The Higgs Mass and Fine-Tuning in Mirage Mediation

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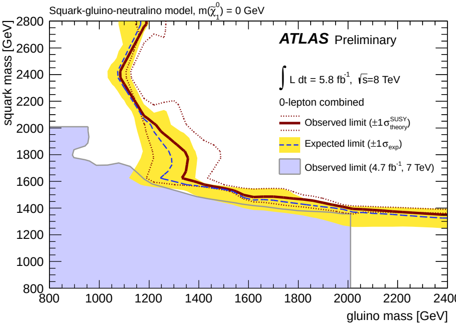
The Little Hierarchy Problem

- electroweak symmetry breaking

$$M_Z^2 = -2\,(m_{H_u}^2 + \mu^2) + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right)$$

- naive expectation $|m_{H_u}| \sim M_Z$
- m_{H_u} affected by soft masses through RGE running
- problem:

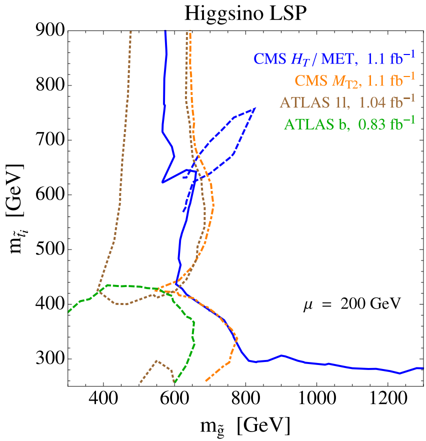


ATLAS-CONF-2012-109

"Natural SUSY"

- m_{H_u} weakly sensitive to 1. and 2. generation:

$$m^2_{H_u}(M_Z) \simeq -1.6\, m^2_{\tilde{g}}(M_{\rm GUT}) + 0.7\, m^2_H(M_{\rm GUT}) - 0.6\, m^2_{\tilde{t}}(M_{\rm GUT})$$



- LHC constraints on stops weak

Papucci et al., JHEP **1209** (2012)

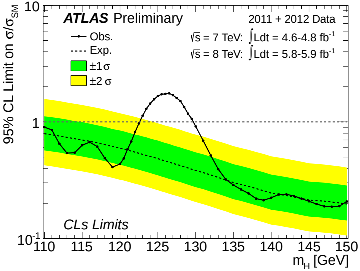
- **"Natural SUSY"**:

light $\tilde{g}$, $\tilde{t}$

$\Updownarrow$

heavy $\tilde{u}$, $\tilde{d}$, $\tilde{s}$, $\tilde{c}$

The Higgs Boson



ATLAS:
$m_h = (126.0 \pm 0.8)$ GeV

CMS:
$m_h = (125.3 \pm 0.9)$ GeV

Phys. Lett. **B716** (2012)

- MSSM Higgs: $m_h^2 = \underbrace{m_{h,\text{tree}}^2}_{< M_Z^2} + \underbrace{m_{h,\text{loop}}^2}_{\propto y_t^2\, m_t^2 \log\left(m_{\tilde{t}}^2/m_t^2\right)}$

  $m_h \simeq 125\,\text{GeV} + 4\,\text{GeV} \times \log\left(m_{\tilde{t}}/6\,\text{TeV}\right)$

- "Natural SUSY" dead? No, because ...
  - ... $m_{h,\text{loop}}$ may increase through stop mixing
  - ... $m_{h,\text{tree}} > M_Z$ in extensions of the MSSM

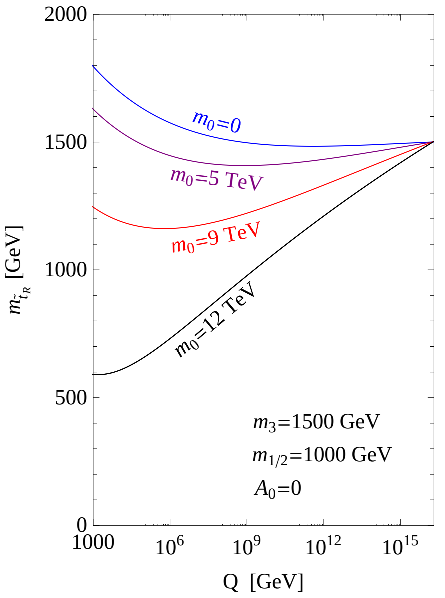
Stop Running in Inverted Hierarchy Models

