The scale-invariant NMSSM and the 125 GeV Higgs boson

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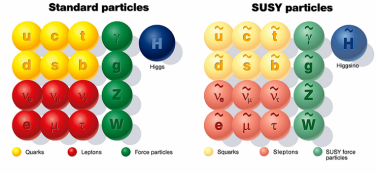
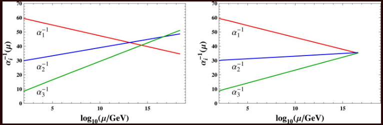
in collaboration with
T. Gherghetta, A. Medina, M. A. Schmidt
[1212.5243]

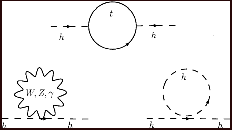
Low-scale supersymmetry is great!



Gauge coupling unification



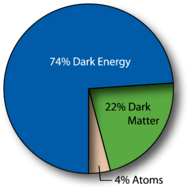
Solution to the hierarchy problem



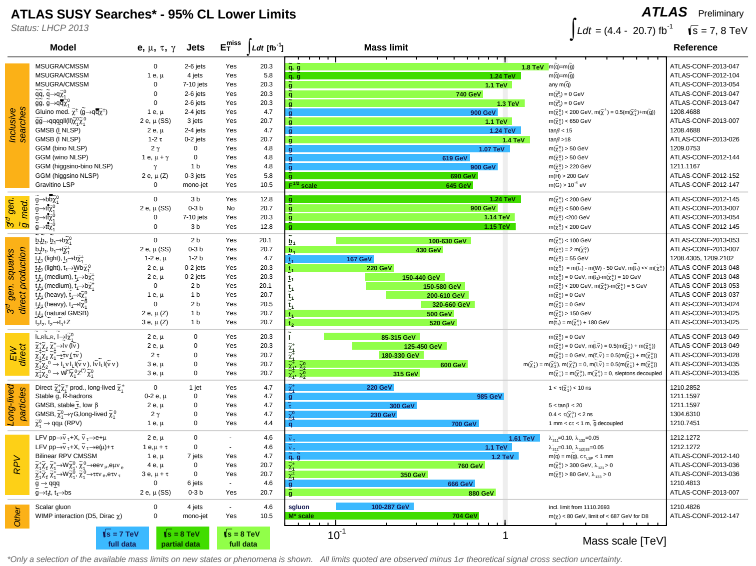
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \ln\frac{\Lambda_{UV}}{m_S} + \dots\right]$$

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

Dark matter candidate



But the LHC doesn't see any superpartners...



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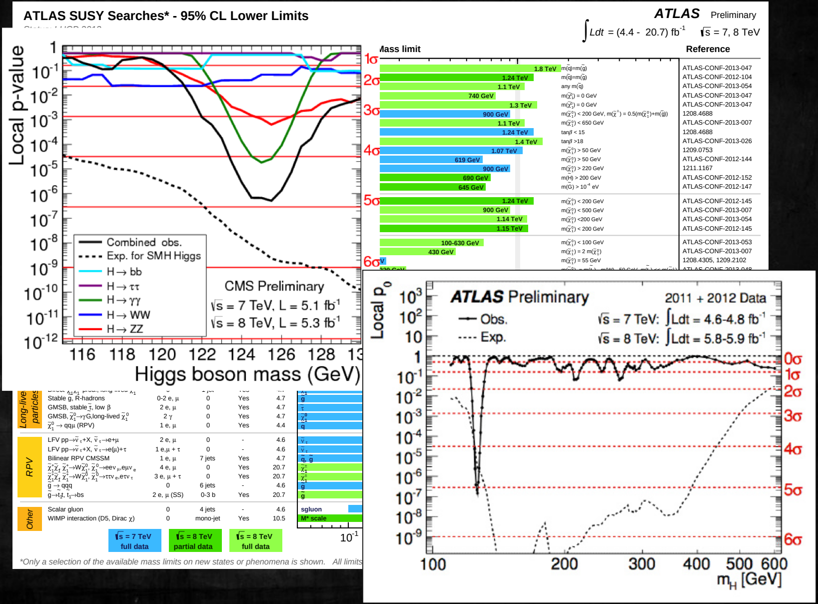

