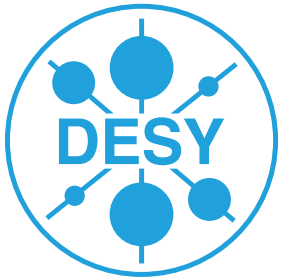
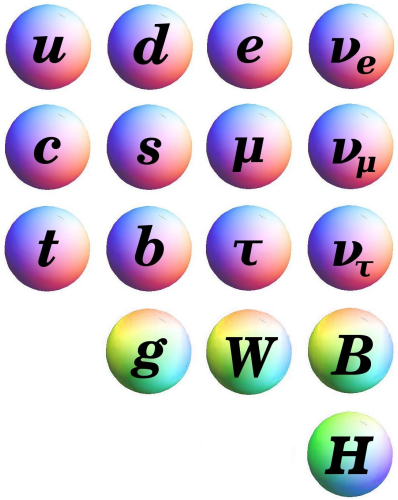
The MSSM after two years of LHC running

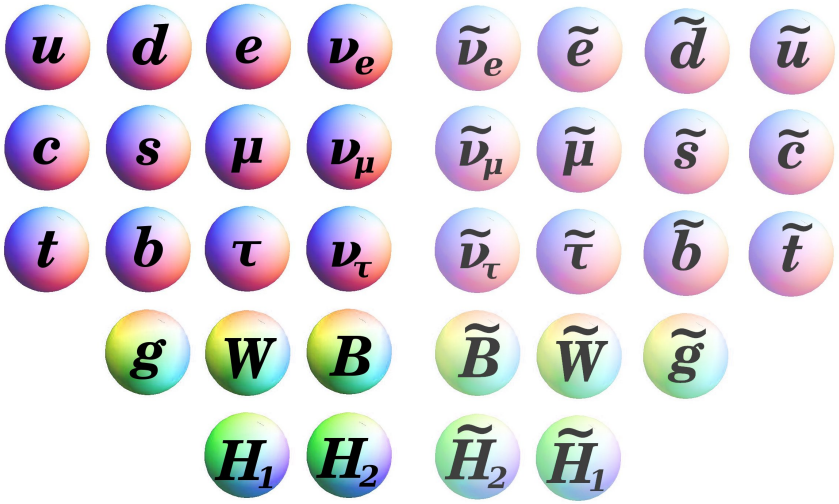
Felix Brümmer
DESY



The Standard Model



Beyond the Standard Model: The MSSM



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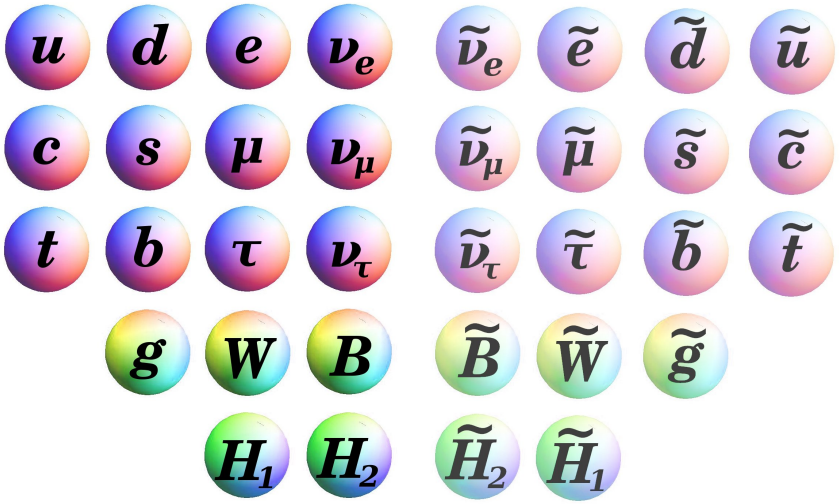

- minimal SUSY extension of Standard Model
- two Higgs doublets
- a scalar s-particle for every SM fermion: squarks, sleptons
- a fermionic particl-ino for every SM boson: gauginos, higgsinos
  $\rightarrow$ charginos $\chi^{\pm}$, neutralinos χ^0
- $\mathcal{O}(100)$ parameters