- toy model with boundaries:
  - $m_{1/2}$ (gauginos)
  - A_0 (trilinear coupling)
  - m_0 (1. + 2. generation sfermions)
  - m_3 (3. generation)
- RGE of $\widetilde{t}_R$:

$$\beta^{\text{1-loop}} \propto -\frac{g_3^2 m_{\tilde{g}}^2}{16\,\pi^2} + \ldots$$

$$\beta^{\text{2-loop}} \propto \frac{g_3^4 m_0^2}{(16\,\pi^2)^2} + \ldots$$

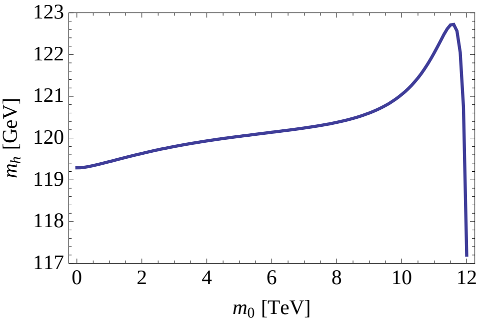
$\Rightarrow$ 2-loop effects important for $m_0 \gg m_{1/2}, m_3$



Radiative Stop Mixing

- stop mixing increases m_h

$$\Delta m^2_{h,\text{loop}} \propto y_t^2 m_t^2 \left[\frac{X_t^2}{m_{\tilde t}^2}\left(1-\frac{X_t^2}{12\,m_{\tilde t}^2}\right)\right] \qquad \left(\text{maximal: } \frac{|X_t|}{m_{\tilde t}}=\sqrt{6}\right)$$



- $X_t \sim A_t \sim 0.4\,A_0 - 1.6\,m_{1/2}$
- $m_{\tilde t} \downarrow$ for $m_0 \uparrow$

$\Rightarrow$ stop mixing through RGE running

Badziak et al. JHEP **1207** (2012)

Fine-Tuning

- fine-tuning: sensitivity of M_Z to parameter a

$$\Delta_a = \left| \frac{a}{M_Z^2} \frac{\partial M_Z^2}{\partial a} \right| \qquad \Delta = \max\{\Delta_a\}$$

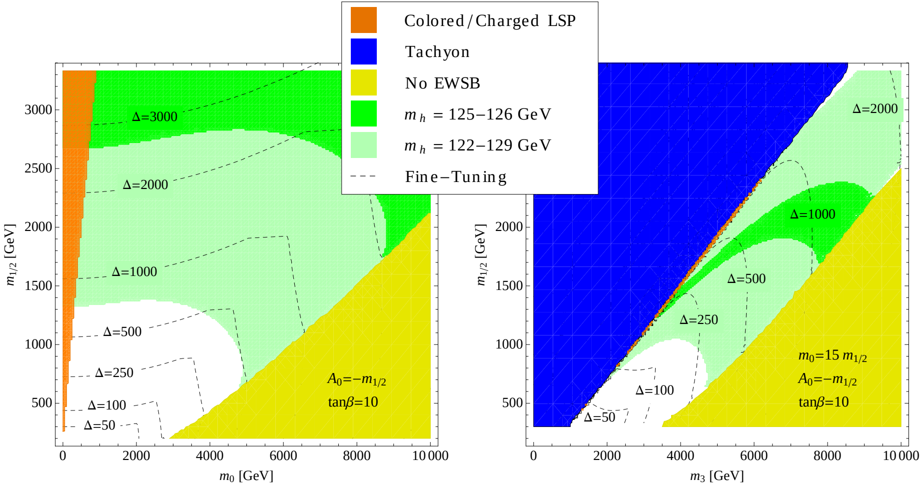
- IH model:

$$M_Z^2 \simeq 3.2 m_{1/2}^2 - 0.1 m_3^2 - 0.01 m_0^2 - 0.85 A_0\, m_{1/2} + 0.25 A_0^2 - 2\mu^2$$

- problem: sizable fine-tuning with respect to $m_{1/2}$
- but: cancellations between $m_{1/2}$ and m_0 for

$$\boldsymbol{m_0 \simeq 15 \dots 20\, m_{1/2}}$$

Comparison with the CMSSM



- for fixed ratio $m_0 = 15\, m_{1/2}$ in the IH model

string theory realization?

