Vacuum stability and SUSY at high scales with 2 H doublets

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1512.07761 (with E. Bagnaschi, W. Buchmüller, A. Voigt and G. Weiglein)

Pre-LHC-8 motivations for supersymmetry

- Solves hierarchy problem
- Provides dark matter candidate
- Helps with gauge coupling unification
- Is an essential ingredient of superstring theory

Post-LHC-8 hangover

- Solves hierarchy problem ×
- Provides dark matter candidate ×
- Helps with gauge coupling unification ×
- Is an essential ingredient of superstring theory ✓

Pessimistic outlook

If LHC-13 doesn't find a gluino soon:

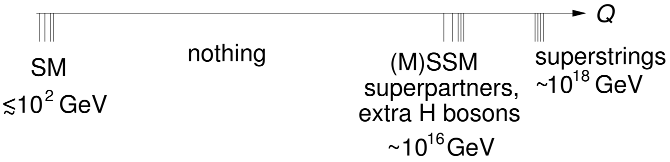
- The main remaining motivation for supersymmetry will be that it's a nice feature of UV completions of the Standard Model usually living at ultrahigh scales $\lesssim M_{\text{Planck}}$.
- From a top-down perspective: no reason for SUSY to be broken at scales far below M_{Planck}.
- Reasonable to speculate about a SUSY breaking scale lower than but close to the string scale:
  - UV completion of SM = SUSY field theory, perhaps around 10^{16-18} GeV.
  - UV completion of SUSY field theory = superstrings around M_{Planck}.
- The hierarchy problem goes unsolved.
  Maybe the solution is in the UV completion. Maybe it's anthropics.

Can we still learn something about TeV-scale physics?

Supersymmetry at high scales

Hypothesis:
The world is supersymmetric but SUSY is broken around $M_{\mathrm{GUT}} - M_{\mathrm{Planck}} \sim 10^{16-18}$ GeV

First variant: "High-scale SUSY"



Doesn't work. → Giudice/Strumia '11

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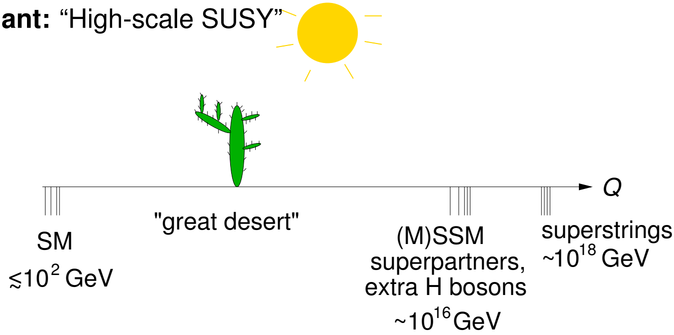

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Why we can't* match the SM to the MSSM at high scales

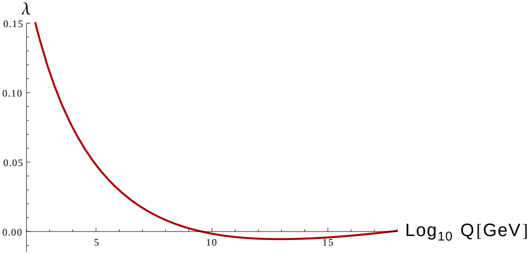
- H potential in SM:

$$V_H = -m^2|H|^2 + \frac{\lambda}{4}|H|^4$$

- quartic potential in the MSSM: positive definite D-term potential
- effective quartic coupling at matching scale:

$$\lambda = \frac{g^2 + g'^2}{8}\cos^2 2\beta \geq 0$$

- RG evolution of quartic coupling in SM:



- $\lambda(Q)$ becomes negative at a scale $Q \approx 10^{10}$ GeV

Why we can't* match the SM to the MSSM at high scales

* Caveat: RG evolution very sensitive to m_t!

$\lambda(M_{\text{Planck}}) > 0$ still allowed at somewhere between $\sim 1.3\,\sigma$ and $\sim 2.8\,\sigma$, depending on whom you ask $\rightarrow$ Buttazzo et al. '13, Alekhin/Djouadi/Moch '13, Andreassen/Frost/Schwartz '14, Bednyakov/Kniehl/Pikelner/Veretin '15...

