Implications of a SM like Higgs for a natural NMSSM with low cutoff

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in collaboration with
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[to appear soon]

Outline

1. Introduction/Motivation
2. Framework
3. Results
4. Conclusions

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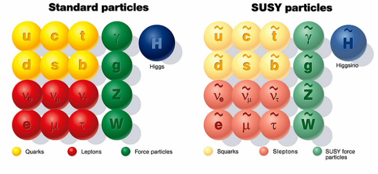
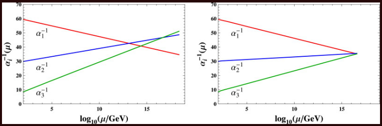
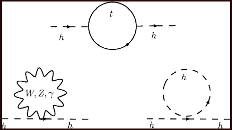
Low-energy Supersymmetry – MSSM



gauge coupling unification



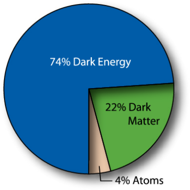
solution to hierarchy problem



$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \ln\frac{\Lambda_{UV}}{m_S} + \dots\right]$$

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{16\pi^2}\left[\Lambda_{UV}^2 + \dots\right]$$

DM candidate

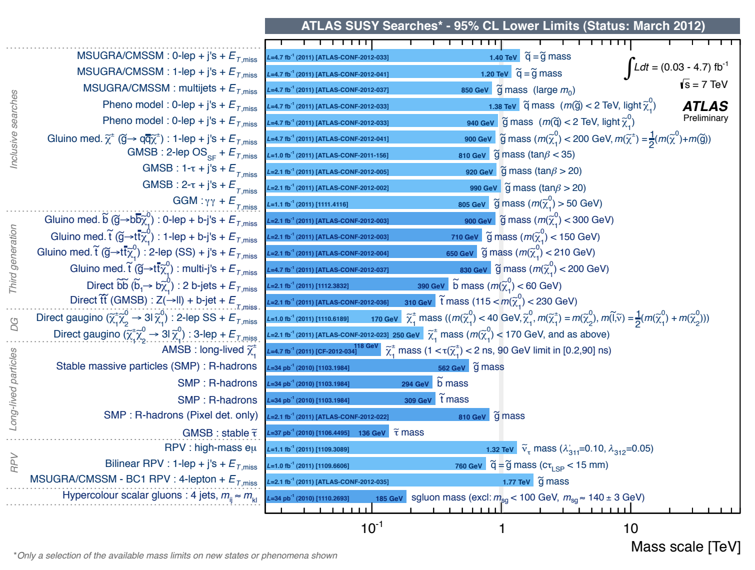


Higgs mass prediction

At tree level

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

LHC constraints



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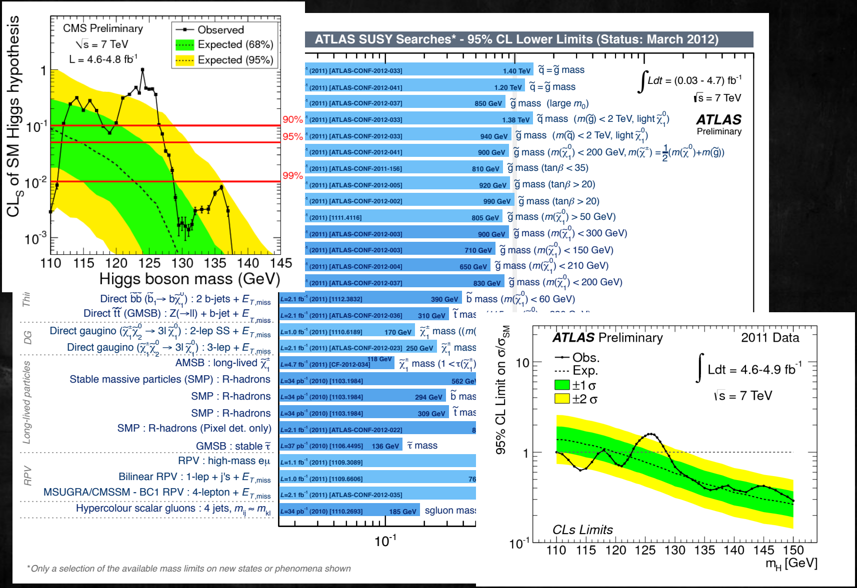