Dilaton Stabilization

- Heterotic MiniLandscape

  Lebedev et al., Phys. Lett. **B645** (2007), Phys. Lett. **B668** (2008), Phys. Rev. **D77** (2008)
- assume: moduli except s fixed supersymmetrically
- dilaton stabilized by gaugino condensate + uplifting sector

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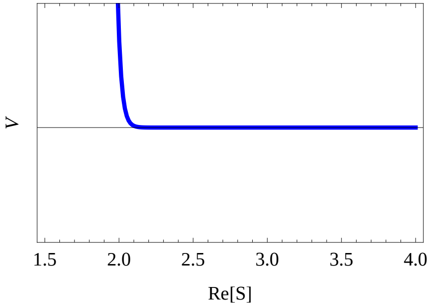

$$W = \underbrace{A\,e^{-b\,s}}_{\text{gaugino condensate}}$$

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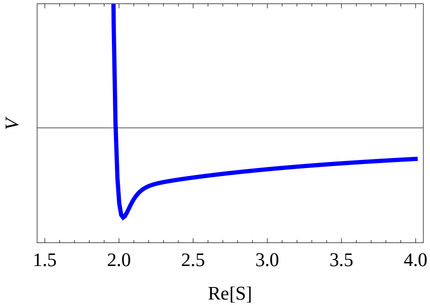

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Kappl et al., Phys. Rev. Lett. **102** (2009)

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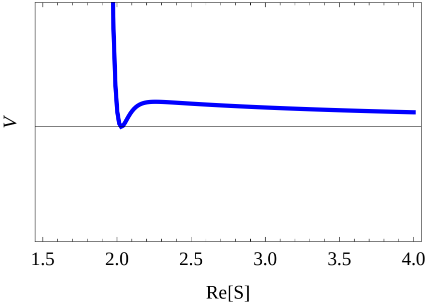

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Kappl et al., Phys. Rev. Lett. **102** (2009)

$$+ \underbrace{W_{\text{up}}}_{\text{uplifting by matter F-term}}$$

Lowen et al., Phys. Rev. **D77** (2008)

The Hidden Gauge Group

- vanishing vacuum energy
- gauge coupling $g^2 = 1/\langle s \rangle \simeq 1/2$

$\left.\right\}$ fixes *const*, W_{up}

- gravitino mass: $m_{3/2} \sim b\,A\,e^{-b\langle s \rangle} \sim 1 \ldots 100$ TeV

  $\Rightarrow\ b \simeq 15 \ldots 20 \qquad (\text{for } A = \mathcal{O}(1))$

- condensing gauge group SU(N):

$$b = \frac{8\,\pi^2}{N} \qquad \Rightarrow\ \boldsymbol{N = 4, 5}\ \text{ required}$$

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>70% of MiniLandscape
models yield N=4,5

Mirage Mediation

- SUSY breaking pattern fixed by dilaton stabilization

$$F_S \simeq \frac{\sqrt{3}F_X}{b} \simeq \frac{3\,m_{3/2}}{b}$$

- matter F-Term F_X dominates, F_S suppressed by $\mathcal{O}(10)$
- **mirage pattern of gaugino masses**

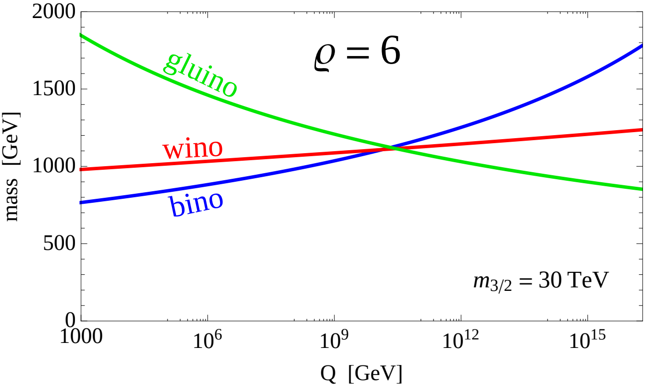
$$M_a = \frac{m_{3/2}}{16\pi^2}\,[\underbrace{\varrho}_{\text{GRAVITY MEDIATION}} + \underbrace{b_a\,g_a^2}_{\text{ANOMALY MEDIATION}}]$$