Restricting the parameter space

$$\begin{aligned}\mathcal{L}_{\not{\text{SUSY}}} = &-\frac{1}{2}\sum_a M_a\,\lambda^a\lambda^a + \text{h.c.} - m_{H_u}^2\,h_u^\dagger h_u - m_{H_d}^2\,h_d^\dagger h_d \\ &- m_Q^2\,\widetilde{Q}^\dagger\widetilde{Q} - m_U^2\,\widetilde{U}^\dagger\widetilde{U} - m_D^2\,\widetilde{D}^\dagger\widetilde{D} - m_L^2\,\widetilde{L}^\dagger\widetilde{L} - m_E^2\,\widetilde{E}^\dagger\widetilde{E} \\ &- \left(A_U y_u\,\widetilde{Q}\widetilde{U}h_u + A_D y_d\,\widetilde{Q}\widetilde{D}h_d + A_E y_e\,\widetilde{L}\widetilde{E}h_d + B\mu h_u h_d\right) + \text{h.c.}\end{aligned}$$

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Benchmark scenarios:

- e.g. CMSSM: $M_{1/2}$, m_0, A_0, $\tan\beta$, $\text{sgn}(\mu)$
- Convenient; self-consistent; not well motivated theoretically
- Do not expect the world to be anywhere close to mSUGRA

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- truncate to a few states relevant for specific signatures
- good starting point for phenomenology; exclusion bounds often too strong
- related: pMSSM, 19 TeV-scale parameters

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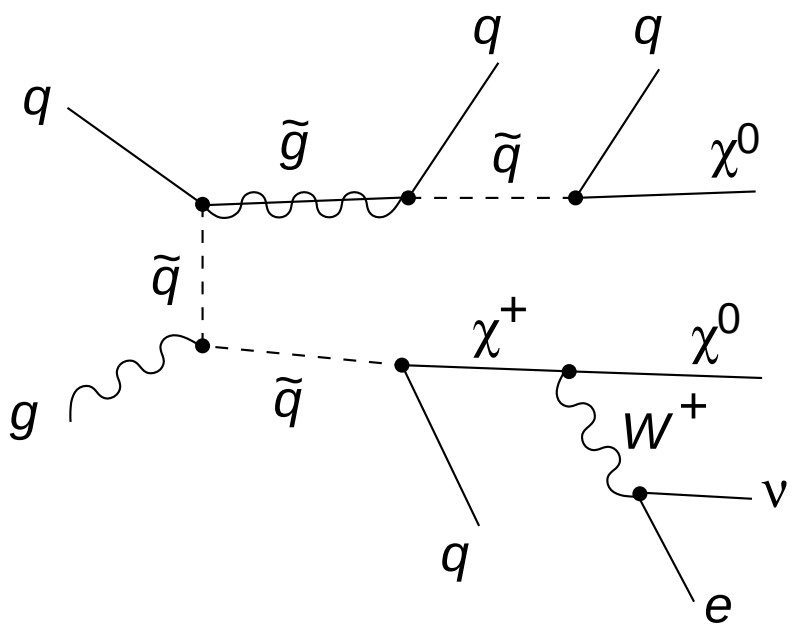
Full models:

- Where to start?
- Realistic, but usually more intricate than needed for LHC
- Exclusion bounds not easily transferrable