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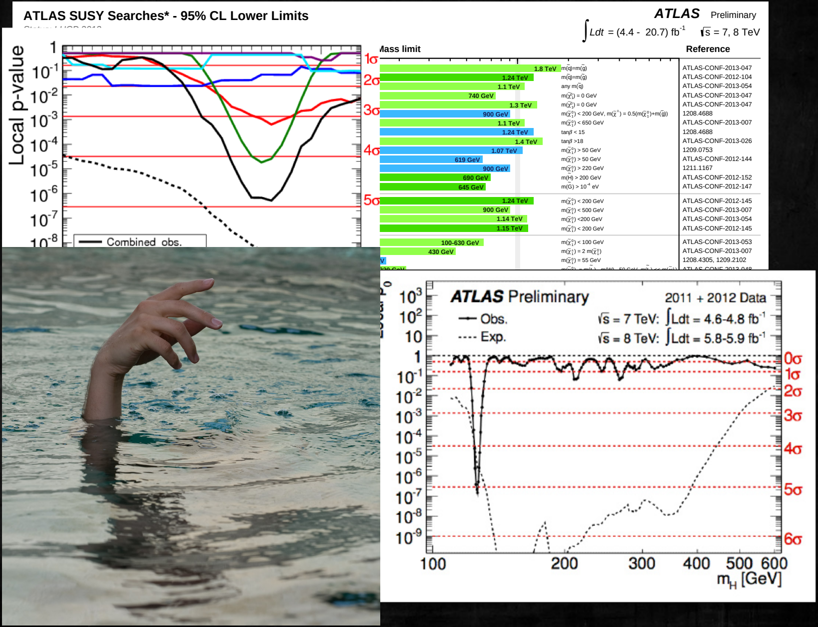

Saving SUSY [Many people . . .]

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There are two issues here:

(1) Why is the Higgs so heavy?

- For simplicity, let's consider MSSM with very SM-like Higgs:

$$\Rightarrow \quad V \simeq -m^2 h^2 + \sigma h^4 \quad \Rightarrow \quad \langle h \rangle \simeq \sqrt{\frac{m^2}{2\sigma}}$$

- Higgs mass: $m_h^2 = 4m^2 \quad \Rightarrow \quad m^2 = (126\,\mathrm{GeV})^2/4$
- In MSSM at tree-level: $\sigma = \mathcal{O}(g_1^2 + g_2^2)$
- With these m^2 and $\sigma \quad \Rightarrow \quad$ wrong $\langle h \rangle$!
- Need to raise σ to allow for right $\langle h \rangle$ and m_h!

Ways out of $\textcircled{1}$:

- Heavy stops (large $m^2_{Q_3}$, $m^2_{u_3}$ or A_t):
  $\Rightarrow \sigma = \sigma_{\text{tree}} + \sigma_{\text{loop}}$ can be sufficiently large.
- But then also $m^2 = m^2_{\text{tree}} + m^2_{\text{loop}}$ with $m^2_{\text{loop}} \gg v^2_{\text{EW}}$.
  $\Rightarrow$ Need fine-tuning to get $m^2 = \mathcal{O}(v^2_{\text{EW}})$!
- Better: NMSSM = MSSM + singlet S and

$$W \supset \lambda S H_u H_d \quad \Rightarrow \quad V \supset \lambda^2 (H_u H_d)^2$$

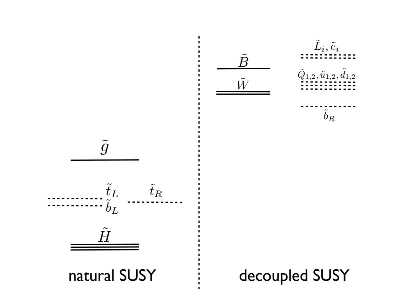
- $\Rightarrow$ Raises σ already at tree-level!

