Higgs Alignment from Extended Supersymmetry

Sophie Williamson

LPTHE, Sorbonne Université, CNRS

Based on work in collaboration with Karim Benakli and Mark Goodsell (arXiv:1801.08849)

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A la carte

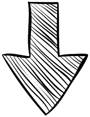
- Introduction
  - Higgs alignment
  - Dirac Gaugino models
  - $\mathcal{N} = 2$ supersymmetry
- Alignment in the MDGSSM
  - Low energy Two-Higgs Doublet Model limit
  - Causes of misalignment
  - Precision Study and results
  - Experimental Constraints
- Simplified MRSSM analysis

Motivation

- Absence of strongly-coupled particles at the LHC $\rightarrow$ interest in new electroweak-coupling particles.
- Is the Higgs boson part of a larger scalar sector?
- Strong LHC constraints imply the heavy Higgs should be aligned with or decoupled from the SM-like one.
- Interested in theories where alignment is untuned.
- Could finding a second Higgs doublet unveil a full SUSY theory?
- If SUSY is discovered, is R-symmetry conserved?

Higgs Alignment

- In minimal SUSY: Two complex $SU(2)$ Higgs doublets - $\mathbf{H_u}$, $\mathbf{H_d} \xrightarrow{\text{EWSB}}$ 5 physical Higgs bosons: h, H, A, $H^{\pm}$.
- However: strong contraints on Higgs couplings from experiment.



- *Higgs Alignment*: Mass eigenstates align with the VEV $\rightarrow$ SM-like Higgs.

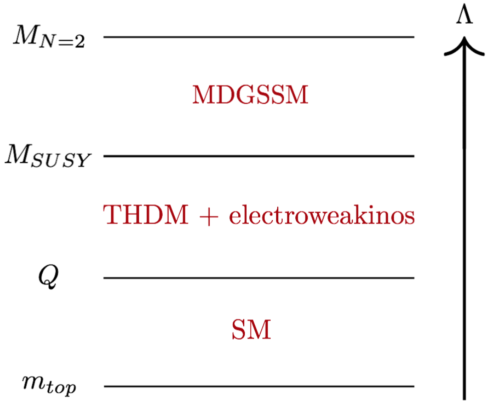
Alignment without decoupling

- Keep m_H light (possible LHC detection).
- Choosing masses/quartic couplings from the bottom-up
  $\rightarrow$ alignment is not generic.
- Interested in deriving the THDM couplings from the top-down
  $\rightarrow$ Find cases where Higgs alignment arises naturally.
- Higgs alignment can be realised from $\mathcal{N} = 2$ supersymmetry.

$\Rightarrow$ Minimal Dirac Gaugino Supersymmetric Standard Model (MDGSSM)

Effective Field Theory Approach

Our Model:

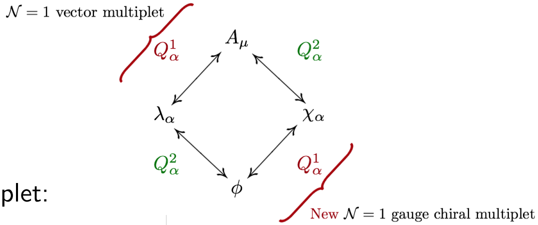


Minimal Dirac Gaugino Supersymmetric Standard Model

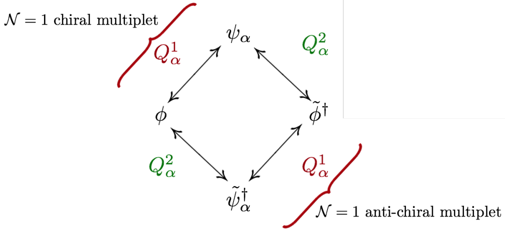
- Add $\mathcal{N} = 1$ chiral multiplets **S** (singlet), **T** ($SU(2)$ triplet), **O** ($SU(3)$ octet) in the adjoint representation of the corresponding gauge groups.
- Majorana gauginos (one Weyl fermion) $\rightarrow$ Dirac Gauginos (Weyl fermion + adjoint chiral fermion)
  - $\mathcal{L} \supset -\frac{1}{2}M_i\lambda_i\lambda_i + h.c. \quad \longrightarrow \quad \mathcal{L} \supset -m_{iD}\chi_i\lambda_i + h.c.$
  - Dirac masses preserve R-symmetry.
- New states destroy of gauge coupling unification.
  - Can add vector-like lepton fields to restore the property.

