The MSSM with degenerate (GUT-scale) Higgs mass matrix

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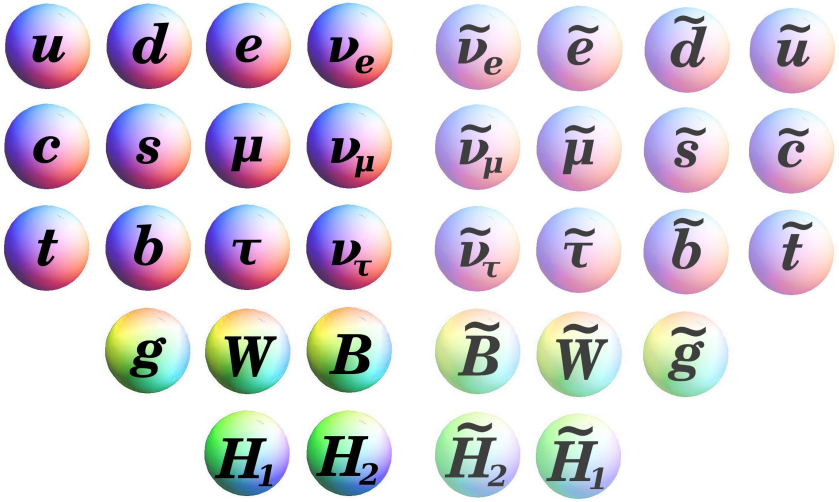
based on
arXiv:0906.2957 with Sylvain Fichet, Arthur Hebecker, Sabine Kraml
arXiv:1006.???? with Sylvain Fichet, Sabine Kraml, Ritesh Singh

Beyond the Standard Model: The MSSM



- minimal SUSY extension of Standard Model
- $\mathcal{O}(100)$ new parameters, mostly soft SUSY breaking terms
- Still $\mathcal{O}(20)$ when demanding no contributions to $\not{CP}$ and FCNCs
- Further reduce number of parameters:
  - e.g. by imposing ad-hoc universality relations: “CMSSM”...
  - or by assuming an underlying model of UV-scale physics

High-scale soft parameters in SUSY GUTs

Popular example: CMSSM

- scalar soft masses equal: $m^2_{\text{sfermions}} = m^2_{H_1} = m^2_{H_2}$
- gaugino masses equal: $M_1 = M_2 = M_3$
- trilinear soft terms equal: A_0
- μ and $B\mu$ parameters: from $\tan\beta$ and M_Z at low scale

In this talk instead: Models with degenerate Higgs mass matrix

- $m^2_{H_1} + |\mu|^2 = m^2_{H_2} + |\mu|^2 = |B\mu|$, i.e.

$$V_{\text{Higgs}} = (\overline{H}_1 \; H_2) \begin{pmatrix} m^2 & m^2 \\ m^2 & m^2 \end{pmatrix} \begin{pmatrix} H_1 \\ \overline{H}_2 \end{pmatrix} + \text{quartic}; \; m^2 \equiv m^2_{H_i} + |\mu|^2 = |B\mu|$$

(and also:)

- gauginos: $M_1 = M_2 = M_3$ (typically)
- $m^2_{\text{sfermions}} = 0$; $A = 0$ for first two generations (sometimes)
- $\{m^2_{\text{squarks}}, A_t, A_b\}$ not independent; $\{m^2_{\text{sleptons}}, A_\tau\}$ neither (sometimes)

Theoretically well-motivated by interesting UV completions.

Origin of mass degeneracy

SUSY GUT with chiral adjoint Φ
Adjoint of GUT group G decomposes under SM gauge group as

$$\begin{aligned} \mathbf{Ad}(G) &\to (\mathbf{1},\mathbf{2})_{-1/2} \oplus (\mathbf{1},\mathbf{2})_{1/2} \oplus \dots \\ \Phi &\to \quad H_1 \qquad \oplus \quad H_2 \qquad \oplus \dots \end{aligned}$$

If Higgs part of $\Phi - \Phi^\dagger$ massless at tree-level — e.g. being a

- pseudo-Nambu-Goldstone Boson
- gauge boson in higher dimensions
- ...