Saving SUSY [Many people . . .]

There are two issues here:

② Why no superpartners at the LHC?

- Raise superpartner masses to satisfy bounds.
- But do so in a clever way!



- Strong LHC constraints on first-generation squarks.
- Fortunately, they are not very important for naturalness!
- Assume split spectrum: heavy first- and second-generation squarks but light stops and sbottoms.

[Papucci, Ruderman, Weiler (2011)]

- In addition: Make Higgs vev less sensitive to loop corrections
  $\Rightarrow$ NMSSM

Outline

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Literature: NMSSM and 125/126 GeV Higgs

- **"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]
- . . .

The scale-invariant NMSSM

Superpotential

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

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Soft breaking terms & *D*-term potential

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

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Bound on lightest Higgs mass m_h

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \to \begin{cases} m_Z^2 & \text{for } \tan\beta \gg 1 \\ \lambda^2 v^2 & \text{for } \tan\beta = 1 \end{cases}$$

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- No gain for $\tan\beta \gg 1$ compared to MSSM $\Rightarrow \tan\beta \sim 1$
- $m_h \approx 126\,\text{GeV}$ at tree-level $\Rightarrow$ relatively large $\lambda \gtrsim 0.7$

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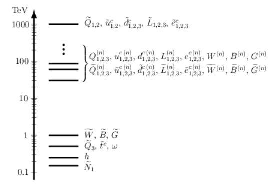
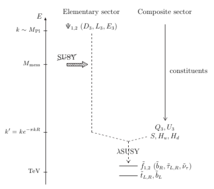
- E.g. within extra-dimensional models



[Gherghetta, BvH, Setzer (2011)]



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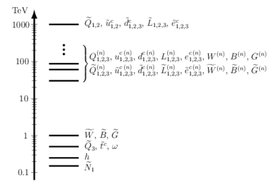

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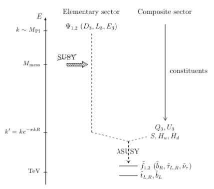

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- Or within Fat Higgs models

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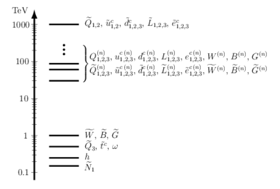

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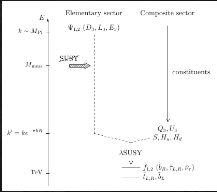

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- Or within Fat Higgs models

  [Harnik, Kribs, Larson, Murayama; Chang, Kilic, Mahbubani; Delgado, Tait]
- Can be consistent with gauge-coupling unification

  [Hardy, March-Russell, Unwin]

Our Study

Goal

- Find the "Golden Region" of small fine-tuning (better than 5%)

How to quantify fine-tuning:

$$\Sigma^v \equiv \max_i \left| \frac{d \log v^2}{d \log \xi_i} \right|$$

Fine-tuning better than 5%
$\Leftrightarrow \; \Sigma^v < 20$

[Barbieri,Giudice (1988)]

Assumptions to minimize fine-tuning:

- NMSSM with largish λ
- split sparticle spectrum
- low messenger scale ($\Lambda_{\rm mess} = 20\,\text{TeV}$)

Parameter scan

Technical details

- Markov-Chain Monte-Carlo (MCMC) to scan parameter space
- (Modified version of) NMHDECAY[Ellwanger, Gunion, Hugonie] to calculate sparticle spectra including most important loop-corrections