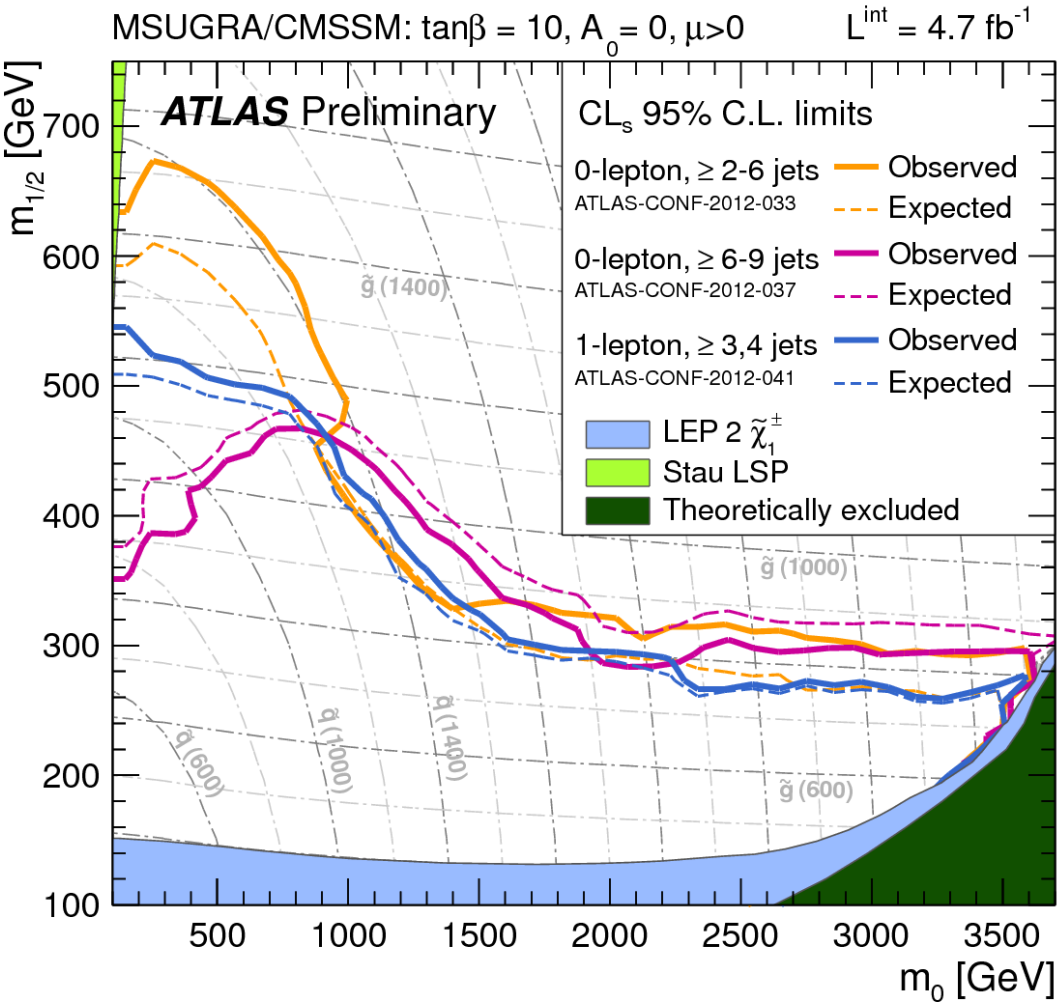
Sparticle production and decays

- R-parity $\Rightarrow$ sparticles produced pairwise
- at hadron collider: mainly $\tilde{q}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}$
- typical decay signature: cascade decays into lightest SUSY particle $\Rightarrow$ MET + jets (+ leptons)



Constraints I: Direct sparticle searches

Stringent limits on first-generation squark and gluino masses:



→ ATLAS-CONF-2012-037

- At $m_{\tilde{u}_1} \approx m_{\tilde{d}_1} \approx M_{\tilde{g}}$: all $\gtrsim 1.4$ TeV
- Beware: model dependence!
- more general pMSSM analysis:
  → Sekmen et al. '11 @ 1 fb^{-1}

