R-symmetry for Higgs alignment

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Based on:
I. Antoniadis - K.B. - A. Delgado - M. Quiròs '06
K. B. - M.D. Goodsell - S. Williamson '18
K. B. - Y. Chen - G. Lafforgue - Marmet '18

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A New Hope

Super brane-worlds for 2HDM

SUSY braneworlds ⟶ Boundaries 4D N=1 SUSY + Bulk 5D N=2 SUSY

- N=2 in the bulk: Non-chiral states (gauge & Higgs sectors)

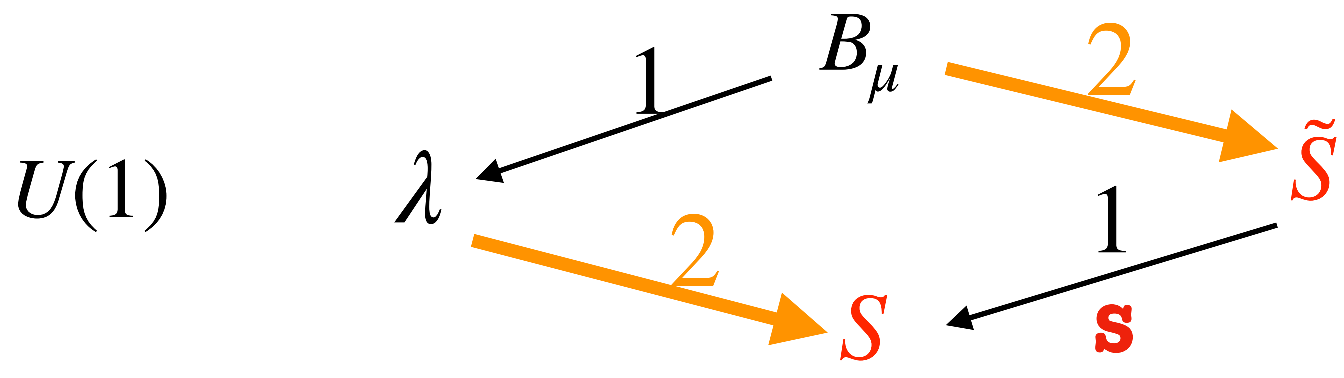
- N=1 on the boundaries: Chiral matter (leptons & quarks)

I. Antoniadis - K.B. - A. Delgado - M. Quiròs, '06

Making the World Double Supersymmetric

- The two MSSM Higgs doublets become an N=2 supersymmetry hypermultiplet.

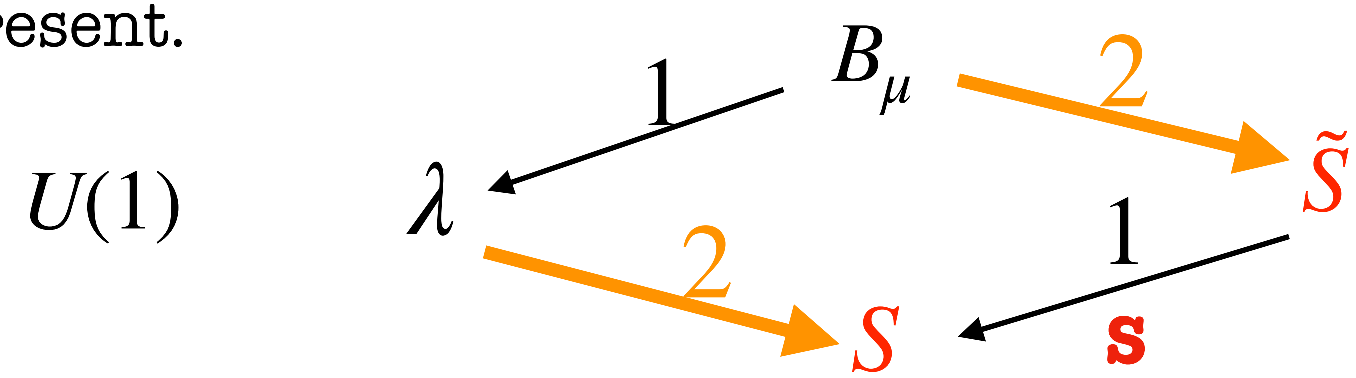
- Two chiral supermultiplets **S** and **T**, adjoints of **U(1)** and **SU(2)** are present.