then

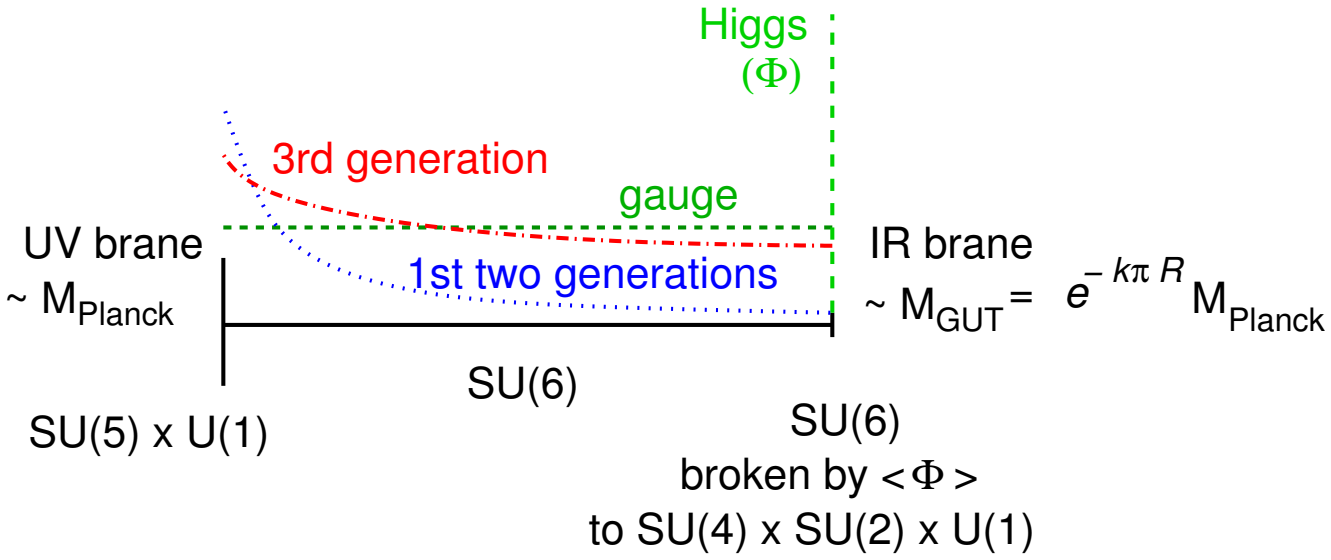
$$\begin{aligned} V \supset m^2 \operatorname{tr}\left(\Phi + \Phi^\dagger\right)^2 &\supset m^2 (H_1 + \overline{H}_2)(\overline{H}_1 + H_2) \\ &= m^2 |H_1|^2 + m^2 |H_2|^2 + m^2 \left(H_1 H_2 + \text{h.c.}\right) \end{aligned}$$

$$\Rightarrow \; m_{H_1}^2 + |\mu|^2 = m_{H_1}^2 + |\mu|^2 = |B\mu|$$

Example 1: “Holographic GUT”