Status of low-energy supersymmetry

- strong limits on squark and gluino masses (mostly in CMSSM/simplified models)
- relatively large Higgs mass

$\rightarrow$ large loop correction to Higgs mass needed

$\rightarrow$ fine tuning

$\Rightarrow$ Simplest SUSY models in bad shape

Barbieri-Giudice fine-tuning measure

[Barbieri/Giudice (1988)]

$$\Sigma_\xi^v \equiv \left| \frac{d \log m_Z^2}{d \log \xi} \right| = \left| \frac{\xi}{m_Z^2} \frac{d m_Z^2}{d\xi} \right| < \Sigma \, ,$$

measures the sensitivity of the weak scale (or m_Z) to the dimensionful parameters ξ of the theory

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measures the sensitivity of the weak scale (or m_Z) to the dimensionful parameters ξ of the theory

How viable is natural low-energy SUSY?

Saving SUSY

Drop one of the assumptions in the (C)MSSM

- give up on small fine-tuning

→ landscape, anthropic principle, . . .

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- Extend MSSM to modify Higgs mass prediction, more specifically raise Higgs mass

$\rightarrow$ e.g. at tree level in NMSSM: introduce gauge singlet S

Literature: NMSSM and 125 GeV

- "A Natural SUSY Higgs Near 126 GeV"
  L. J. Hall, D. Pinner and J. T. Ruderman.
  arXiv:1112.2703 [hep-ph]
  JHEP **1204**, 131 (2012)
- "Higgs bosons near 125 GeV in the NMSSM with constraints at the GUT scale"
  U. Ellwanger and C. Hugonie.
  arXiv:1203.5048 [hep-ph]
- "The 125 GeV Higgs in the NMSSM in light of LHC results and astrophysics constraints"
  D. A. Vasquez, G. Belanger, C. Boehm, J. Da Silva, P. Richardson and C. Wymant.
  arXiv:1203.3446 [hep-ph]
- "A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM"
  J. Cao, Z. Heng, J. M. Yang, Y. Zhang and J. Zhu.
  arXiv:1202.5821 [hep-ph]
  JHEP **1203**, 086 (2012)
- "NMSSM Higgs Benchmarks Near 125 GeV"
  S. F. King, M. Muhlleitner and R. Nevzorov.
  arXiv:1201.2671 [hep-ph]
  Nucl. Phys. B **860**, 207 (2012)
- "The Constrained NMSSM and Higgs near 125 GeV"
  J. F. Gunion, Y. Jiang and S. Kraml.
  arXiv:1201.0982 [hep-ph]
  Phys. Lett. B **710**, 454 (2012)
- "A Higgs boson near 125 GeV with enhanced di-photon signal in the NMSSM"
  U. Ellwanger.
  arXiv:1112.3548 [hep-ph]
  JHEP **1203**, 044 (2012)
- "The fine-tuning of the generalised NMSSM"
  G. G. Ross and K. Schmidt-Hoberg.
  arXiv:1108.1284 [hep-ph] "The generalised NMSSM at one loop: fine tuning and phenomenology"
  G. G. Ross, K. Schmidt-Hoberg and F. Staub.
  arXiv:1205.1509 [hep-ph]
- ...

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Superpotential

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

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

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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

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- No gain for large $\tan\beta$ compared to MSSM
- small $\tan\beta \Rightarrow$ large $\lambda \gtrsim 0.7$ or additional stop loop contribution

$\rightarrow$ Landau pole below GUT scale $\rightarrow$ low cutoff required

NMSSM with low cutoff $\Lambda = 10\,\mathrm{TeV}$

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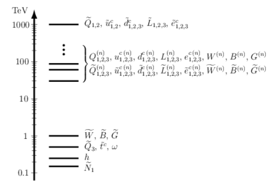
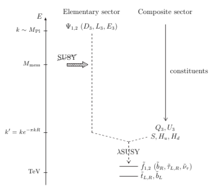