Dirac Gauginos

➡ The two MSSM Higgs doublets become an N=2 supersymmetry hypermultiplet.

➡ Two chiral supermultiplets **S** and **T**, adjoints of **U(1)** and **SU(2)** are present.



➡ **S** and **T** fermionic components combine with **U(1)** and **SU(2)** gauginos to generate Dirac masses for gauginos.

P. Fayet, '78

N=2/N=1 versus N=1 (MDGSSM vs MSSM)

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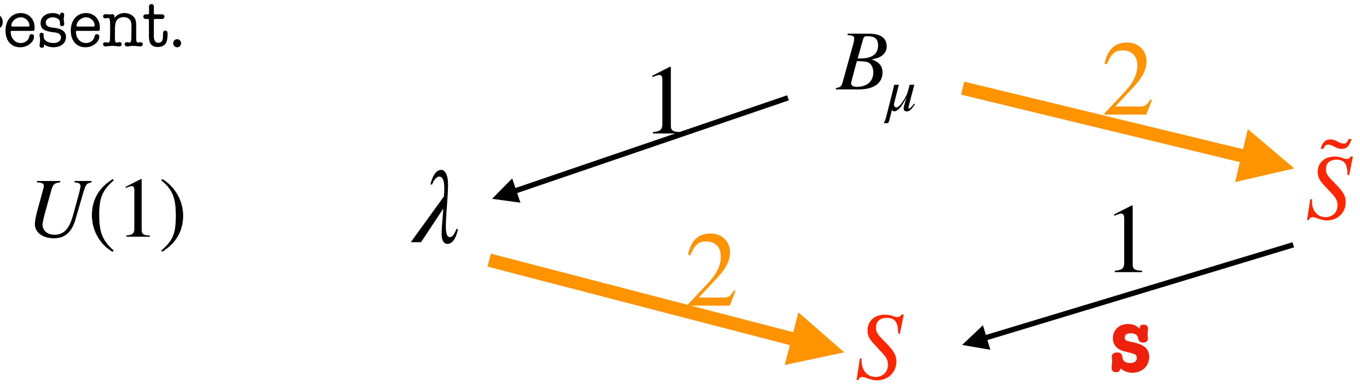
➡ Two chiral supermultiplets **S** and **T**, adjoints of **U(1)** and **SU(2)** are present.



➡ **S** and **T** fermionic components combine with **U(1)** and **SU(2)** gauginos to generate Dirac masses for gauginos.

P. Fayet, '78

➡ The N=1 Higgs superpotential has a new form:

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

➡ The N=2 origin implies: $\lambda_S = \frac{g'}{\sqrt{2}}, \qquad \lambda_T = \frac{g_2}{\sqrt{2}}$