$\mathcal{N} = 2$ Supersymmetry

- Two supersymmetry generators: Q^1_α, Q^2_α.
- $\mathcal{N} = 2$ multiplets:
  - $\mathcal{N} = 2$ vector multiplet:



  - $\mathcal{N} = 2$ hypermultiplet:



$\mathcal{N} = 2$ Supersymmetry in a Dirac Gaugino model

- A fully $\mathcal{N} = 2$ supersymmetric lagrangian only permits gauge interactions.
- But isn't the matter sector fundamentally chiral and therefore $\mathcal{N} = 1$?

  $\rightarrow$ Assume $\mathcal{N} = 2$ supersymmetry in the Higgs/gauge sector only.

- 2 Higgs doublets of MSSM naturally sit in an $\mathcal{N} = 2$ hypermultiplet.
- New chiral superfields $\rightarrow$ $\mathcal{N} = 2$ extended gauge sector.

Modifications to the Higgs sector

- Choose $\mathcal{N} = 2$ conserving superpotential.
- Modification to the MSSM Higgs sector:

$$W_{\text{Higgs}} = \mu\, \mathbf{H_u} \cdot \mathbf{H_d} + \lambda_S \mathbf{S}\, \mathbf{H_u} \cdot \mathbf{H_d} + 2\lambda_T\, \mathbf{H_d} \cdot \mathbf{T} \mathbf{H_u}$$

- At tree level:
  $\mathcal{N} = 2$ supersymmetry imposes:

$$\lambda_S = \frac{g'}{\sqrt{2}}\,, \qquad \lambda_T = \frac{g}{\sqrt{2}}\,,$$

The Two-Higgs Doublet Model Limit: I

- Map the MDGSSM onto the two-Higgs doublet model (THDM)
  $\rightarrow$ Integrate out the adjoint scalars.
- THDM parametrization:

$$\begin{aligned} V_{EW} &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c}] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left[\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c} \right] , \end{aligned}$$

- To map the MDGSSM onto this, we make the identifications
  $\Phi_2 = H_u$,
  $\Phi_1^i = -\epsilon_{ij} (H_d^j)^*$
- In the limit of $|m_{DY}| \ll m_S, |m_{D2}| \ll m_T$

$$\lambda_1, \lambda_2 \rightarrow \frac{1}{4}(g_2^2 + g_Y^2), \qquad \lambda_3 \rightarrow \frac{1}{4}(g_2^2 - g_Y^2) + 2\lambda_T^2, \qquad \lambda_4 \rightarrow -\frac{1}{2} g_Y^2 + \lambda_S^2 - \lambda_T^2,$$

The Two-Higgs Doublet Model Limit: II

- Low energy theory: type-II two-Higgs doublet model with an additional Dirac Bino and Wino.
  - Mass of electroweakinos $\ll m_S, m_T$.
  - The gluino remains heavy: LHC constraints $\rightarrow \mathcal{O}(2 \text{ TeV})$.
- Running: Fix the boundary conditions at high energies, and run down.

Tree Level Alignment: I

Alignment basis:

- Mass matrices for the CP-even scalars:

$$\mathcal{M}_h^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} \qquad \text{with } Z_i = Z_i(\lambda_i).$$

- Alignment when $Z_6 \to 0$.
- With $\mathcal{N} = 2$ supersymmetry, at tree level:

$$Z_6 = -\frac{1}{2}\sin(2\beta)\cos(2\beta)\left[\frac{(g_2^2 + g_Y^2)}{2} - (\lambda_S^2 + \lambda_T^2)\right]$$

$\Rightarrow$ when the couplings take their $\mathcal{N} = 2$ values $\lambda_S^2 + \lambda_T^2 = \frac{g_2^2 + g_Y^2}{2}$, the Higgs doublets are automatically aligned!

Tree Level Alignment: II

The Higgs mass at tree level:

- Lightest Higgs mass given by the (1,1) component of $\mathcal{M}_h^2$
  $\rightarrow m_h^2 = Z_1 v^2$
- In terms of λ_i:

$$Z_1 v^2 = m_Z^2 + v^2 \left[(2\lambda_S^2 - g_Y^2) + (2\lambda_T^2 - g_2^2) \right] \sin(\beta)^2 \cos(\beta)^2$$

$\Rightarrow$ In alignment limit, see that $m_h^2 \rightarrow m_z^2$.

$\Rightarrow$ When couplings deviate from $\mathcal{N} = 2$ relations, get a tree-level boost to m_h.

Tree Level Alignment: Summary

- Heavy CP-even neutral scalar does not take part in EWSB.
- The model shows alignment for any value of $\tan\beta$:
  - $m_h^{N=2} = m_Z\,,\qquad m_H^{N=2} = m_A$
  - $m_{H^\pm}^{2,N=2} = m_A^2 + 2m_W^2 - m_Z^2\,.$

  $\Rightarrow$ First demonstrated by Antoniadis, Benakli, Delgado and Quirós in the context of gauge mediation arXiv:hep-ph/0610265.