Supersymmetry at high scales

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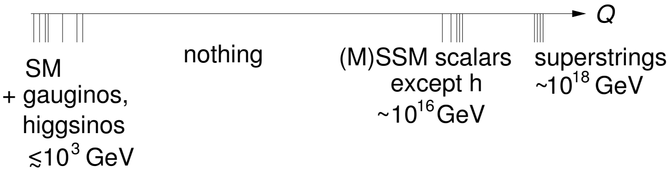
Second variant: "Split SUSY"



Even worse. → Bagnaschi/Giudice/Slavich/Strumia '14

Reason: By adding fermions with Yukawa couplings to H, running of λ is accelerated.

Supersymmetry at high scales

Hypothesis:
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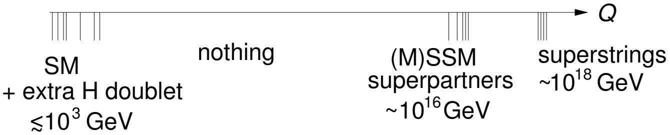
Third variant: SUSY at high scales with two light H doublets



This works → Lee/Wagner '15, BBBVW '15 and is the subject of this talk.

The THDM with high-scale SUSY

Setup:

- "Light" ($\lesssim$ TeV) d.o.f. = SM + second H doublet.
- "Heavy" (around $M_S \gtrsim M_{GUT}$) d.o.f. = squarks, sleptons, (gauginos, higgsinos)
- The general THDM has several quartic couplings. Some are not generated by matching to supersymmetry. Relevant here:

$$V_4 = \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4|H_1^\dagger H_2|^2$$

- Tree-level matching conditions at $Q = M_S$:

$$\lambda_1 = \frac{1}{4}\left(g^2 + g'^2\right), \qquad \lambda_2 = \frac{1}{4}\left(g^2 + g'^2\right),$$
$$\lambda_3 = \frac{1}{4}\left(g^2 - g'^2\right), \qquad \lambda_4 = -\frac{1}{2}g^2 .$$

Allows $m_h = 125$ GeV $\rightarrow$ Lee/Wagner '15

Vacuum stability

Quartic potential manifestly stable at matching scale: matching to global SUSY

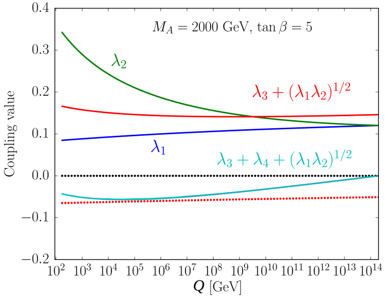
Nontrivial: Vacuum stability at intermediate scales

Vacuum stability conditions in THDM: → Deshpande/Ma '77

$$\lambda_1 > 0\,, \qquad \lambda_2 > 0\,, \qquad \lambda_3 + (\lambda_1\lambda_2)^{1/2} > 0\,, \qquad \lambda_3 + \lambda_4 + (\lambda_1\lambda_2)^{1/2} > 0\,.$$

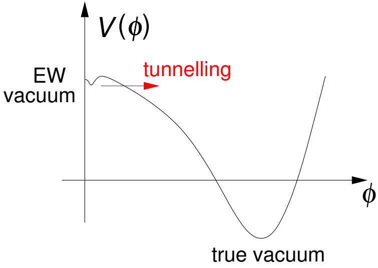
Need to satisfy this at all intermediate scales Q for stable EW vacuum.

Counterexample:



What happens when vacuum stability is violated?

Sketch of section of effective *H* potential (not to scale):



Along some direction ϕ in scalar field space the potential will steeply decrease at large ϕ towards another vacuum.

Eventually the EW vacuum will decay: bubble nucleation/tunnelling

→ Coleman '77

- Metastability: $\tau > 10$ Gyr
- Instability: $\tau < 10$ Gyr

Technicalities

- 2-loop RGEs → SARAH (Staub '08–'15)
- 1-loop, partial 2-loop matching → FlexibleSUSY (Athron/Park/Stöckinger/Voigt '14)
- High-scale thresholds neglected ⇒ large ±3 GeV theory uncertainty on h mass prediction. Small effect on stability conditions.
  - Rationale 1: we don't know the ~~SUSY~~ model.
  - Rationale 2: there is at least one ~~SUSY~~ model where they are suppressed → Buchmüller/Dierigl/Ruehle/Schweizer '15
- If vacuum unstable at intermediate scales: ∃ a preferred direction (steepest direction in field space) along which vacuum wants to decay. Effective quartic along this direction:

$$\lambda \equiv \frac{4\sqrt{\lambda_1\lambda_2}\,(\lambda_3+\lambda_4+\sqrt{\lambda_1\lambda_2})}{\lambda_1+\lambda_2+2\sqrt{\lambda_1\lambda_2}}$$