[Gherghetta, v.Harling, Setzer (2011)]



[Larsen, Nomura, Roberts (2012)]

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[Harnik, Kribs, Larson, Murayama; Chang, Kilic, Mahbubani; Delgado, Tait; Birkedal, Chacko, Nomura]

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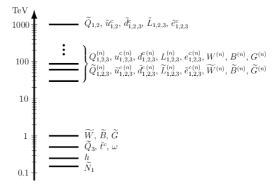

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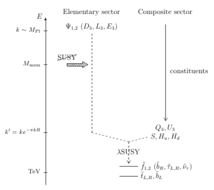

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Our Study

- Aim: Find the "Golden Region" of small fine-tuning (better 10%), i.e. the natural region of parameter space in the NMSSM
- assuming "SM-like" Higgs with $m_h \approx 125\,\text{GeV}$ [$(124 - 126)\,\text{GeV}$]

Our Study

Assumptions

- Cutoff $\Lambda = 10\,\text{TeV}$
- no CP violation
- First two generations of squarks and all sleptons decoupled
- impose LEP bounds on particle masses
- Neutralino LSP (EW gauginos not decoupled)
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Analysis

- Markov-Chain Monte-Carlo (MCMC)
- with modified version of NMHDECAY [Ellwanger, Gunion, Hugonie]
- No Landau pole below the cutoff scale $\Lambda = 10\,\text{TeV}$
- Electroweak precision test: S and T taking into account
  - Neutralino-Chargino sector
  - Higgs sector
  - T in stop-sbottom sector (S is small [Barbieri, Hall, Nomura, Rychkov])

Analysis

- Input values are specified at

$$M_{SUSY}^2 = \frac{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 + m_{\tilde{b}_1}^2 + m_{\tilde{b}_2}^2}{4}$$

- range of input values:

$$\begin{aligned}
0\,\text{TeV} &< M_1,\ M_2 < 3\,\text{TeV} \\
700\,\text{GeV} &< M_3 < 3\,\text{TeV} \\
0\,\text{TeV} &< m_{Q_3},\ m_{u_3},\ m_{d_3} < 3\,\text{TeV} \\
-3\,\text{TeV} &< A_\lambda,\ A_\kappa,\ A_t,\ A_b < 3\,\text{TeV} \\
\lambda &> 0 \\
a_\kappa = \kappa\, A_\kappa &\geq 0 \\
\tan\beta &> 0.5
\end{aligned}$$

Fine-Tuning

Loop corrected Minimisation Conditions

$$v_u(Q)\left(m_{H_u}^2+\mu_{eff}^2+\lambda^2 v_d(Q)^2+\frac{g_1^2+g_2^2}{4}\left(v_u(Q)^2-v_d(Q)^2\right)\right)=v_d(Q)\mu_{eff}B_{eff}-\frac{1}{2}\frac{\partial\Delta V_{eff}}{\partial v_u(Q)}$$

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$$s(Q)\left(m_S^2+\kappa A_\kappa s(Q)+2\kappa^2 s^2(Q)+\lambda^2(v_u^2(Q)+v_d^2(Q)-2\lambda\kappa v_u(Q)v_d(Q)\right)=\lambda A_\lambda v_u(Q)v_d(Q)-\frac{1}{2}\frac{\partial\Delta V_{eff}}{\partial s(Q)}$$

with $\mu_{eff}=\lambda s(Q)$, $B_{eff}=A_\lambda+\kappa s(Q)$ and

$$v_u(Q)=v_u/\sqrt{Z_{H_u}} \qquad v_d(Q)=v_d/\sqrt{Z_{H_d}} \qquad s(Q)=s/\sqrt{Z_s}$$

- Three minimisation conditions result in linear system of equations for $\frac{dv^2}{d\xi}$, $\frac{d\tan\beta}{d\xi}$ and $\frac{ds}{d\xi}$.
- which determines the usual fine-tuning: $\Sigma_\xi^v \equiv \left|\frac{\xi^2}{v^2}\frac{dv^2}{d\xi^2}\right| < \Sigma$

Fine-Tuning 2

- Are the parameters at the SUSY scale fine-tuned?