  $\Rightarrow$ Phenomenological study done by Ellis, Quevillon, Sanz taking $M_{\mathcal{N}=2} = Q$ arXiv:1607.05541.

Misalignment: $\mathcal{N}=2$ to $\mathcal{N}=1$ SUSY

Radiative Corrections: Chiral Matter

- Chiral fields present at the $\mathcal{N}=2$ scale.
- Splitting of λ_S, λ_T from their $\mathcal{N}=2$ scale values during running:

$$Z_6(M_{SUSY}) = \frac{1}{4} s_{2\beta} c_{2\beta} \left[(2\lambda_S^2 - g_Y^2) + (2\lambda_T^2 - g_2^2) \right] + \text{threshold corrections.}$$

- Can find an approximate magnitude of the splitting by integrating over the difference in β_{λ_S} and β_{λ_T}:

$$\begin{aligned} \left[2\lambda_S^2 - g'^2\right]_{M_{SUSY}} &= -\frac{2g'^2}{16\pi^2}\left[3|y_t|^2 + 3|y_b|^2 + |y_\tau|^2 - 10g'^2\right] \log\left(\frac{M_{\mathcal{N}=2}}{M_{SUSY}}\right), \\ \left[2\lambda_T^2 - g^2\right]_{M_{SUSY}} &= -\frac{2g^2}{16\pi^2}\left[3|y_t|^2 + 3|y_b|^2 + |y_\tau|^2 - 6g^2\right] \log\left(\frac{M_{\mathcal{N}=2}}{M_{SUSY}}\right). \end{aligned}$$

$\Rightarrow$ Estimate e.g. $|Z_6(M_{SUSY})| \lesssim \mathcal{O}(0.1)$.

Misalignment: $\mathcal{N}=1$ to $\mathcal{N}=0$

Radiative Corrections: Mass splitting

- Mass splitting between the fermionic/bosonic components of the superpartners:

$$Z_6(v) \simeq Z_6(M_{SUSY}) + s_\beta^3 c_\beta \times \frac{3y_t^4}{8\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

- Less misalignment than in the MSSM:
  - No tree-level contribution to Z_6.
  - Stop correction to m_h smaller in the MDGSSM.
    $\rightarrow \mathcal{O}(\frac{1}{2})$ for $\tan\beta = 2$ because of:
    - Tree-level boost to m_h (so smaller stop contributions required)
    - Only small stop mixing is possible

Precision Study: Implementation

$Q \to M_{SUSY}$

- 1l matching Yukawas to SM values + 2l strong corrections to y_t.
- 1l gauge threshold corrections.
- 2l corrections to m_h.
- Running: 2l Low energy THDM + Dirac electroweakinos in SARAH.

$M_{SUSY} \to M_{\mathcal{N}=2}$

- Tree-level corrections from DG-masses and 1l corrections to λ_i.
- Conversion of $\overline{MS} \to \overline{DS}$ gauge + Yukawa couplings.
- Running: 2l MDGSSM in SARAH.

Assumptions

- $Q = 400$ GeV.
- M_{SUSY}: Stop masses; other MSSM particles $\to$ vary to obtain $m_h = 125.15$ GeV at 2l.

Other Inputs: Numerical values

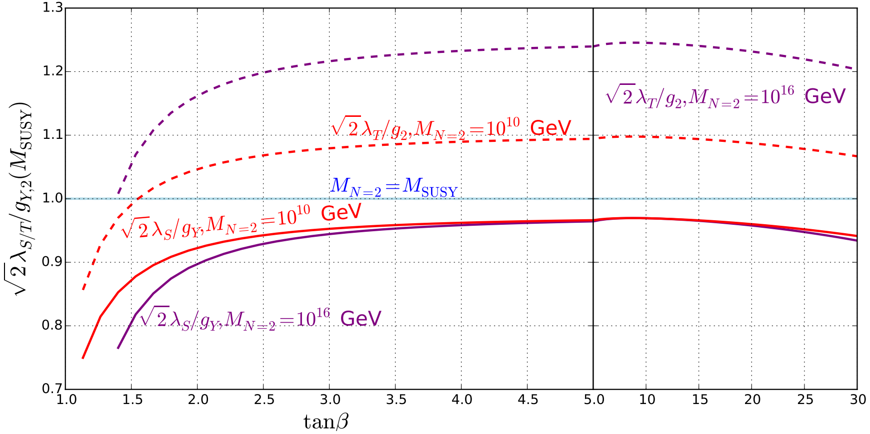
The precision study implemented scans over $\tan\beta$, M_{SUSY} and $M_{\mathcal{N}=2}$ and defined

- $M_{scalars}$ (heavier S, T scalars) $= 5$ TeV.
- $(m_{DY}, m_{D2}, \mu) = (400, 500, 600)$ GeV.
- $m_A^{tree} = 600$ GeV.
  - In the scans we see that $m_A^{tree} \sim m_H \sim m_{H^\pm}$ because of small mixing.
  - $\Rightarrow$ results not particularly sensitive to m_A^{tree}.