- A-parameters

$$A_{ijk} = \frac{m_{3/2}}{16\pi^2}[-\varrho + (\gamma_i + \gamma_j + \gamma_k)]$$

Gaugino Mass Pattern

- $\varrho = \mathbf{6}$ for hidden SU(4), $\varrho = \mathbf{7.5}$ for SU(5)



- prediction: $m_{\widetilde{B}} : m_{\widetilde{W}} : m_{\widetilde{g}} = \begin{cases} 1 : 1.3 : 2.6 & \text{SU(4)} \\ 1 : 1.4 : 2.9 & \text{SU(5)} \end{cases}$

Sfermions

- $\underbrace{\text{untwisted sector: } Q_{3L},\, t_R,\, H_u,\, H_d,\, (\tau_R)}_{\text{suppressed soft mass}}$
- $\underbrace{\text{twisted sector: 1. + 2. generation, } b_R,\, \tau_L,\, (\tau_R)}_{\text{unsuppressed soft mass}}$

$\Rightarrow$ **UV realization of "Natural SUSY"**

Krippendorf et al., Phys. Lett. **B712** (2012)

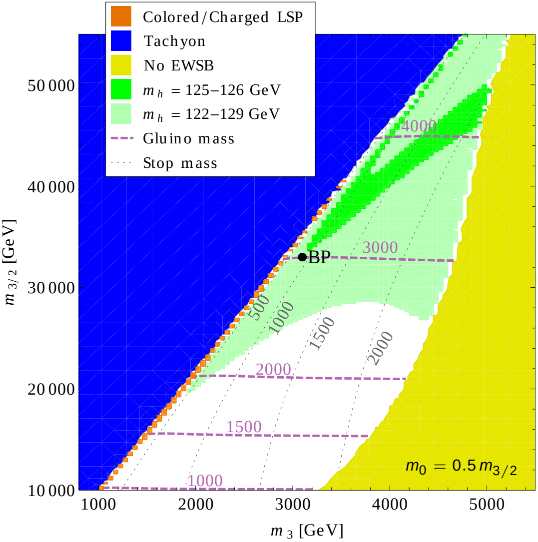
- benchmark model:

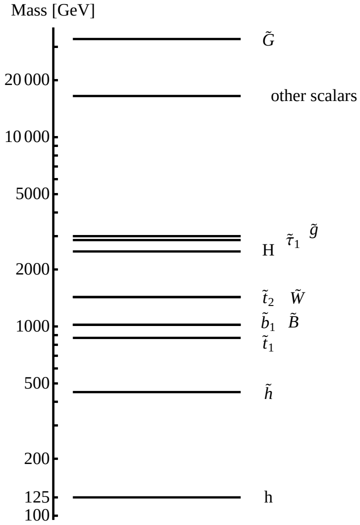
$$m_i^2 = \begin{cases} m_3^2 + \text{(anomaly)} & \text{(untwisted sector)} \\ m_0^2 + \text{(anomaly)} & \text{(twisted sector)} \end{cases}$$

$$m_0 \sim m_{3/2}, \qquad m_3 \ll m_{3/2}$$

- reduced fine-tuning: cancellations M_3, m_0 contribution to M_Z

Parameter Scan





Predictions

gauginos:

- compressed spectrum with fixed pattern
- $m_{\tilde{g}} \gtrsim 2$ TeV (from Higgs mass)

scalars:

- inverted hierarchy
- $\tilde{t}_1$ lightest sfermion ($m_{\tilde{t}} \sim 500$ GeV ... (few) TeV)

LSP:

- typically higgsino

gravitino:

- $m_{3/2} \gtrsim 20$ TeV (from Higgs mass)