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Quantum Corrections between SUSY scale and cutoff Λ

For example stop contribution to m_{H_u}:

$$\delta m_{H_u}^2 \approx \frac{3}{16\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + A_t^2\right) \log\left[\frac{\Lambda^2}{M_{SUSY}^2}\right]$$

- Are the parameters at the SUSY scale fine-tuned?
- Consider fine-tuning measure for each dimensionful coupling

$$\text{e.g. } \Sigma_{m_{Q_3}^2}^{m_{H_u}^2} \equiv \frac{m_{Q_3}^2}{m_{H_u}^2} \frac{d\delta m_{H_u}^2}{dm_{Q_3}^2}$$

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- Fine-tuning of EW scale with respect to $m_{Q_3}^2$:

$$\left|\Sigma_{m_{Q_3}^2}^{v}\right| \approx \left|\Sigma_{m_{Q_3}^2}^{v,MC} + \sum_i \frac{m_{Q_3}^2}{v^2}\frac{dv^2}{d\xi_i}\frac{d\delta\xi_i}{dm_{Q_3}^2}\right| = \left|\Sigma_{m_{Q_3}^2}^{v,MC} + \sum_i \Sigma_{m_{Q_3}^2}^{\xi_i}\Sigma_{\xi_i}^{v,MC}\right| < \Sigma$$

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- Hence, the overall fine-tuning of the EW scale is given by

$$\Sigma^v \equiv max_i\left|\Sigma_{\xi_i}^{v}\right|$$

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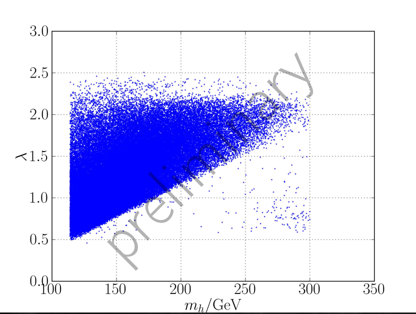
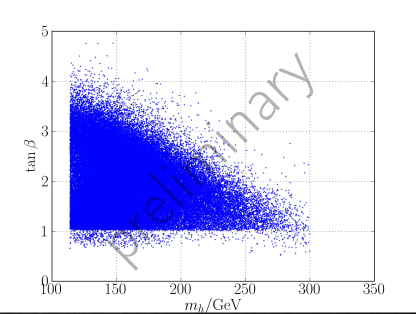
Higgs mass





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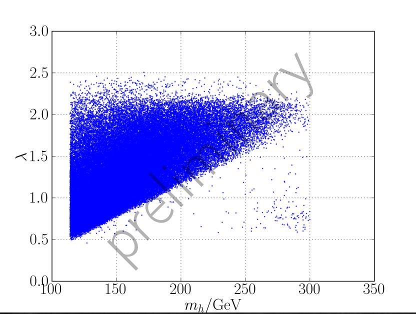