Precision Study: Results I (at M_{SUSY})

Dependence of the couplings on the $\mathcal{N} = 2$ scale:

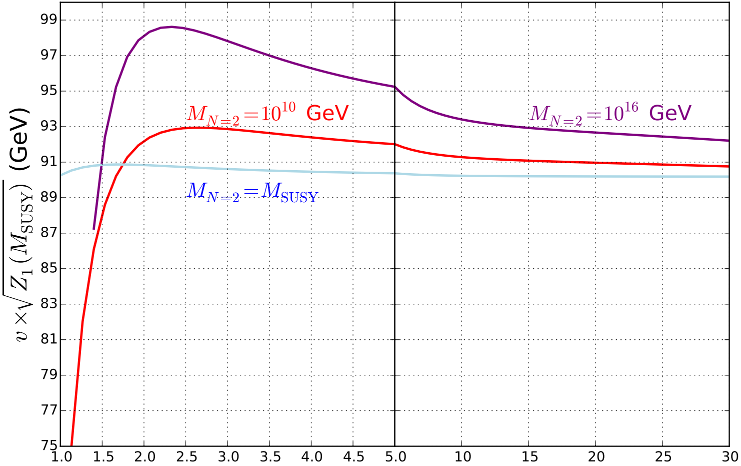
- Find $g_Y \sim 0.37$ and $g_2 \sim 0.64$ both at Q and M_{SUSY}, with little dependence on $M_{\mathcal{N}=2}$.
- Ratios show stronger dependence on $M_{\mathcal{N}=2}$.



$\rightarrow$ Enhancement of m_h due to λ_T splitting.

Precision Study: Results II (at M_{SUSY})

Tree level m_h before running $M_{SUSY} \to Q$.



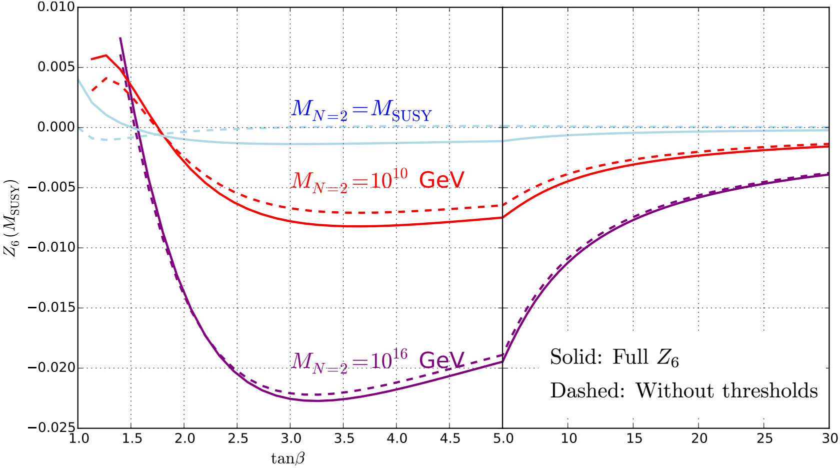
- Increasing $M_{\mathcal{N}=2}$ increases m_h.
- MSSM: m_h^{tree} goes like $m_Z|\cos\beta| \to$ drops off for small $\tan\beta$.

Precision Study: Results III (at M_{SUSY})

Alignment in the Dirac Gaugino Model: $Z_6(M_{SUSY})$

Recall:

$$Z_6(M_{SUSY}) = \frac{1}{4} s_{2\beta} c_{2\beta} \left[(2\lambda_S^2 - g_Y^2) + (2\lambda_T^2 - g_2^2) \right] + \text{threshold corrections}.$$