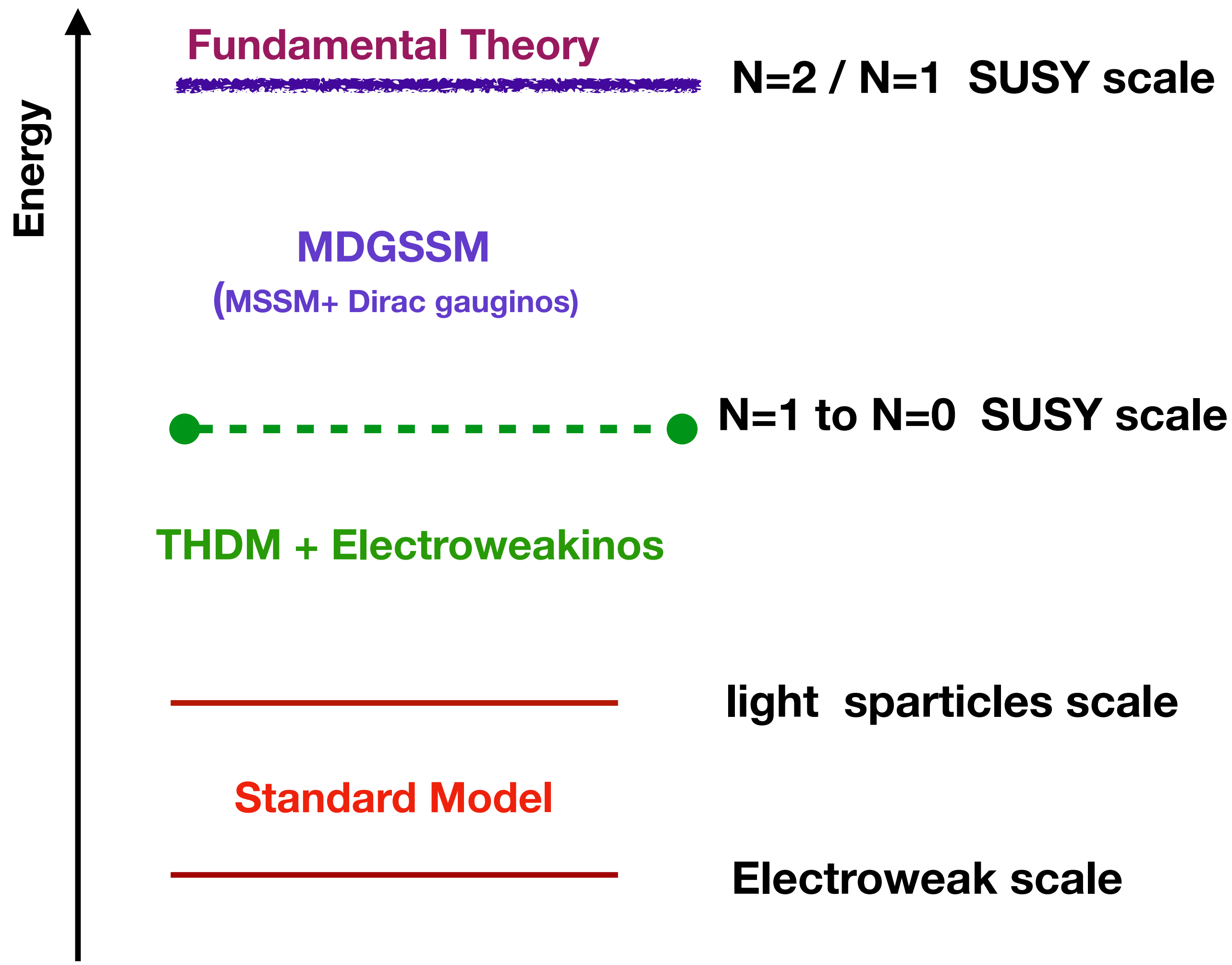
I. Antoniadis - K.B. - A. Delgado - M. Quiròs, '06

Decoupling the S and T scalars: 2HDM

SUSY braneworlds ⟶ Boundaries 4D N=1 SUSY + Bulk 5D N=2 SUSY

Make the scalars in ***S*** and ***T*** adjoints very heavy ⟶ 2HDM effective model

- N=2 in the bulk: Non-chiral states (gauge & Higgs sectors)
- N=1 on the boundaries: Chiral matter (leptons & quarks)



I. Antoniadis - K.B. - A. Delgado - M. Quiròs, '06

Higgs potential (neutral components)

$$V_{EW} = V_0 + V_1 + V_2$$

The first part is the MSSM contribution.

$$V_0 = \frac{(m_{H_u}^2 + \mu^2)}{2} h_u^2 + \frac{(m_{H_d}^2 + \mu^2)}{2} h_d^2 - B_\mu h_u h_d + \frac{g^2 + g'^2}{32}(h_u^2 - h_d^2)^2$$

V_1 is a quartic term:

$$V_1 = \frac{{\lambda_S}^2 + {\lambda_T}^2}{4} h_u^2 h_d^2$$

V_2 contains the explicit dependence on the mass parameters of S and T

$$m_S \to \infty \quad \& \quad m_T \to \infty \quad \Rightarrow \quad V_2 \to 0$$