→ Nomura/Poland/Tweedie ’06

RS-I type model on slice of AdS_5

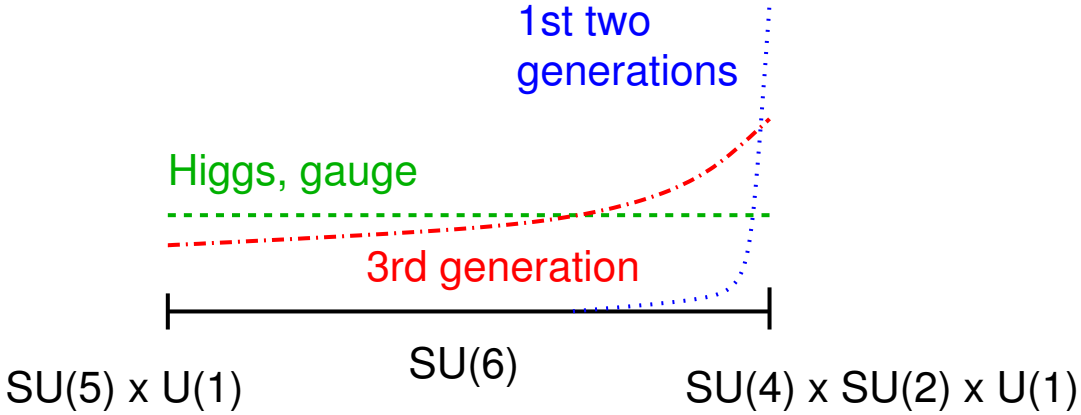


- In gaugeless limit: $\Phi - \Phi^\dagger$ contains pNGBs of broken SU(6)
- With gauge couplings: not all pNGBs eaten, no $H_1 - \overline{H}_2$ mass at tree-level $\Rightarrow$ degenerate Higgs mass matrix

Example 2a: 5d Gauge-Higgs unification

→ Burdman/Nomura '03

Flat extra dimension comactified with radius $R \sim 1/M_{GUT}$



$$\text{5d gauge supermultiplet} \rightarrow \text{4d gauge supermultiplet } -\theta\bar{\theta}A_\mu\sigma^\mu + \ldots$$
$$\oplus \text{ 4d chiral adjoint } \Phi = \Sigma + iA_5 + \ldots$$

5d gauge invariance: mass term only for $\Sigma \sim \Phi + \Phi^\dagger$, not for $A_5 \sim \Phi - \Phi^\dagger$
Boundary conditions: only $H_1, H_2 \subset \Phi$ have zero modes

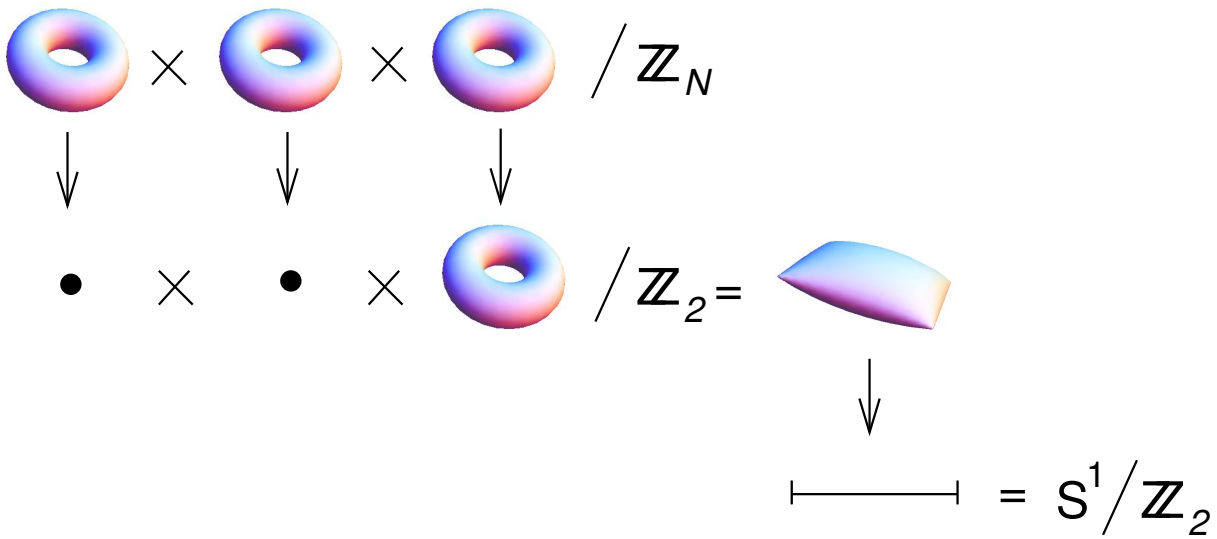
$$\Rightarrow \; V \supset m^2(H_1 + \overline{H}_2)(\overline{H}_1 + H_2) + \ldots$$

$$\Leftrightarrow \text{ degenerate Higgs mass matrix}$$

Example 2b: Heterotic strings on orbifolds

Some heterotic orbifold GUTs admit anisotropic 5d limit with GHU
$\rightarrow$ same argument $\rightarrow$ s.a. Antoniadis et al. '94, Brignole et al. '97...