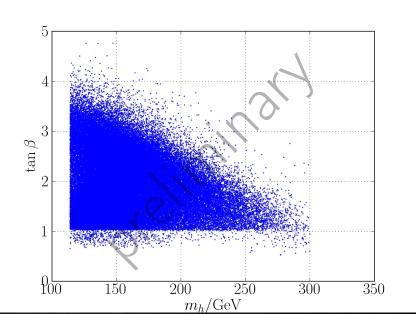

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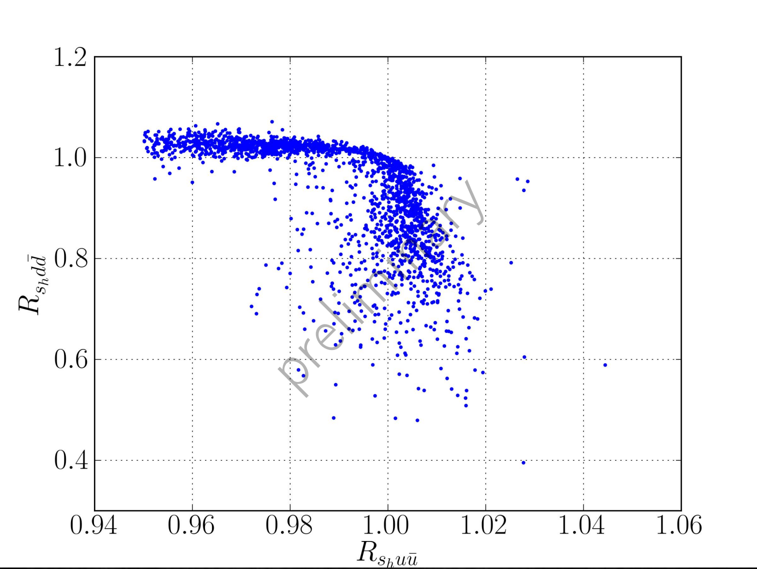
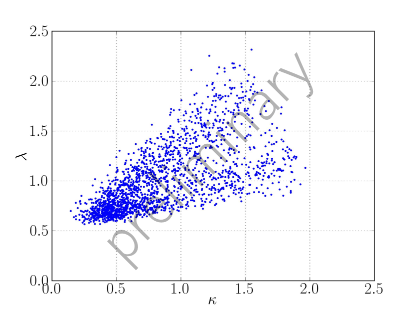
In the following

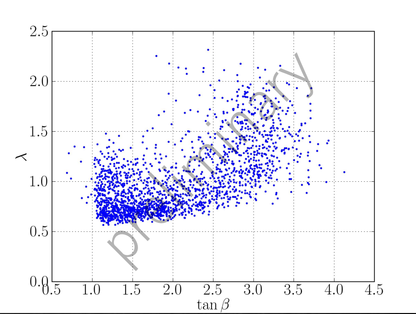
- $124\,\text{GeV} < m_h < 126\,\text{GeV}$
- "SM-like" Higgs: $|R_{ZZh} - 1| < 0.05$ and $|R_{u\bar{u}h} - 1| < 0.05$

Higgs couplings



$\lambda - \kappa$





- $0.6 \lesssim \lambda \lesssim 2.3$
- $\lambda \sim \kappa$
- running of κ stronger than $\lambda \Rightarrow \max \kappa < \max \lambda$
- $\tan \beta$ bounded due to contribution to T parameter

Neutralinos and T parameter

Neutralinos

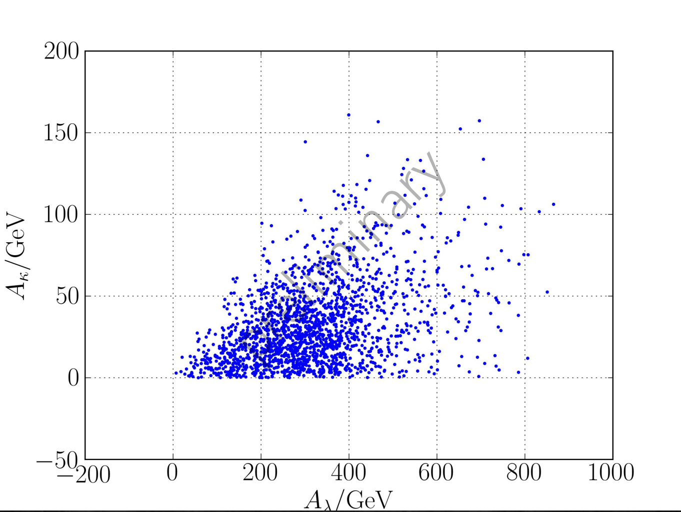
$$\begin{pmatrix} M_1 & 0 & -\cos\beta\sin\theta_W m_Z & \sin\beta\sin\theta_W m_Z & 0 \\ . & M_2 & \cos\beta\cos\theta_W m_Z & -\sin\beta\cos\theta_W m_Z & 0 \\ . & . & 0 & -\mu & -\lambda v\sin\beta \\ . & . & -\mu & 0 & -\lambda v\cos\beta \\ . & . & . & . & -2\frac{\kappa}{\lambda}\mu \end{pmatrix}$$