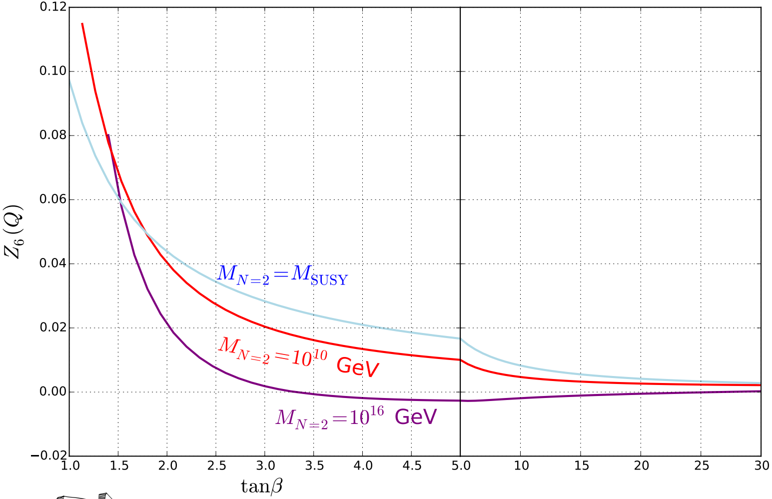
Estimation of Z_6 at Q

- Interpret corrections δ_{λ_i} as effect of integrating out supersymmetric particles at Q
  - Their effect is typically suppressed compared to the stop correction by
    - a numerical factor
    - g_2/y_t
- Effect of running from λ_S, λ_T non-negligible.
- Take m_A large with respect to m_h and m_Z, then

$$\Rightarrow Z_6 \approx \frac{0.12}{t_\beta} - \frac{1}{2}\frac{t_\beta}{1+t_\beta^2}\left[(2\lambda_S^2 - g_Y^2) + (2\lambda_T^2 - g_2^2)\right]$$

Precision Study: Results IV (at Q)

Alignment in the Dirac Gaugino Model: $Z_6(Q)$



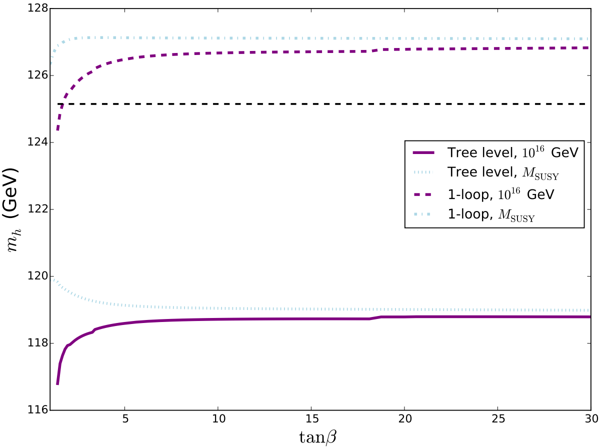
Independent of m_A, m_h is very SM-like for $\tan\beta \geq 3$.

Discussion: $Z_6(Q)$

- Reasonable fit of $Z_6(Q)$ with approximate formula
- Squark corrections enhance m_h but also misalignment
- This misalignment is compensated for by the running of λ_S and λ_T.
- $\Rightarrow$ Partial or total cancellation of misalignment contributions!

Precision Study: Results V

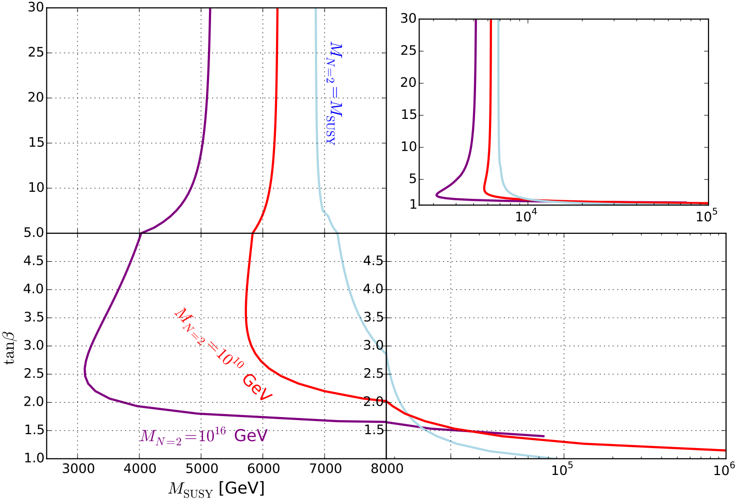
Effects of loop corrections in the low-energy theory on m_h.



→ Loop effects from tops, heavy Higgses and electroweakinos boost m_h by ~ 5 GeV.

Precision Study: Results VI

Higgs mass bounds on the SUSY scale



- Minimum for M_{SUSY} around $\tan\beta \in (2,3)$.

Discussion: Errors on M_{SUSY} scale in the MDGSSM

- Uncertainty on the Higgs mass bounds very difficult to estimate.
- Expect contributions not included to be small.

  $\Rightarrow$ Expect $\Delta m_h \leq$ GeV in comparison with the MSSM.
- Expect smaller errors at lower M_{SUSY}.