Constraints

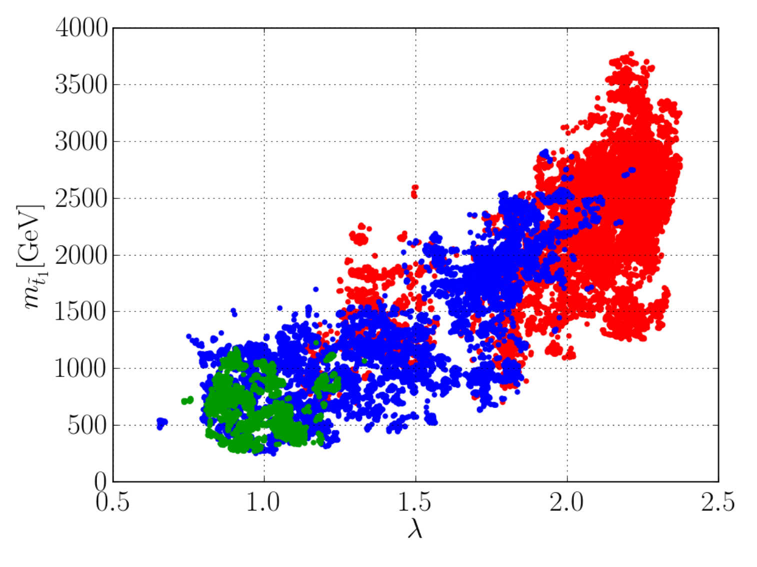
- LEP and Tevatron bounds on sparticle masses
- LHC bounds on heavier Higgses & stops, sbottoms and gluino
- limits on Higgs couplings
- flavour constraints
- electroweak precision tests

Range of input values

$$
\begin{aligned}
0 < \lambda < 3,\ |\kappa| &< 2.75 \\
M_{1,2} &< 8\,\text{TeV} \\
500\,\text{GeV} < M_3 &< 8\,\text{TeV} \\
m_{Q_3,\,u_3} < 5\,\text{TeV},\ m_{d_3} &< 8\,\text{TeV} \\
|A_t| < 5\,\text{TeV},\ |A_b| &< 8\,\text{TeV} \\
|A_\lambda| < 2\,\text{TeV},\ |A_\kappa| &< 1\,\text{TeV} \\
\tan\beta > 0.08,\ |\mu_{\text{eff}}| &< 1\,\text{TeV}
\end{aligned}
$$

Outline

Stop masses with fine-tuning better than 5%



The role of λ

Large λ helps

- Minimization conditions in NMSSM:

$$v^2 = \frac{-m_{H_u}^2 + \cdots}{\lambda^2}$$

- Effect of stops on $m_{H_u}^2$, e.g. for $m_{Q_3}^2$:

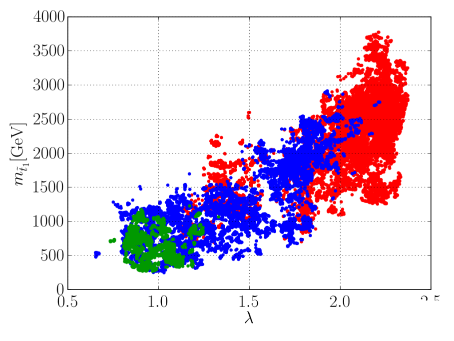
$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2} m_{Q_3}^2 \log\left[\frac{\Lambda_{\text{mess}}}{\Lambda_{\text{EW}}}\right] + \cdots$$

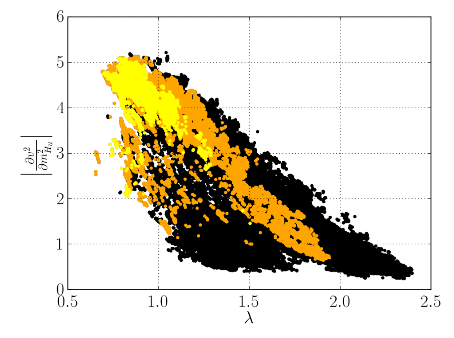
- Contribution of $m_{Q_3}^2$ to fine-tuning measure:

$$20 \geq \Sigma^v \geq \left|\frac{d\log v^2}{d\log m_{Q_3}^2}\right| = \left|\frac{dv^2}{dm_{H_u}^2} \times \text{const.} \times \frac{m_{Q_3}^2}{v^2}\right|$$

$$\frac{dv^2}{dm_{H_u}^2} \propto \frac{1}{\lambda^2} \;\Rightarrow\; \max(m_{Q_3}^2) \propto \lambda^2$$