Constraints II: A 125 GeV Higgs

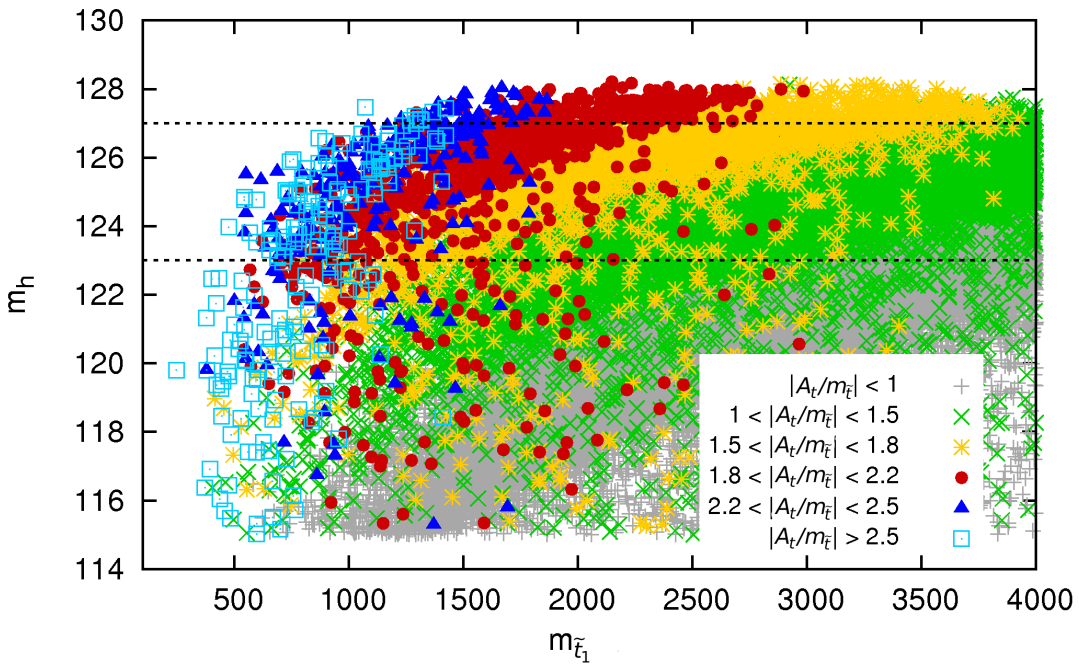
Further constraints on stop sector:

Suppose a SM-like Higgs is at $m_{h^0} = 125 \pm 2$ GeV

$m_{h^0} > m_Z$ needs large loop contributions (from large stop masses/mixings)

$$m_{h^0}^2 = m_Z^2 + \frac{3}{4\pi^2} y_t^4 v^2 \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{A_t^2}{12\, m_{\tilde{t}}^2} \right) \right) + \dots$$

$$125^2 = 91^2 + 86^2$$



Needs

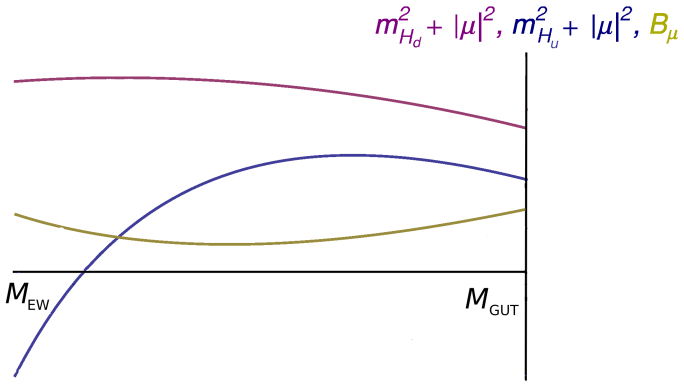
- $m_{\tilde{t}} \gtrsim 2$ TeV, heavy stops
- or large $|A_t/m_{\tilde{t}}| \approx 2$, "maximal stop mixing"

Fine-tuning I: The Little Hierarchy

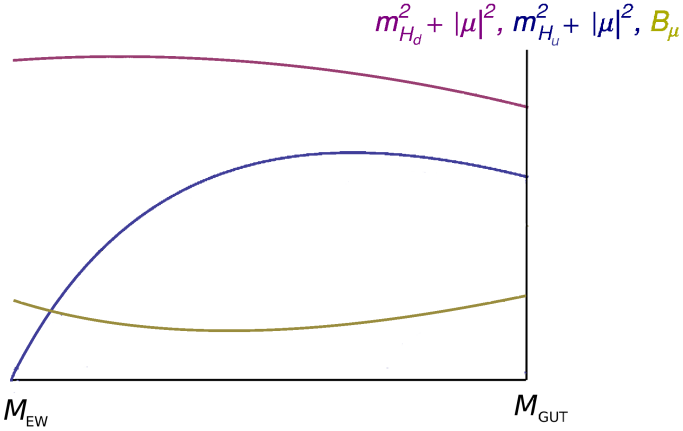
$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2)$$