Schematically: $E_8 \times E_8$ heterotic on $T^6/\mathbb{Z}_N$ $\rightarrow$ e.g. Buchmüller et al. '05/'06
Compactify five radii at $\sim 1/M_{\text{Planck}}$, one at radius $\sim 1/M_{\text{GUT}}$
$\Rightarrow$ effective 5d orbifold GUT



DHMM whenever anisotropic limit is possible
— not just at points in moduli space where it is actually realized

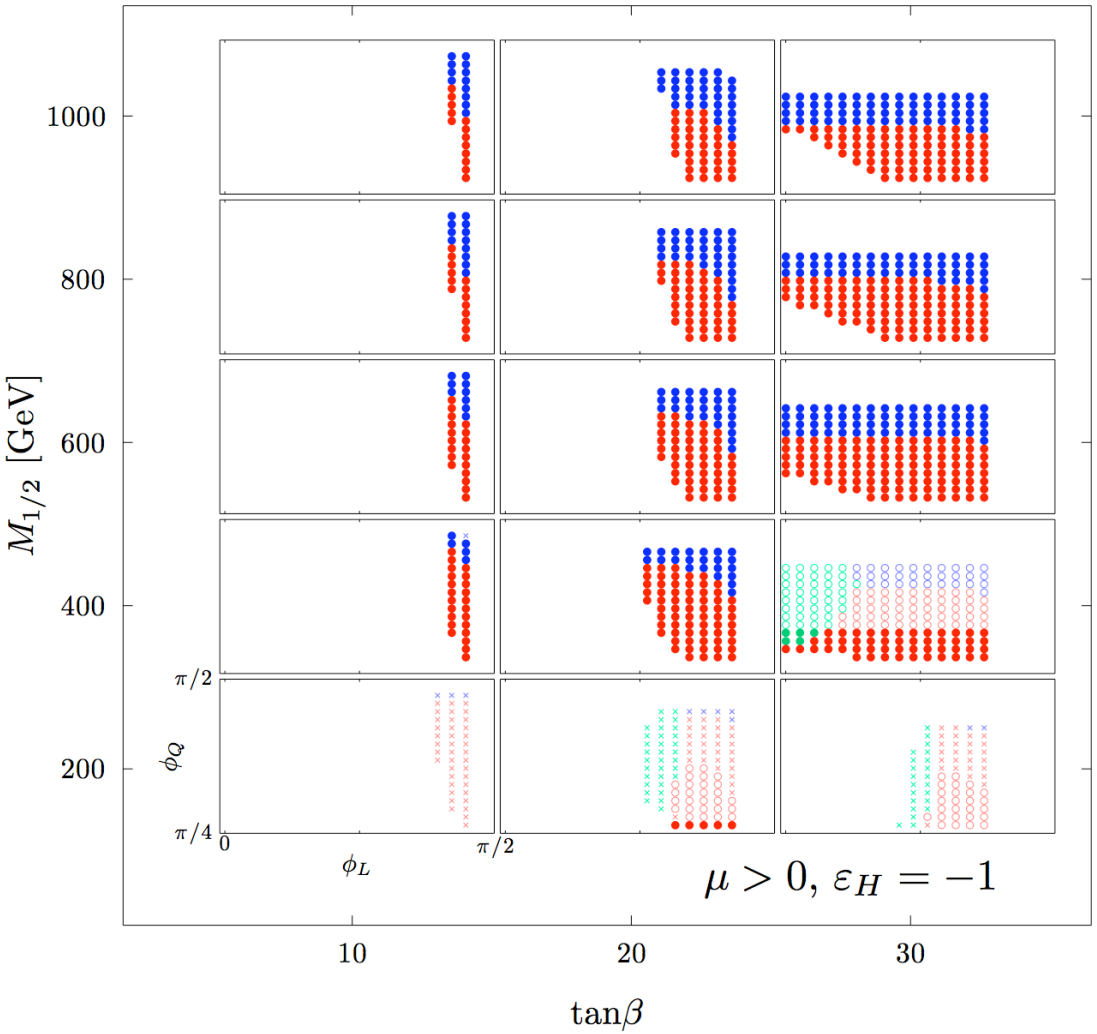
Example 2a studied in detail

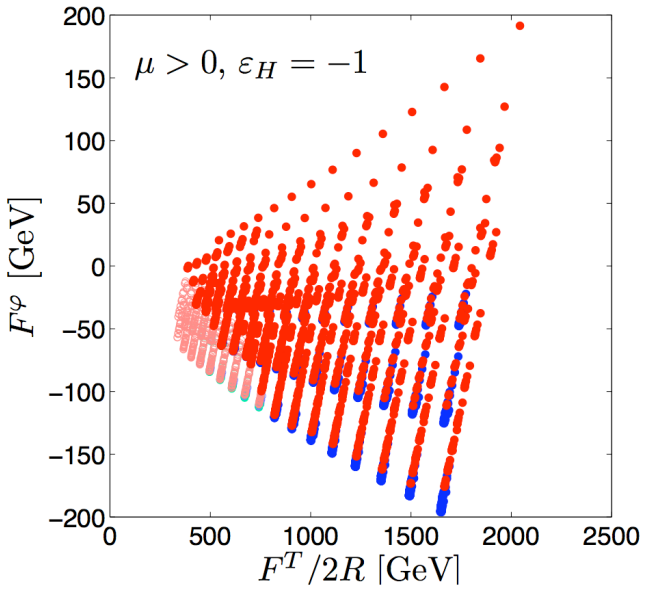
Higgs mass degeneracy at GUT scale constrains Higgs potential at electroweak scale.
Can we get realistic phenomenology?

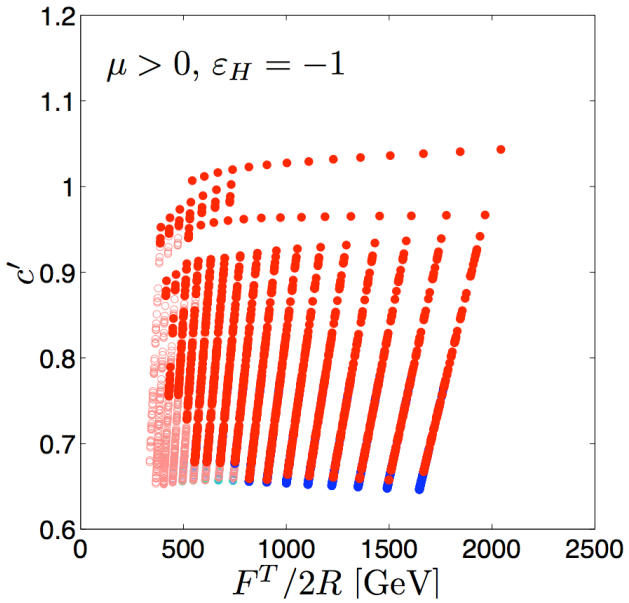
Example model: $\rightarrow$ Burdman/Nomura '03, Hebecker/March-Russell/Ziegler '08

- 5d gauge-Higgs unified model
- 3rd generation in bulk; first two generations on brane
- SUSY breaking: $F^T \neq 0$ (where $\langle T \rangle = R + F^T \theta^2$: "radion superfield") and $F^\varphi \neq 0$ (SUSY breaking in 4d gravitational multiplet)
- 5d Chern–Simons term crucial for gauge-Higgs sector soft terms $\rightarrow$ extra parameter: CS coefficient c
- 3rd generation matter soft terms $\leftarrow$ 2 bulk-brane mixing angles ϕ_Q, ϕ_L
- fundamental model parameters thus $\{F^T, F^\varphi, c, \phi_Q, \phi_L\}$
  $\leftrightarrow \{M_{1/2}, \tan\beta, M_Z, \phi_Q, \phi_L\}$

Can find points with realistic EWSB







Neutralino, stau, selectron LSP.
Small points excluded by LEP or B-physics.
Note CS parameter necessary: $c = 0$ excluded.

More general parameter space scan

- What choices of parameters for MSSM with degenerate Higgs mass matrix are "best compatible" with phenomenology?
- What regions of parameter space are already ruled out?
- Does DHMM lead to predictions independent of model details?

Explore parameter space with Markov Chain Monte Carlo methods

→ Baltz/Gondolo '04, Allanach/Lester '05, de Austri et al. '06...