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

- $\tan\beta \lesssim 5$ limited by stop contribution to T [Barbieri, Hall, Nomura, Rychkov]

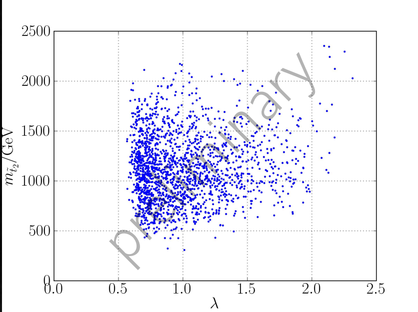
$\rightarrow$ Higgsino-Singlino mixing restricted

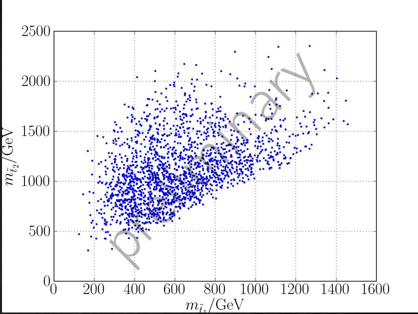
$A_\lambda - A_\kappa$



- small A terms: $A_\kappa \lesssim A_\lambda < 1$ TeV

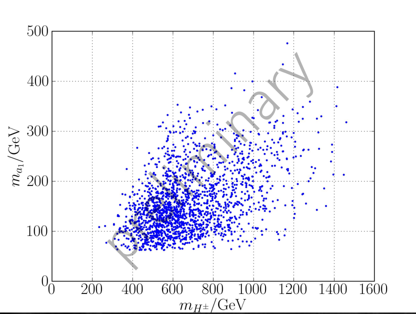
stop masses

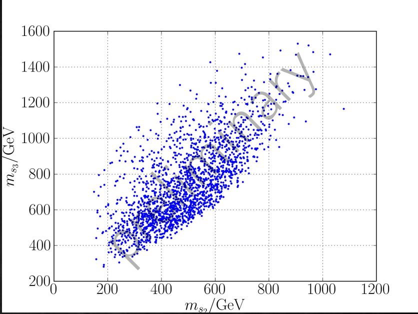




- $m_{\tilde{t}_2} \lesssim 2.4$ TeV
- natural region with no light stops
- consistent with results obtained for
  $W_{NMSSM} = \lambda S H_u H_d + \hat{\mu} H_u H_d + \frac{M}{2} S^2$ [Hall, Pinner, Ruderman (2011)]

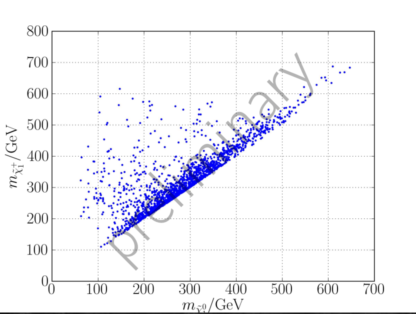
What is light? – Higgs sector

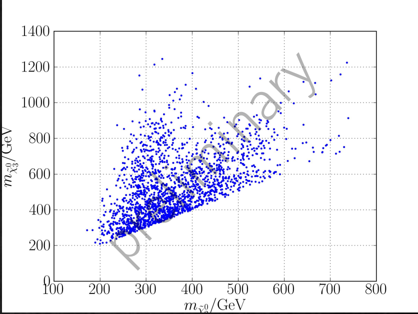




- one CP odd Higgs $< 500\,\text{GeV}$
- at least one CP even Higgs $\lesssim 1\,\text{TeV}$
- $b \to s\gamma$ will constrain light charged Higgs mass, but it is already mostly above 400 GeV

What is light? – Neutralino-Chargino sector





- several light neutralinos ($< 1\,\text{TeV}$)
- lightest chargino $m_{\chi_1^\pm} < 700\,\text{GeV}$

Outline

1. Introduction/Motivation
2. Framework
3. Results
4. Conclusions

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$\Rightarrow$ Testing the whole parameter space of natural SUSY at the LHC not easy

Thank you very much for your attention.