μ = Higgsino mass, $m_{H_u}^2$ = up-type Higgs soft mass (< 0 by EWSB)

- m_{H_u}, $m_{\tilde{t}}$, $M_{\tilde{g}}$ generically of similar magnitude $m_{\not{\text{SUSY}}}$
- therefore $m_Z \sim m_{\not{\text{SUSY}}}$ unless
  - large cancellation between $|\mu|^2$ and $m_{H_u}^2$, or
  - $|m_{H_u}| \ll m_{\not{\text{SUSY}}}$ accidentally at the weak scale (and μ small)
- Either way: fine-tuning of parameters needed for $m_Z \ll m_{\not{\text{SUSY}}}$



Generic: $m_Z \sim m_{\not{\text{SUSY}}}$

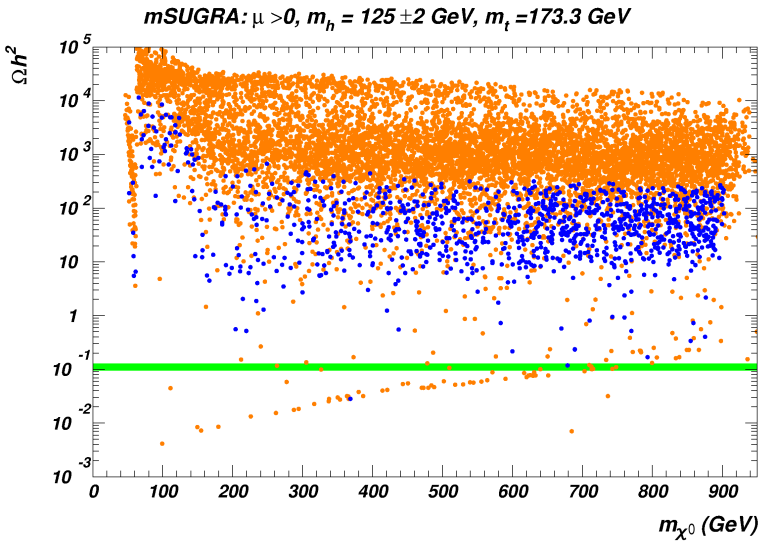


Fine-tuned: $m_Z \ll m_{\not{\text{SUSY}}}$

Fine-tuning II: Neutralino dark matter

Bino relic density too large: need

- $\tilde{\tau}$ or $\tilde{t}$ coannihilation
- resonant h^0 or A^0 exchange
- some higgsino admixture (focus point)



$0 < m_0 < 5$ TeV, $5 < m_0 < 20$ TeV

$\rightarrow$ Baer, Barger, Mustafayev '12

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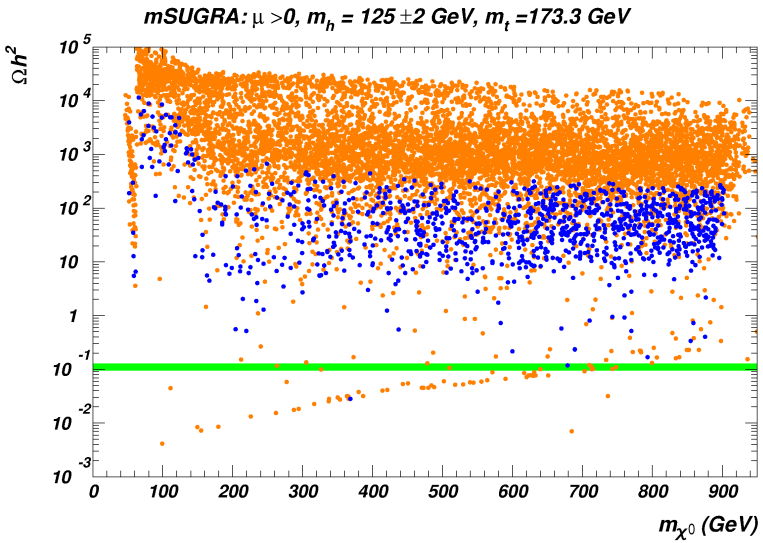