Collider Phenomenology I

case: only $m_{\widetilde{h}} <$ TeV

- Drell-Yan production: $u\bar{d} \to \widetilde{h}^0\widetilde{h}^+ \to \not{E}_T + \text{soft } \ell$
- ℓ too soft to trigger on, huge backgrounds with $\not{E}_T$
  $\Rightarrow \widetilde{h}$-search at LHC seems hopeless

case: $m_{\widetilde{t}_1}, m_{\widetilde{h}} <$ TeV

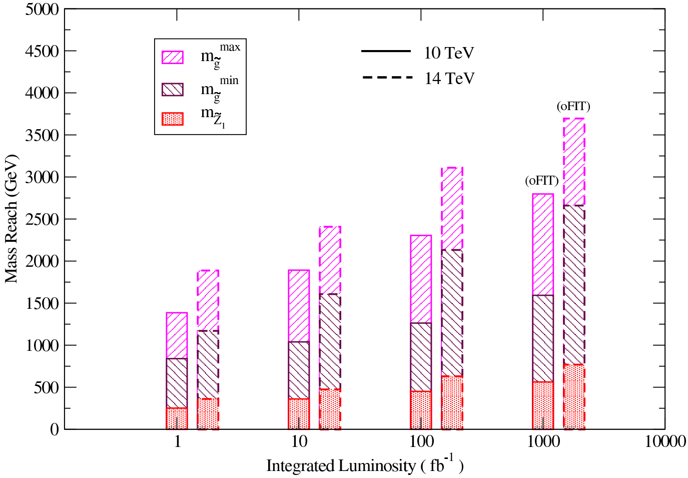
- stop production: $\widetilde{t} \to b + \widetilde{h}^+ \to \text{(b-jet)} + \not{E}_T + \text{soft } \ell$
- distinct from vanilla SUSY:
  - b-jet $\neq$ u,d-jets (higher multiplicity, larger spread, ...)
  - lacking events with hard isolated leptons

    Bobrovskyi et al., JHEP **1201** (2012)

problem: b-jet often fail hadronic activity cuts

Collider Phenomenology II

- gluinos detectable for $m_{\tilde{g}} \lesssim 2.5$ TeV



Baer et al., JHEP **0909** (2009)

Higgsino Dark Matter

- thermal production inefficient

$$\Omega_{\tilde{h},\text{thermal}} < \Omega_{DM}$$

- non-thermal production:
  - dilaton gets displaced from its minimum by inflation, finite temperature effects

    Kalosh et al., JHEP **1204** (2004)

    Buchmüller et al., Nucl. Phys. **B699** (2004)

$$\Delta s \sim \frac{T_R^4}{m_S^2 M_P} \quad \text{(reheating)}$$

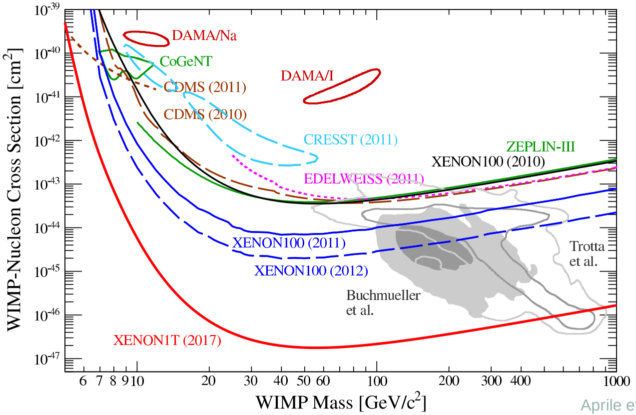
  - coherent oscillations, redshift as (scale factor)$^{-3}$
  - dilaton decays directly or indirectly to $\tilde{h}$

$$\Omega_{\tilde{h},\text{non-thermal}} \sim \Omega_{DM} \qquad \text{for } T_R \sim 10^9\ \text{GeV}$$

Dark Matter Direct Detection

- for $m_{\tilde{h}} \ll m_{\widetilde{W}} \sim m_{\tilde{B}}$

$$\sigma_p \sim 10^{-45}\,\text{cm}^2 \times \left(\frac{\text{TeV}}{m_{\widetilde{W}}}\right)^2 \sim 10^{-45}\,\text{cm}^2 \left(\frac{30\,\text{TeV}}{m_{3/2}}\right)^2$$



testable at XENON1T

Aprile et al., arXiv:**1206.6288** (2012)

Conclusion

- low energy implications in a class of MSSM models arising from the heterotic string
- mirage pattern of gaugino masses
- mirage scale fixed by dilaton stabilization
- inverted hierarchy in the sfermion sector
- stop mixing generated through RGE running
- cancellations gluino scalar contribution to M_Z

  } reduced fine-tuning (stop mixing; cancellations)
- typically higgsino LSP
  - distinct LHC signatures in combination with light stop
  - non-thermal higgsino dark matter, testable at XENON1T