Experimental Constraints I

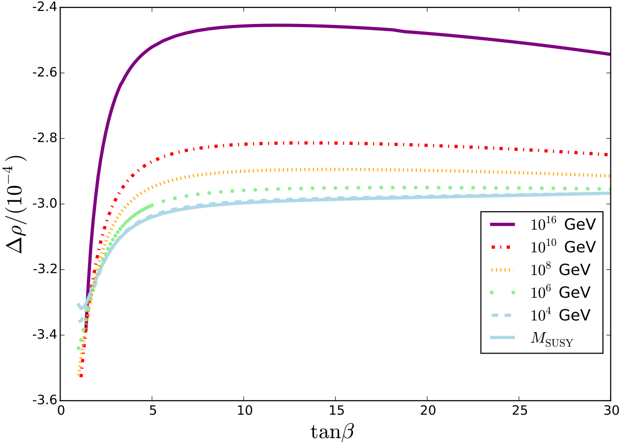
Higgs couplings

- Model realises excellent alignment → no significant constraint from Higgs couplings.

Electroweak precision corrections

Current bound:
$\Delta\rho = (3.7 \pm 2.3) \times 10^{-4}$
→ central value restricts $m_{T_+} > 2$ TeV.

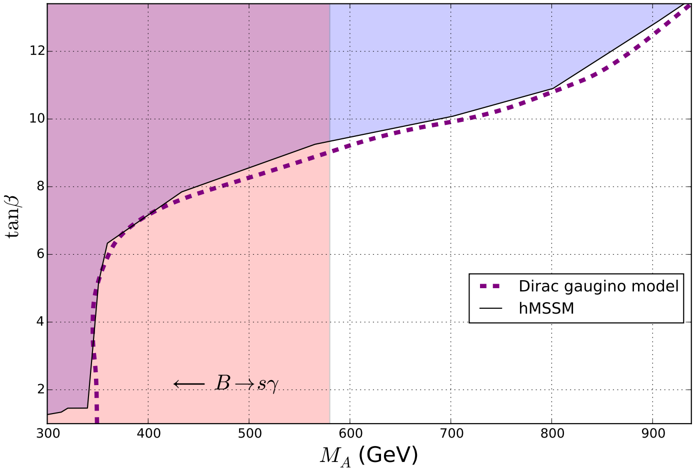
→ Always well within experimental bounds.



Experimental Constraints II

Strongest constraints come from flavour searches:

- B $\to$ sγ
- $pp \to H/A \to \tau\tau$



Bounds $m_{H^\pm}$ > 580 GeV indep. of t_β.

Simplified analysis
in other Dirac Gaugino models

The Minimal R-Symmetric Supersymmetric Standard Model (MRSSM)

- Preserve exact continuous R-symmetry by including two R-Higgs doublet superfields.
- Superpotential becomes:

$$W_{\mathsf{Higgs}}^{\mathrm{MRSSM}} = \quad \mu_u \, \mathbf{R_u} \cdot \mathbf{H_u} + \mu_d \, \mathbf{R_d} \cdot \mathbf{H_d} + \lambda_{S_u} \mathbf{S} \, \mathbf{R_u} \cdot \mathbf{H_u} + \lambda_{S_d} \mathbf{S} \, \mathbf{R_d} \cdot \mathbf{H_d} + 2\lambda_{T_u} \, \mathbf{R_u} \cdot \mathbf{T H_u} + 2\lambda_{T_d} \, \mathbf{R_d} \cdot \mathbf{T H_d} \, .$$

- $\mathcal{N} = 2$ supersymmetry must be imposed:

$$\lambda_{S_u} = \frac{g_Y}{\sqrt{2}}, \qquad \lambda_{S_d} = -\frac{g_Y}{\sqrt{2}}, \qquad \lambda_{T_u} = \lambda_{T_d} = \frac{g_2}{\sqrt{2}}.$$

- Can treat (R_u, H_u) and (R_d, H_d) as hypermultiplets.

Tree-Level Parameters

Tree-level THDM model parameters:

- In the limit of $|m_{DY}| \ll m_S, |m_{D2}| \ll m_T$
- Recall for the MDGSSM:

$$\lambda_1, \lambda_2 \to \frac{1}{4}(g_2^2 + g_Y^2), \qquad \lambda_3 \to \frac{1}{4}(g_2^2 - g_Y^2) + 2\lambda_T^2, \qquad \lambda_4 \to -\frac{1}{2}g_Y^2 + \lambda_S^2 - \lambda_T^2,$$

- For the MRSSM: $\lambda_i^{\mathrm{MRSSM}} \to \lambda_i^{MSSM}$ and so

$$\lambda_i^{\mathrm{MSSM}}, \lambda_2^{\mathrm{MSSM}} \to \frac{1}{4}(g_2^2 + g_Y^2), \qquad \lambda_3^{\mathrm{MSSM}} \to \frac{1}{4}(g_2^2 - g_Y^2), \qquad \lambda_4^{\mathrm{MSSM}} \to -\frac{1}{2}g_Y^2.$$

