrOMEGAs 2.4.5 for DM
- We scanned linearly in 14-dimensional parameter space

$\tan\beta$	$\tan\beta > 0.08$	m_{Q_3}	$\Delta_{\tilde{g}} m_{Q_3} < m_{Q_3} < 5$ TeV	M_1	$0 < M_1 < 8$ TeV
μ	$\|\mu\| < 1$ TeV	m_{u_3}	$\Delta_{\tilde{g}} m_{u_3} < m_{u_3} < 5$ TeV	M_2	$0 < M_2 < 8$ TeV
λ	$0 < \lambda < 3$	m_{d_3}	$0 < m_{d_3} < 8$ TeV	M_3	0.5 TeV $< M_3 < 8$ TeV
κ	$\|\kappa\| < 2.75$	A_t	$\|\Delta_{\tilde{g}} A_t\| < \|A_t\| < 5$ TeV	v	174 GeV
A_λ	$\|A_\lambda\| < 2$ TeV	A_b	$\|A_b\| < 8$ TeV	Λ	20, 100, 1000 TeV
A_κ	$\|A_\kappa\| < 1$ TeV				

⇒ We did not sample the full parameter space. Therefore, there is no statistical interpretation of the scatter plots.

- Likelihood function: product of Gaussians for the Higgs mass centered at 126 GeV and for the VEV finetuning centered at 0.
- We impose the hard cuts summarised in the table as well as

$$|\xi(\Lambda) - \xi(m_{\text{soft}})| < |\xi(\Lambda)| \quad \text{for } \xi = m_{Q_3}^2, m_{u_3}^2, m_{d_3}^2, A_t, A_b$$

similar to "gluino sucks the stop mass up" [Arvanitaki, Craig, Dimopoulos, Villadoro(2012)]

- We conservatively impose the collider, EW precision and flavour constraints.

Electroweak Precision Tests (EWPT)

- impose EWPT at 2σ with $m_{h,ref} = 117$ GeV [PDG(2012)].

  $S_0 = -0.04 \pm 0.09$, $T_0 = 0.07 \pm 0.08$ and correlation of 88% at 95% C.L.

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- Consistent with previous analyses[Barbieri et. al.(2006); Franceschini, Gori (2010)], we find
- Higgs and singlet scalars do not contribute much to S,T
- (3rd gen) squarks: $\tan\beta$ can not be too large unless cancellation
  $\tan\beta \neq 1$ breaks custodial SU(2) $\rightarrow$ contribution to T

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- (3rd gen) squarks: $\tan\beta$ can not be too large unless cancellation
  $\tan\beta \neq 1$ breaks custodial SU(2) $\rightarrow$ contribution to T
- Neutralino/chargino sector imposes strong constraint on λ as well as $\tan\beta$

$$M_{\psi^0} = \begin{pmatrix} M_1 & 0 & -\cos\beta\sin\theta_W m_Z & \sin\beta\sin\theta_W m_Z & 0 \\ . & M_2 & \cos\beta\cos\theta_W m_Z & -\sin\beta\cos\theta_W m_Z & 0 \\ . & . & 0 & -\mu & -\lambda v\sin\beta \\ . & . & -\mu & 0 & -\lambda v\cos\beta \\ . & . & . & . & -2\frac{\kappa}{\lambda}\mu \end{pmatrix}$$

$$M_{\psi^\pm} = \begin{pmatrix} 0 & X^T \\ X & 0 \end{pmatrix} \quad \text{with} \quad X = \begin{pmatrix} M_2 & \sqrt{2}m_W\sin\beta \\ \sqrt{2}m_W\cos\beta & \mu \end{pmatrix}$$

in gauge-basis $\psi^0 = (\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$ and $\psi^\pm = (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$

- We find $\tan\beta \lesssim 5$ depending on λ

SUSY searches

Assuming a neutralino LSP, we conservatively exclude the following regions:

- gluino search: $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$ [ATLAS-CONF-2012-151]

$$m_{\tilde{g}} < 1310\ \text{GeV} \qquad \text{if} \quad m_{\tilde{\chi}_1^0} < 650\ \text{GeV}$$

- sbottom search [PDG (2012); CMS-PAS-SUS-12-028; ATLAS-CONF-2012-106]

$$m_{\tilde{b}} < 89\ \text{GeV}$$
$$150\ \text{GeV} < m_{\tilde{b}} < 650\ \text{GeV} \qquad \text{if } m_{\tilde{\chi}_1^0} < 230\ \text{GeV}$$

- stop search [PDG(2012); ATLAS (1208.1447, 1208.2590)]

$$m_{\tilde{t}} < 95.7\ \text{GeV}$$
$$220\ \text{GeV} < m_{\tilde{t}} < 500\ \text{GeV} \qquad \text{if} \quad m_{\tilde{\chi}_1^0} < 160\ \text{GeV}$$

- chargino search [PDG (2012)]

$$m_{\tilde{\chi}^\pm} < 94\ \text{GeV}$$

The neutralino/chargino searches by ATLAS/CMS did not lead to further constraints.