I. Antoniadis - K.B. - A. Delgado - M. Quiròs, '06

G. Belanger - K.B. - M. Goodsell - C. Moura, '09

Remind:

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

Basis change

Go to the basis where one Higgs has a vev:

$$\begin{pmatrix} h_d \\ h_u \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} s_\beta & c_{\beta-\alpha} \\ c_\beta & -s_\beta \end{pmatrix} \begin{pmatrix} v + \tilde{h} \\ \tilde{H} \end{pmatrix}$$

The mass matrix is written as:

$$\mathcal{M}^2_{Higgs} \equiv \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}$$

If $Z_6 \neq 0 \rightarrow$ another rotation:

$$\begin{pmatrix} \tilde{h} \\ \tilde{H} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} s_{\beta-\alpha} & c_{\beta-\alpha} \\ c_{\beta-\alpha} & -s_{\beta-\alpha} \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

If $Z_6 = 0 \rightarrow$ **Alignment without decoupling** $h = \tilde{h}$

J. Gunion - H. Haber, '02

Alignment without decoupling

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In our N=2/N=1 model:

$$Z_6 = -\frac{1}{2} s_{2\beta} c_{2\beta} \left[\frac{(g^2 + g'^2)}{2} - ({\lambda_S}^2 + {\lambda_T}^2) \right]$$

N=2 Higgs requires:

$$\lambda_S = \frac{g'}{\sqrt{2}}, \qquad \lambda_T = \frac{g_2}{\sqrt{2}}$$

$\Rightarrow Z_6 = 0 \quad \Rightarrow$ Alignment for all values of β

I. Antoniadis - K.B. - A. Delgado - M. Quiròs, '06

The N=2 Strikes Back

The N=2 SUSY strikes back

In 2006 (Before the LHC)

I. Antoniadis - K.B. - A. Delgado - M. Quiròs, '06

In 2016 (in the LHC era)

J. Ellis - J. Quevillon - V. Sanz, '16

This model in light of LHC searches:
doubling up SUSY: a way to alignment
SUSY phenomenology different from the MSSM

Now

- This is a tree-level alignment. What is the size of the misalignment induced by radiative corrections?

- **What is at the origin of this alignment?**

The Quantum Menace

Standard 2HDM parameters

Map our N=2/N=1 model onto the 2HDM with the identification:

$$\Phi_2 = H_u, \qquad \Phi_1^i = -\epsilon_{ij}(H_d^j)^* \leftrightarrow \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = \begin{pmatrix} \Phi_1^0 \\ -(\Phi_1^+)^* \end{pmatrix}$$

$$V_{4\Phi} = \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+ \left[\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \textbf{h.c}\right]$$