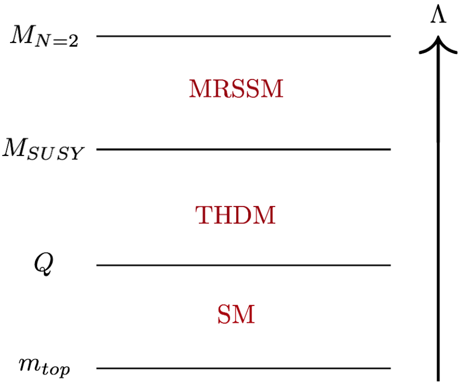
Alignment in the $\mathcal{N} = 2$ MRSSM

- No automatic alignment.
- For m_S, m_T large: THDM parameters $\lambda_i \to \lambda_i^{MSSM}$
  - $\Rightarrow$ No contribution from $\lambda_{T_{u,d}}, \lambda_{S_{u,d}}$ to Z_6.
- With radiative corrections: for non-zero $\lambda_{T_{u,d}}, \lambda_{S_{u,d}}$
  - No shift to Z_6 from the adjoint scalars.
  - Enhancement of Z_1.
  - Insignificant Z_1 enhancement if $m_S, m_T \sim m_{\tilde{t}}$
  - If m_S, m_T very heavy:
    - Improved alignment compared to the MSSM.
- Alignment never as good as in MDGSSM because of tree-level contribution to misalignment.

Effective Field Theory Tower for the MRSSM

- Alignment only different from MSSM when m_S, m_T very large
  - For a precise analysis, would need a tower of EFTs and appropriate threshold corrections.

$\Rightarrow$ Simplified model:



Numerical Analysis in the MRSSM: Procedure

Iterative method to converge λ_i and $\lambda_{S,T_{u,d}}$ couplings, before mapping back onto the Higgs quartic, λ.

$m_{top} \to Q$

- 2l matching Yukawas, gauge and Higgs quartic couplings to SM values.
- Running: 2l SM in SARAH.

$Q \to M_{SUSY}$

- Iterative process to determine λ_i.
- Running: 2l Low energy THDM in SARAH.

$M_{SUSY} \to M_{\mathcal{N}=2}$

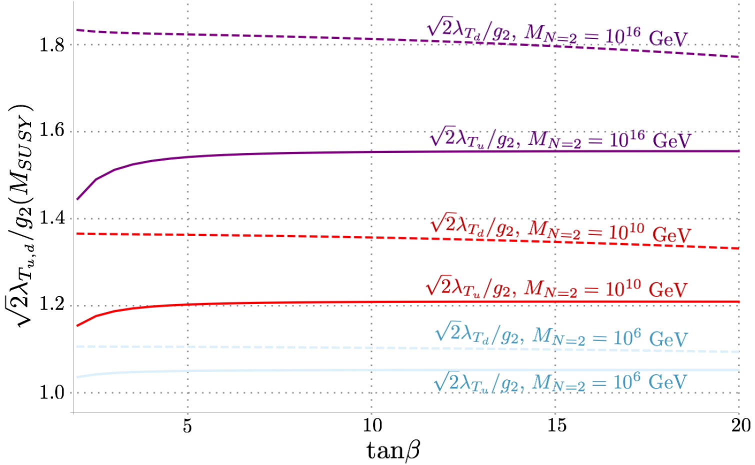
- 1l threshold corrections to S, T.
- Running: 2l MRSSM in SARAH.

Assumptions

- Neglect all loop-level thresholds other than those from S and T.
- $Q = 600$ GeV.
- Degenerate adjoint scalar masses, M_Σ.

MRSSM results: I

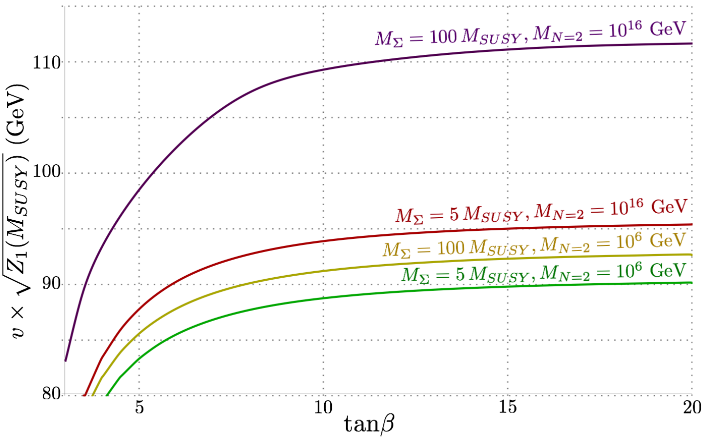
Dependence of $\lambda_{T_{u,d}}/g_2$ on the $\mathcal{N}=2$ scale