The role of λ





The role of λ

Large λ hurts

- Higgs mass in NMSSM:

$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta m_{\rm mix}^2 + \delta m_{\rm loop}^2$$

- Large λ and (EWPT $\Rightarrow$) small $\tan\beta$:

$$m_h^2 \approx 10 \times (126\,\text{GeV})^2 + \text{ corrections}$$

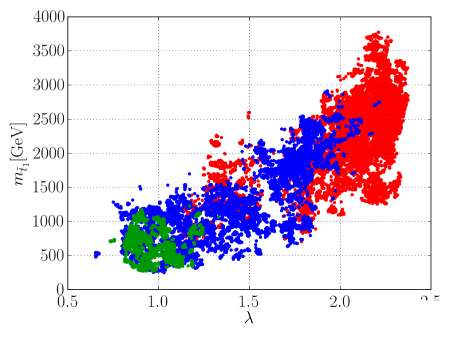
- For $\lambda \gtrsim 1$, need accidental cancellation to get $m_h = 126\,\text{GeV}$!
- Quantify this fine-tuning with

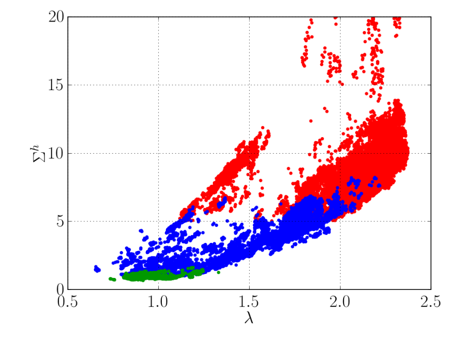
$$\Sigma^h \equiv \max_i \left| \frac{d \log m_h^2}{d \log \xi_i} \right|$$

- Define total fine-tuning as

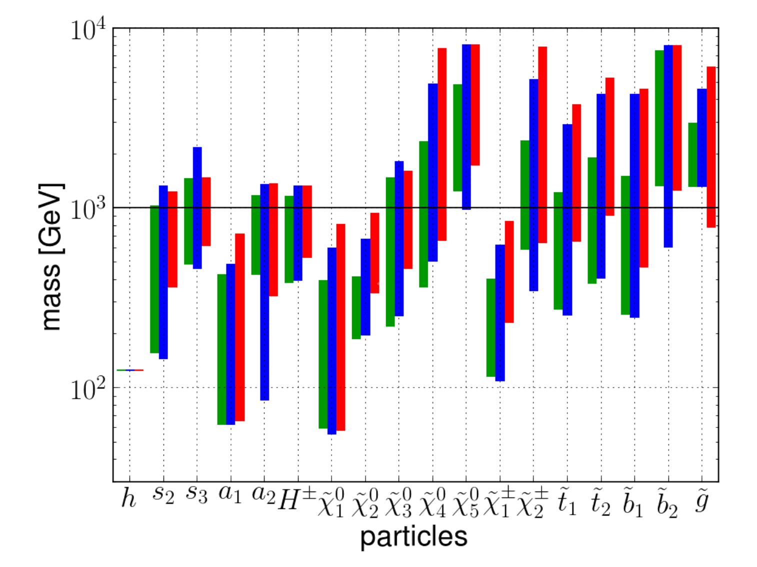
$$\Sigma^{\text{total}} \equiv \Sigma^h \times \Sigma^v$$