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

$$\lambda_5 = \lambda_6 = \lambda_7 = 0.$$

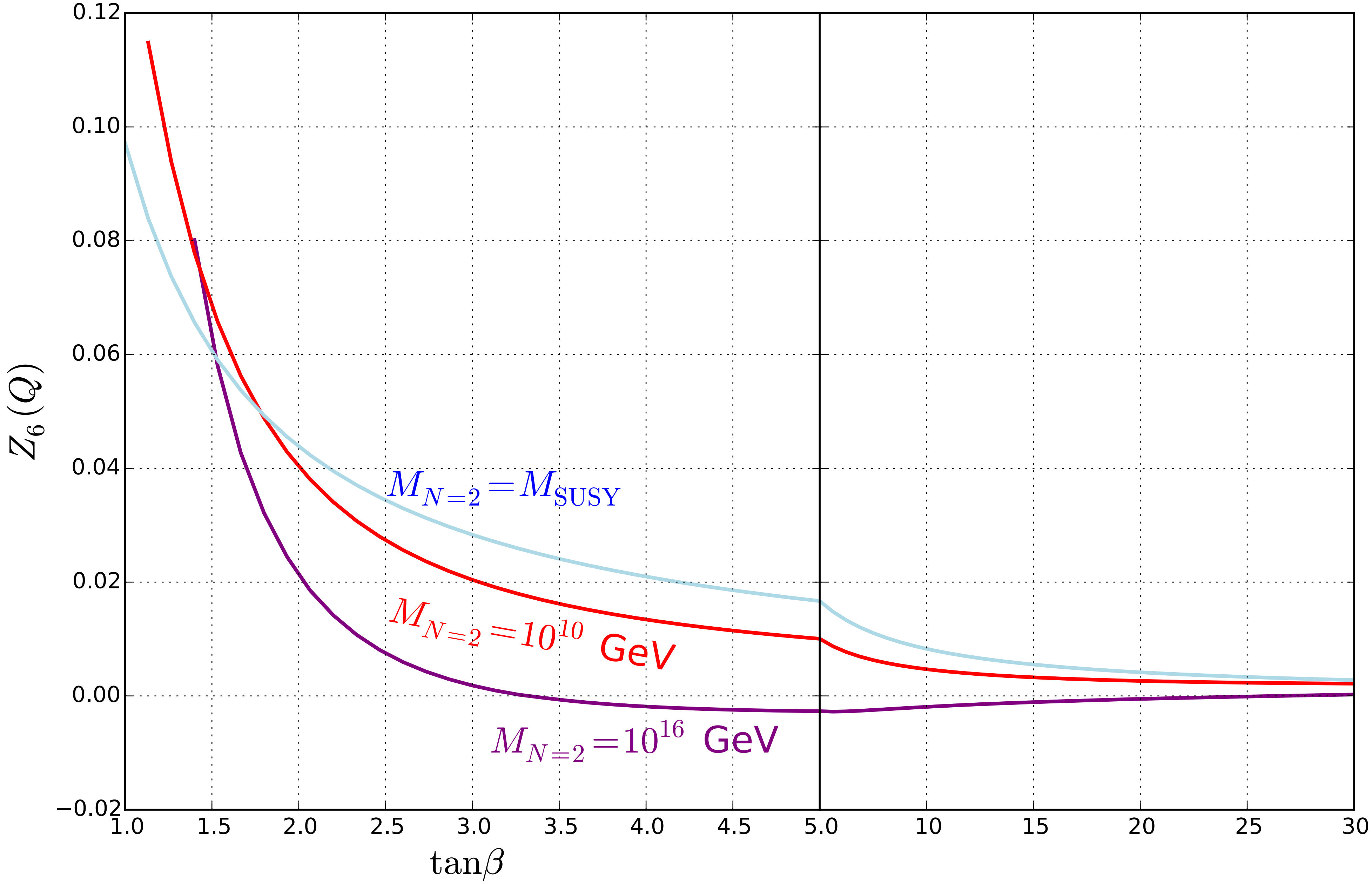
Compute:

$$Z_6 = -\frac{1}{2}s_{2\beta}\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \lambda_5)\, c_{2\beta}\right]$$

with the radiative corrections

Quantitative Misalignment

K.B. - M. Goodsell - S. Williamson, '18



- Q=400 GeV for the low-energy matching scale.
- Good alignment for all values.
- Raising the N=2 scale improves the alignment.

The N=2 SUSY strikes back

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I. Antoniadis - K.B. - A. Delgado - M. Quiròs, '06

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The SU(2) Awakens

A global non-abelian symmetry

N=2 SUSY implies an $U(1)_R \otimes SU(2)_R$ symmetry:

- $(\Phi_1, \Phi_2)^T$ form a doublet of $SU(2)_R$

A global non-abelian symmetry

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- The scalar potential can be written as a sum

$$V_{4\Phi} = \sum_{l,m} \lambda_{|l,m>} |l, m\rangle$$

I. Ivanov, '07

where $|l, m\rangle$ are the representations of $SU(2)_R$

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I. Ivanov, '07

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For our N=2/N=1 SUSY model:

- $\left(ReF_{(S,T)} \; , \; \frac{D^a}{\sqrt{2}} \; , \; ImF_{(S,T)}\right)$ form a triplet of $SU(2)_R$

$$\Rightarrow \quad \lambda_S = \frac{g'}{\sqrt{2}}, \qquad \lambda_T = \frac{g_2}{\sqrt{2}} \qquad \text{in:}$$