$M_{SUSY} = 10$ TeV
$M_\Sigma = 10\ M_{SUSY}$

MRSSM results: II

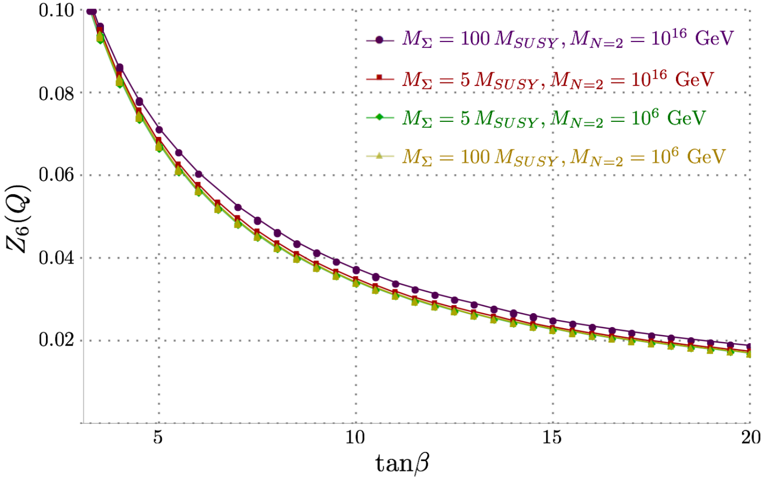
"Tree level" Higgs mass at M_{SUSY}



- Extremely boosted value for extreme M_Σ and $M_{\mathcal{N}=2}$ due to almost non perturbative λ_T couplings

MRSSM results: III

Alignment at Q



Little deviation in Z_6, regardless of M_Σ and $M_{\mathcal{N}=2}$.

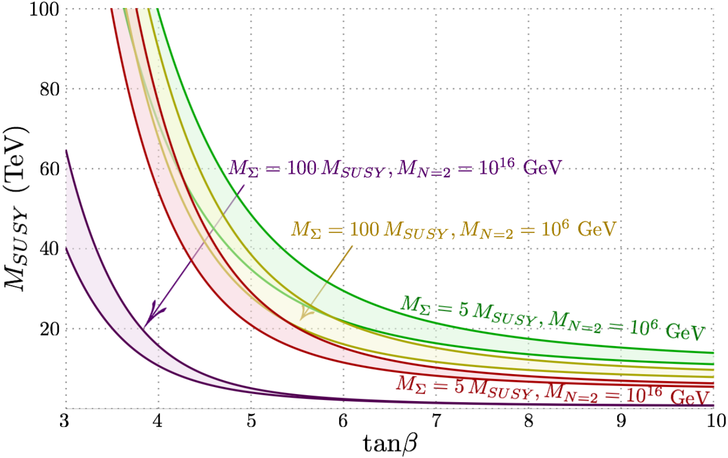
Discussion: Alignment in the MRSSM

- $Z_6(Q)$ similar to in the MSSM case.
- Adjoint scalars never give a large boost to the Higgs quartic.
- When very high $M_{\mathcal{N}=2}$ and heavy M_Σ, the couplings are considerably enhanced

  $\Rightarrow$ Worse alignment.

MRSSM results: IV

Approximate Higgs mass bounds on M_{SUSY} in the MRSSM



- For $\tan\beta < 4$, $M_{SUSY} \geq 20$ TeV.
- Potentially unreliable results for large M_Σ and M_{SUSY}.

Discussion: M_{SUSY} in the MRSSM

- S, T give very small boost to m_h but see noticeable effects in M_{SUSY}.

Errors

- Here we take $m_h = 125 \pm 0.5$ GeV.
- Error on M_{SUSY} grows as M_{SUSY} increases:
  - Recall corrections to parameters $\propto y_t^4 \log \frac{m_{\tilde{t}}^2}{m_t^2}$
  - As $M_{SUSY} \uparrow$, $y_t \downarrow$

    $\Rightarrow$ Require bigger shift in M_{SUSY} to get m_h
  - Results at lower M_{SUSY} more accurate.
- EFT approach is less accurate when $M_{SUSY} \leq$ TeV.

Conclusions

In the MDGSSM:

- Alignment is realised naturally in $\mathcal{M}_h$, and preserved by quantum corrections.
- The splitting of λ_S and λ_T from the $\mathcal{N} = 2$ relations
  - Boosts m_h
  - Lowers M_{SUSY}
  - Improves alignment
- M_{SUSY} could be as low as 3 TeV.

In the MRSSM:

- Enforced $\mathcal{N} = 2$ can increase alignment with respect to the MSSM, in the limit of large adjoint scalar masses