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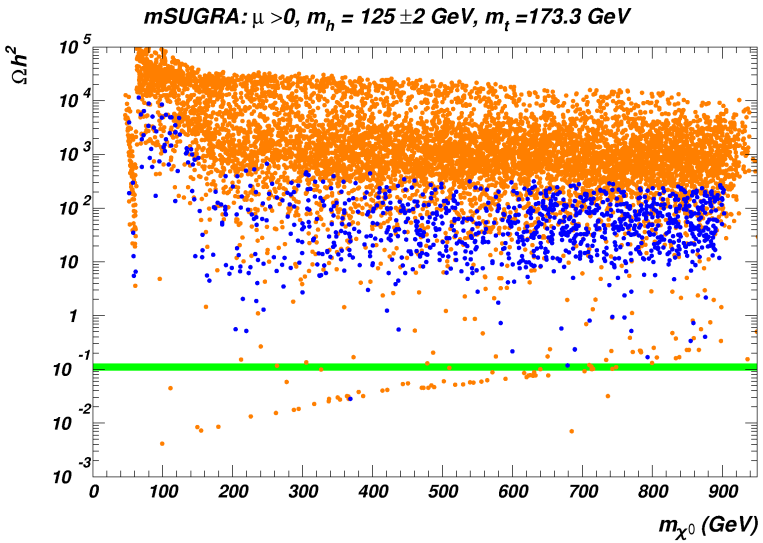

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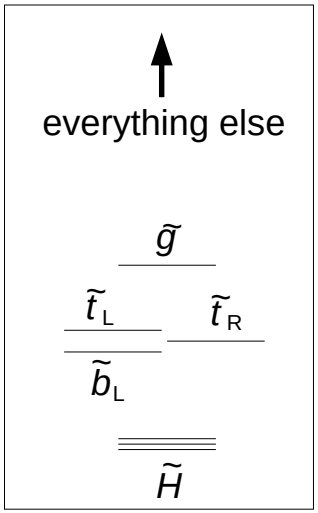
- Caution: this is just for CMSSM
- Still "WIMP miracle" losing some of its appeal
- (SUSY doesn't need thermal WIMPs. Gravitinos, axinos, nonthermally produced higgsinos? . . .)

Natural SUSY

Idea: keep states related to naturalness "light" → Papucci/Ruderman/Weiler '11

$$\mu, m_{H_u}, m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_L}, (M_{\tilde{g}}) \lesssim 1 \text{ TeV}$$

- first-generation squarks $\gg$ 1 TeV
- $\widetilde{W}$- and $\widetilde{B}$-like $\chi^{\pm}$, χ^0 undetermined
- direct $\tilde{q}, \tilde{g}$ search bounds evaded
  Higgs mass still problematic
- LHC should find higgsinos, $\tilde{t}$, $\tilde{b}$, ($\tilde{g}$)



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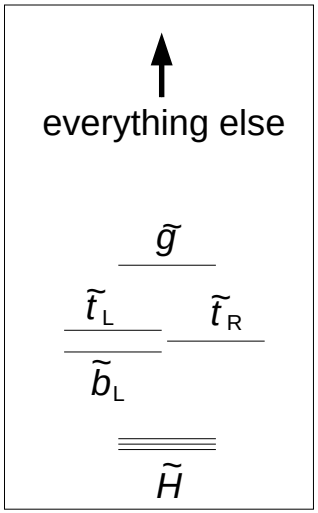

Comments:

- Phenomenological ansatz: soft terms prescribed at TeV scale
  Not clear a priori if realizable in a UV-scale model
- Some proposals: → Craig/McCullough/Thaler, Craig/Dimopoulos/Gherghetta, Krippendorf/Nilles/Ratz/Winkler, Csaki/Randall/Terning, Larsen/Nomura/Roberts...