Higgs searches

$$R_X \equiv \frac{\sigma(h) \times BR(h \to X)}{\sigma(h_{\rm SM}) \times BR(h_{\rm SM} \to X)}$$

- Higgs resonance at 126 GeV

[ATLAS (1207.7214), ATLAS-CONF-2012-162; ATLAS-CONF-2012-170; CMS (1207.7235), CMS-HIG-12-045]

$$0.81 < R_{ZZ} < 1.32, \qquad 0.74 < R_{WW} < 1.40,$$
$$0 < R_{b\bar{b}} < 1.10, \qquad 0.27 < R_{\tau\tau} < 1.15,$$

- Heavy Higgs searches [CMS-PAS-Higgs-11-024,CMS-PAS-Higgs-11-041]

$$\frac{\sigma(s_i) \times BR(s_i \to ZZ)}{\sigma(h_{\rm SM}) \times BR(h_{\rm SM} \to ZZ)} < 0.09$$
$$\frac{\sigma(s_i) \times BR(s_i \to WW)}{\sigma(h_{\rm SM}) \times BR(h_{\rm SM} \to WW)} < 0.2$$

- Charged Higgs [PDG(2012)]

$$m_{H^\pm} \gtrsim 79.3\,\text{GeV}$$

Flavour Constraints

We use the following flavour physics constraints

- B-meson mixing [HFAG (1207.1158)]

$$\Delta M_s = (17.719 \pm 0.086)\,\mathrm{ps}^{-1}$$
$$\Delta M_d = (0.507 \pm 0.008)\,\mathrm{ps}^{-1}$$

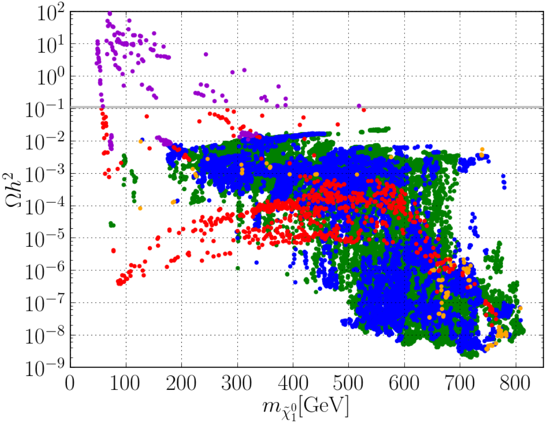
- rare B-decays [HFAG (1207.1158)]

$$\mathrm{Br}(B^+ \to \tau^+ \nu_\tau) = (1.67 \pm 0.60) \times 10^{-4}$$
$$\mathrm{Br}(B \to X_s \gamma) = (3.55 \pm 0.48 \pm 0.18) \times 10^{-4}$$

- recently measured rare decay $B_s^0 \to \mu^+\mu^-$ [LHCb (1211.2674)]

$$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = 3.2^{+3.0+1.0}_{-2.4-0.6} \times 10^{-9}$$

Dark Matter



- WMAP-7 constraint: $\Omega_{LSP} h^2 < \Omega_{WMAP-7} h^2 = 0.1120 \pm 0.0056$
- green (singlino), blue (Higgsino), orange (wino), red (bino) DM
- Purple points overclose the Universe or are excluded by XENON100

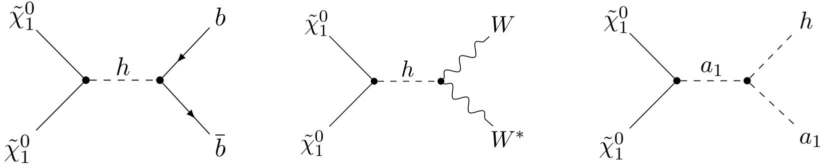
$\Rightarrow$ but they are viable if the gravitino is the LSP.