→ Talk by A. Casas

"Random walk in parameter space"

Two representative choices for sfermion soft terms:

- universal sfermion soft terms
- vanishing 1st and 2nd generation sfermion soft terms

Two kinds of prior probability distribution:

- flat prior in dimensionful parameters and in $\tan\beta$
- "naturalness prior", disfavouring fine-tuned points

Results for flat prior, universal sfermions

Parameter ranges:

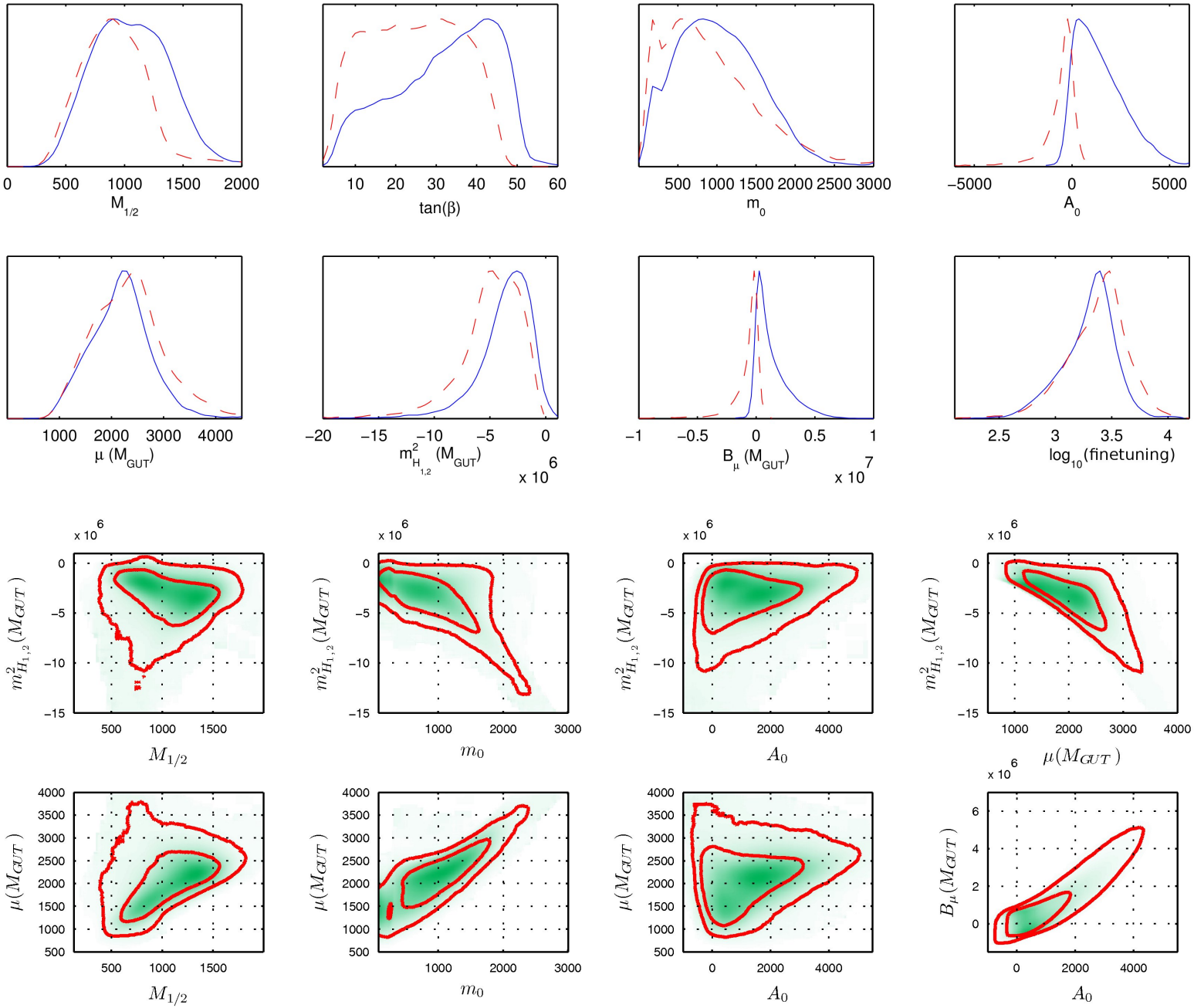
parameters	from	to
$\tan\beta$	2	60
$M_{1/2}$	0	2 TeV
$m_{\text{sfermions}}$	0	5 TeV
A_0	-10 TeV	10 TeV