Heavy stops

Idea: Maybe heavy stops can be reconciled with naturalness
$m_Z \ll m_{\not{\text{SUSY}}}$ due to model relations between soft terms

Prototype: Focus point $\rightarrow$ Chan/Chattopadhyay/Nath '97, Feng/Matchev/Moroi '99

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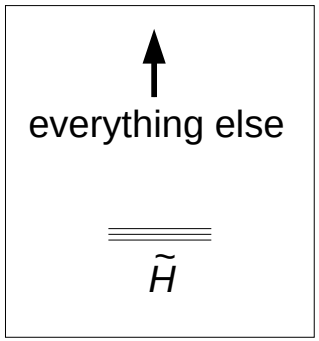
Variations: non-universal gaugino masses contributing to $m_Z \ll m_{\not{\text{SUSY}}}$
→ Abe/Kobayashi/Omura '07, Horton/Ross '09, FB/Buchmüller '11, '12, Younkin/Martin '12

- Potentially all superparticles heavy (except higgsinos?)
- Difficult to test at LHC



Criticism: high sensitivity to dimensionless (Yukawa, gauge) couplings
→ Romanino/Strumia '99

Large stop mixing

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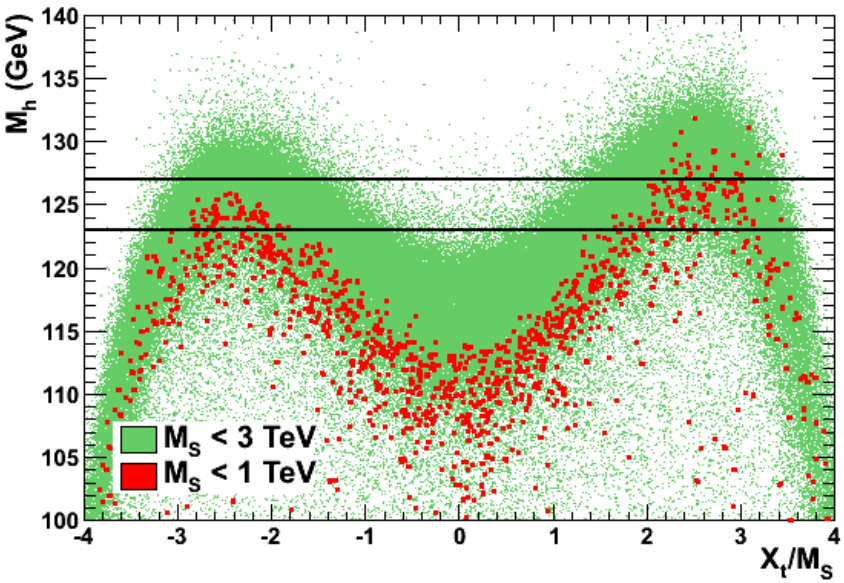

→ Arbey/Battaglia/Djouadi/Mahmoudi/Quevillon

- $X_t = A_t - \mu \cot\beta$:
  stop mixing parameter
- $|X_t/m_{\tilde{t}}| \approx 2$ at TeV scale
  $\Rightarrow$ large m_{h^0} possible
- Non-trivial to get this from a model
  → Draper et al. '11,
  Aparicio/Cerdeño/Ibañez '12,
  FB/Kraml/Kulkarni, in progress, ...
- e.g. gauge mediation or AMSB:
  no way (so far)

Signatures from unusual spectra

Compressed spectra: Squarks and gluinos in reach but hidden

→ Conley et al. '11, LeCompte/Martin '11, ...

- CMSSM searches assume $m_{\tilde{g}} : m_{\chi_1^0} \simeq 6 : 1$
- Smaller $\Delta m \Rightarrow$ low cut efficiencies
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Split spectra: Only Higgsinos accessible

- Higgsinos with EW-scale masses produced abundantly, e.g. in Drell-Yan
- Small mass splittings $\Rightarrow$ soft decay products $\Rightarrow$ signal buried under BG
  → Baer/Barger/Huang '11, Bobrovskyi/FB/Buchmüller/Hajer '11
- Monojets (from ISR) + MET?
  Displaced vertices/charged tracks from long-lived charginos?

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- Maximal stop mixing helps with m_{h^0}, but hard to realize in realistic models
- Experiments: look out for
  - direct stop / sbottom production
  - light higgsinos (Monojets + MET? Chargino tracks?)
  - compressed spectra
  - jets + MET (+leptons), but this time please find something!