Dark Matter 2

- A mostly Bino with Higgsino admixture is viable DM candidate
- We find:
  - lightest chargino mostly Higgsino with $m_{\chi^\pm} \gtrsim 200\,\text{GeV}$
  - charged Higgs $m_{H^+} \gtrsim 750\,\text{GeV}$

$\Rightarrow$ t-channel annihilation via chargino and LSP-chargino coannihilation via charged Higgs are suppressed

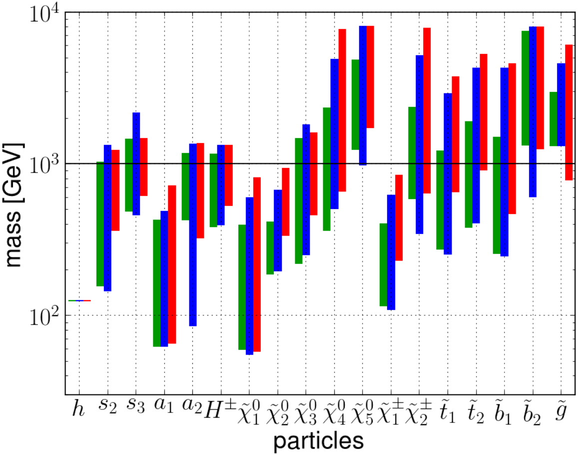
- Dominant annihilation channels:



- on resonance for CP even Higgs-mediated annihilation (p-wave)
- s-wave CP odd Higgs-mediated annihilation
- Why did we not find more points, which fit WMAP-7?

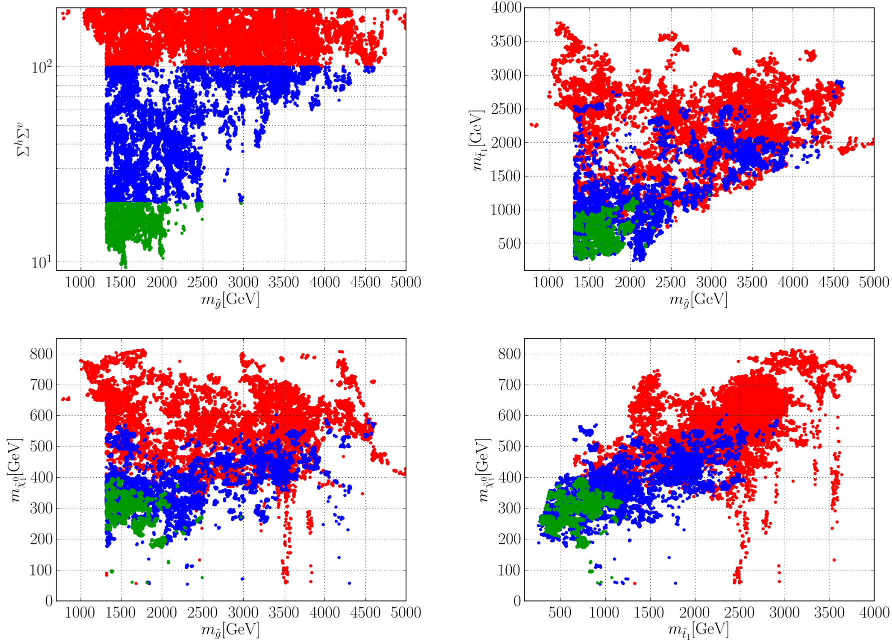
$\rightarrow$ scan linearly in parameters $\rightarrow$ large values are prefered, M_1 generally large

Particle spectrum

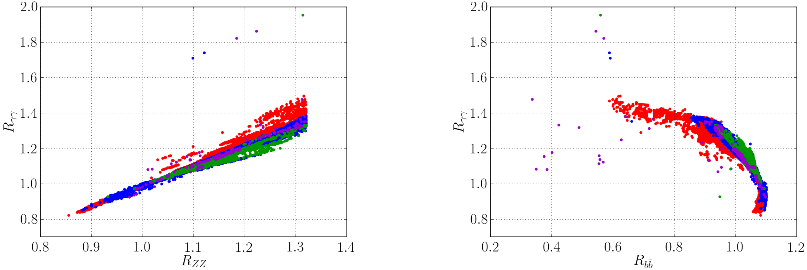


- all colored particles can be above 1 TeV with tuning better than 5%
- but light EW sector required
- due to limits on invisible widths: $m_{a_1} \gtrsim \frac{m_h}{2}$ and $m_{\tilde{\chi}_1^0} \gtrsim \frac{m_Z}{2}$ (or $\frac{m_h}{2}$)