- Tunnelling probability for decay of EW vacuum → Isidori/Ridolfi/Strumia '01

$$p \approx \max_Q\,(\tau Q)^4 \exp\left(-\frac{8\pi^2}{3|\lambda(Q)|}\right)\,,$$

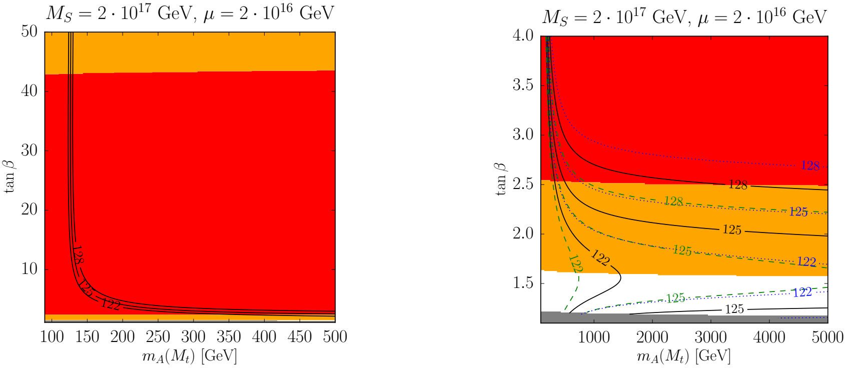
should be $\ll 1$ for $\tau = 10$ Gyr.

Results

Red = vacuum unstable

Orange = vacuum metastable

Contour lines = m_h in GeV for $m_t = 173.34^{+0.8}_{-0.8}$ GeV

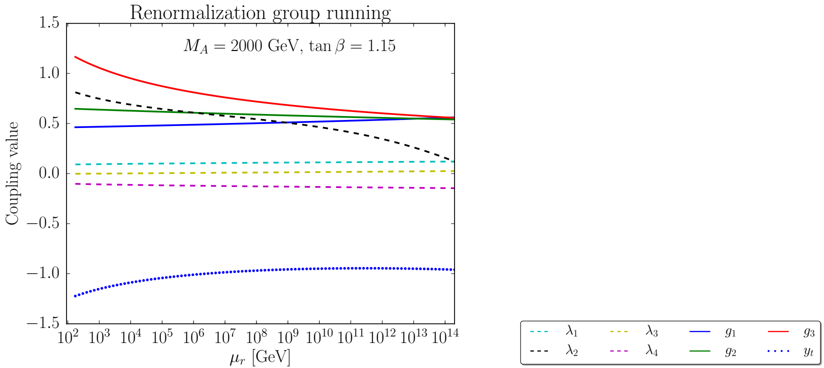


Note metastable region at low m_A, large $\tan\beta$ is ruled out by $A \to \tau\tau$, $b \to s\gamma$

Why do we need low tan β for stability?

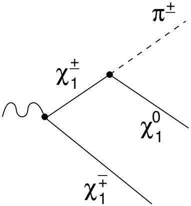
Somewhat counterintuitively, large y_t is favoured:

- The larger y_t, the faster λ_2 runs
- In SM: quartic fixed at EW scale by observation. Fast running to negative values $\Rightarrow$ instability at high scales
- In THDM: λ_2 fixed at scale M_S by matching to SUSY. Fast running to positive values $\Rightarrow$ stability at low scales



Variations on the theme

- THDM with light higgsinos: similar but more constrained.
  More interesting experimentally as the higgsino mass can be as low as 100 GeV
  LHC is starting to constrain this using disappearing chargino tracks:



$\rightarrow$ ATLAS-CONF-2013-069, CMS-EXO-12-034

- THDM with light higgsinos and gauginos (“split-THDM”):
  too constrained, $m_h = 125$ GeV unattainable

Summary

- SUSY might be broken at very high scales if the low-energy effective field theory is not the SM.
- The low-energy EFT could instead be a two-*H* doublet model.
- Large parts of the parameter space are constrained by vacuum (meta-)stability.
- What survives is the low $\tan\beta$, high m_A region.
- Extra *H* bosons at $\gtrsim$ 1 TeV out of reach for LHC, although future colliders might get there.
- A variation of the scenario has two *H* doublets and their superpartners as "light" d.o.f. Higgsino-like charginos and neutralinos can be (and are being) searched for by ATLAS and CMS.