Experimental constraints:

observable	limit
m_h	> 114.4 GeV
m_t	173.1 ± 1.4 GeV
m_W	80.398 ± 0.025 GeV
$b \to s\gamma$	$(3.52 \pm 0.34) \times 10^{-4}$

observable	limit
$B_s \to \mu^+\mu^-$	$\leq 5.8 \times 10^{-8}$
$\Delta a_\mu^{\text{SUSY}}$	$\leq 4.48 \times 10^{-9}$
Ωh^2	0.113 ± 0.0105
SUSY masses	LEP + Tevatron limits

Results for flat prior, universal sfermions

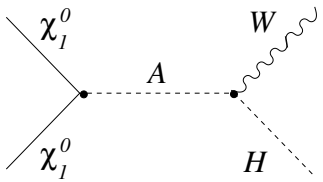


The dark matter constraint

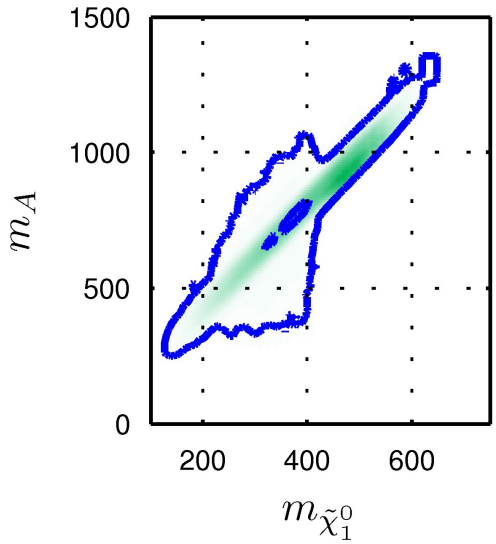
Assuming all dark matter is neutralino LSP:

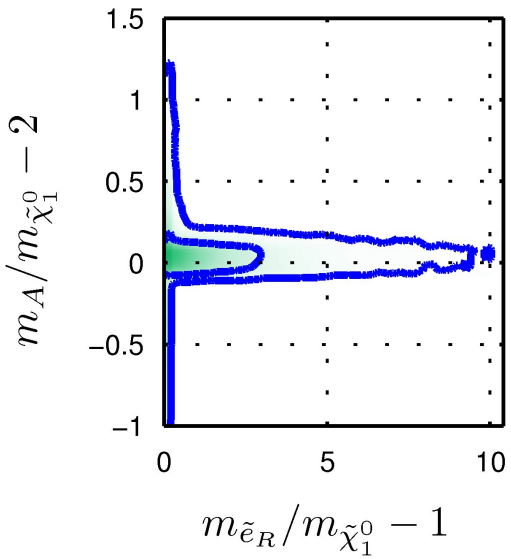
Stringent constraint from χ_1^0 relic density, $\Omega_{\rm DM} h^2 = 0.113 \pm 0.011$ (WMAP)

- In generic regions of parameter space: relic density too large
- Need to enhance annihilation cross section. Most important mechanism: near-resonant pseudoscalar Higgs exchange, requires $m_A \approx 2 m_{\chi_1^0}$



- potentially also important: coannihilation with sleptons if $m_{\tilde{e},\tilde{\tau}} \approx m_{\chi_1^0}$





Conclusions

Summary:

- Higgs mass degeneracy $m_{H_1}^2 + |\mu|^2 = m_{H_2}^2 + |\mu|^2 = |B\mu|$ well-motivated
  Predicted by large class of high-scale models
- Can be made to work in a realistic example model:
  5d gauge-Higgs unification with radion-mediated SUSY breaking
- More general parameter space scans to be published soon
  A stringent pre-LHC constraint: dark matter relic density

To do:

- Implications for flavour physics in gauge-Higgs unified models
- Model discrimination possible?