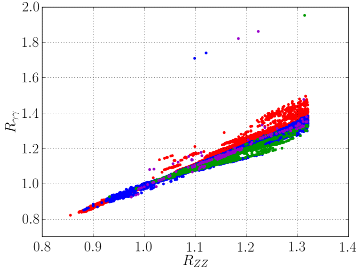
SUSY searches

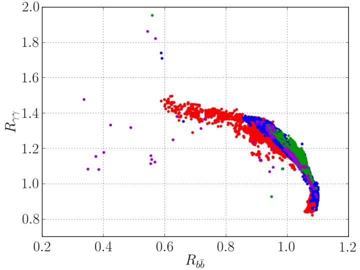


Higgs diphoton rate

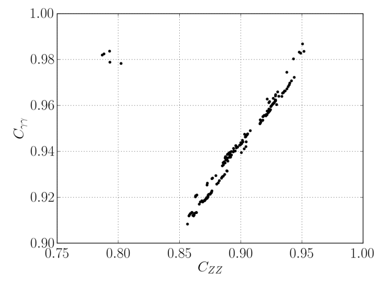


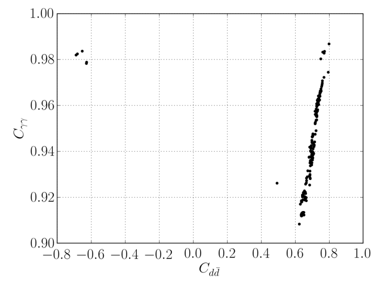
Higgs diphoton rate





Require $h \to \gamma\gamma$ to be within 1σ: $1.40 < R_{\gamma\gamma} < 1.99$





Outline

Conclusions

- natural SUSY is not excluded (yet)
- TeV-scale stop masses allowed with 5% tuning for a cutoff scale of 20 TeV
- a large value of λ reduces tuning in Higgs VEV, Σ^v
- but introduces an additional tuning in the Higgs mass, Σ^h

$\Rightarrow$ consider combined tuning $\Sigma^v \Sigma^h$

Conclusions

- natural SUSY is not excluded (yet)
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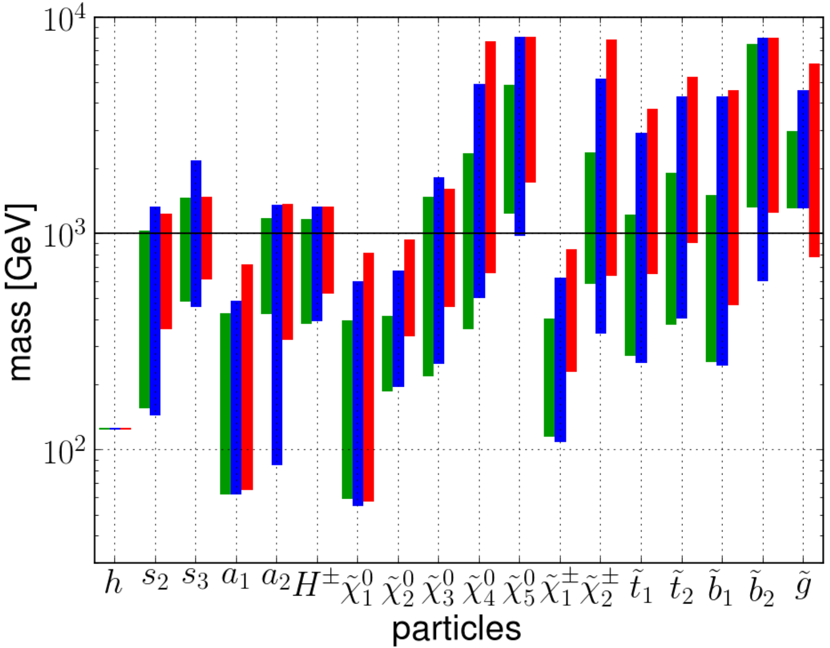
Particle spectrum

We find for the particle spectrum with a combined tuning, $\Sigma^v \Sigma^h$, better than 5(1)% with $\Lambda = 20$ TeV

- lightest stop $m_{\tilde{t}_1} \lesssim 1.2(2.6)$ TeV
- gluino masses $m_{\tilde{g}} \lesssim 3.0(4.6)$ TeV
- lightest EW sparticles (charginos/neutralinos) $m_{\tilde{\chi}} \lesssim 400(600)$ GeV

$\rightarrow$ We have to wait for the 14 TeV LHC



10^4
10^3
10^2
mass [GeV]
h s_2 s_3 a_1 a_2 $H^\pm$ $\tilde{\chi}^0_1$ $\tilde{\chi}^0_2$ $\tilde{\chi}^0_3$ $\tilde{\chi}^0_4$ $\tilde{\chi}^0_5$ $\tilde{\chi}^\pm_1$ $\tilde{\chi}^\pm_2$ $\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$ $\tilde{g}$
particles