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

Quartic 2HDM potential in the MDGSSM

K.B. - Y. Chen - G. Lafforgue-Marmet, '18

The quartic part of the scalar potential takes the form:

$$V_{4\Phi} = \lambda_{|0_1,0>} |0_1,0\rangle \quad + \quad \lambda_{|0_2,0>} |0_2,0\rangle$$

where

$$|0_1,0\rangle = \frac{1}{2}\left[(\Phi_1^\dagger\Phi_1) + (\Phi_2^\dagger\Phi_2)\right]^2$$

$$|0_2,0\rangle = -\frac{1}{\sqrt{12}}\left[\left((\Phi_1^\dagger\Phi_1) - (\Phi_2^\dagger\Phi_2)\right)^2 + 4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)\right]$$

and

$$\lambda_{|0_1,0>} = \frac{3g_2^2}{8} \qquad \lambda_{|0_2,0>} = \frac{(-2g_2^2 + g_Y^2)}{8}$$

Also:

$$Z_6 = \frac{1}{2}s_{2\beta}\left[\sqrt{2}\lambda_{|1,0>} - \sqrt{6}\lambda_{|2,0>}c_{2\beta} + (\lambda_{|2,-2>} + \lambda_{|2,+2>})c_{2\beta}\,.\right]$$

$\longrightarrow$ 0 for our model

Quadratic 2HDM potential

The quadratic part of the scalar potential takes the form:

$$V_{2\Phi} = \frac{m_{11}^2 + m_{22}^2}{\sqrt{2}} \times \frac{1}{\sqrt{2}} \left[(\Phi_1^\dagger \Phi_1) + (\Phi_2^\dagger \Phi_2) \right]$$

$$+ \frac{m_{11}^2 - m_{22}^2}{\sqrt{2}} \times \frac{1}{\sqrt{2}} \left[(\Phi_1^\dagger \Phi_1) - (\Phi_2^\dagger \Phi_2) \right] \quad - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \textbf{h.c}]$$

Only the first line is   invariant

The minimisation equations lead to: **H. Haber - R. Hempfling, '93**

$$0 = \frac{1}{2}(m_{11}^2 - m_{22}^2) s_{2\beta} + m_{12}^2 c_{2\beta} \equiv Z_6 v^2$$

For our N:2/N=1 model, this fixes β

K.B. - Y. Chen - G. Lafforgue-Marmet, '18

Misalignment

Misalignment origins:

K.B. - M. Goodsell - S. Williamson, ‘18
K.B. - Y. Chen - G. Lafforgue-Marmet, ‘18

- Threshold corrections from integrating out heavy fields (small)
- Radiative corrections from chiral matter

1. $N=2 \to N=1$ SUSY running of the couplings:

$$\lambda_S = \neq \frac{g'}{\sqrt{2}}, \qquad \lambda_T \neq \frac{g_2}{\sqrt{2}} \qquad \Rightarrow \qquad \delta Z_6^{(2\to1)} = -\frac{\sqrt{6}}{2}\, s_{2\beta}\, c_{2\beta}\, \delta\lambda^{(2\to1)}_{|2,0>}$$

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

2. $N=1 \to N=0$ SUSY breaking:

$$m_{\tilde{t}}^2 \neq m_t^2 \qquad \Rightarrow \qquad \delta Z_6^{(1\to0)} \simeq s_\beta^3 c_\beta \times \frac{3y_t^4}{8\pi^2}\log\frac{m_{\tilde{t}}^2}{m_t^2}$$

The two contributions are of order 0.1 but with opposite signs.