The role of λ





Sparticle spectrum

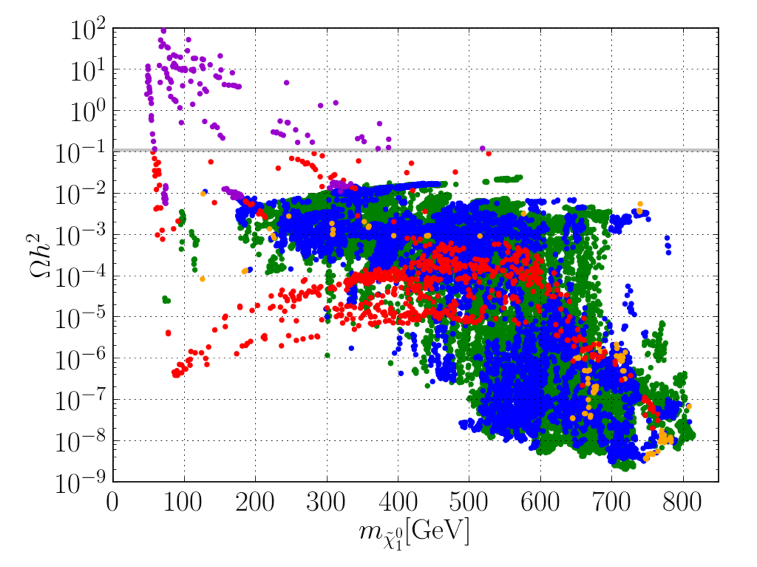


The LSP

- focused on neutralino LSP in scan
- but if $\Lambda_{\text{mess}} = 20\,\text{TeV}$ associated with messenger sector as in e.g. gauge mediation $\Rightarrow$ gravitino LSP with $m_{3/2} \approx 10^{-2}\,\text{eV}$
- expect our result to be not significantly affected because
  - lightest NMSSM sparticle almost exclusively neutralino in scan
  - LHC bounds on sparticle masses roughly similar for neutralino and gravitino LSP
- can have neutralino LSP e.g. in warped constructions of

[Larsen, Nomura, Roberts (2012)], [Gherghetta, BvH, Setzer (2011)]

Relic density of neutralino LSP $\tilde{\chi}_1^0$



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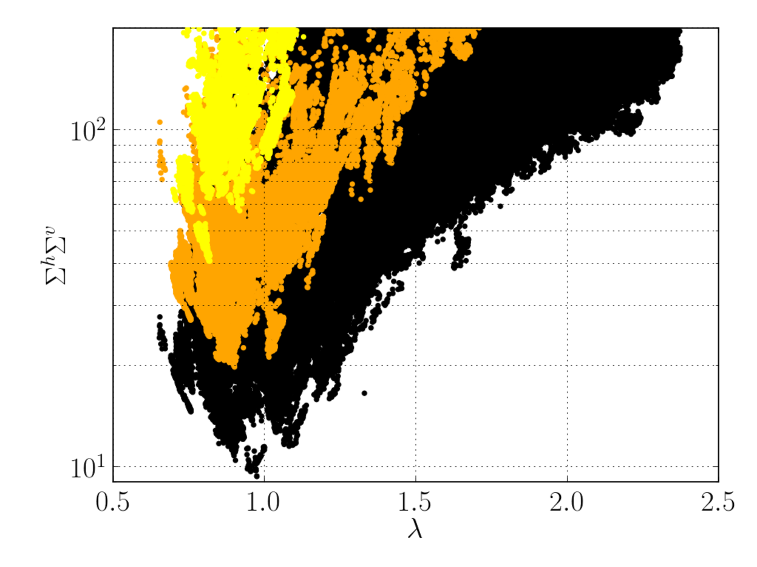
$\rightarrow$ Possibly no coloured particles below 1 TeV

$\Rightarrow$ Challenging to test entire parameter space of natural SUSY at the LHC

Thank you very much for your attention.

Backup Slides

Total tuning



Higgs couplings