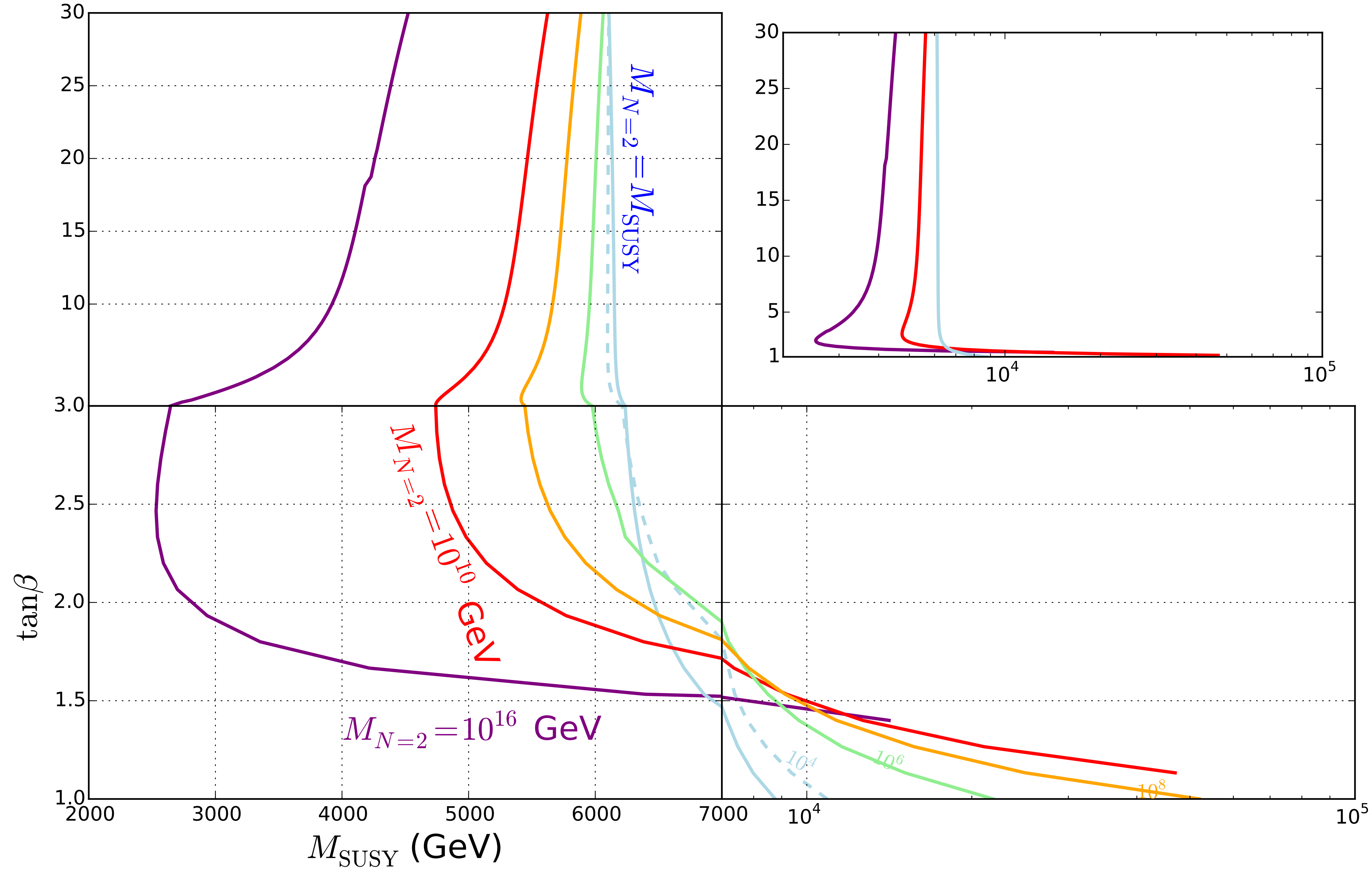
→ Small misalignment

Summary

- Quartic and quadratic Higgs potential have different (tree-level) symmetries.
- N=2 SUSY leads to SU(2) R-symmetry for the quartic potential.
- SU(2) symmetry of quartic potential leads to alignment.
- Radiative corrections under control lead to small misalignment.

Thank You!

Fitting 125 GeV



- SUSY fitting 125.2 GeV Higgs. The cases M_{N=2} =M_SUSY, 10^10 GeV, 10^16 GeV are the solid lines in blue, red and purple respectively and are labelled in full; the cases M_{N=2} = 10^4, 10^6, 10^8 GeV are respectively shown in blue dashed, solid green and solid orange curves and only labelled with{ 10^4, 10^6, 10^8}.