Heterotic NMSSMs

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Why the NMSSM ?

- μ–problem: why is $\mu \ll M_{\rm GUT}$?

$$\lambda S H_u H_d \subset W \qquad \rightarrow \qquad \mu = \lambda \langle S \rangle$$

- fine-tuning / little hierarchy problem:

  SUSY tree level prediction $m_h \leq m_Z$ vs. LEP bound

  MSSM $\quad m_h > 114$ GeV $\quad \rightarrow$ very heavy superpartners

  large finetuning ☹

  NMSSM $\quad m_h > 90$ GeV $\quad \rightarrow$ light superpartners

  small / no fine-tuning ☺

- PQ limit can solve simultaneously the strong CP-problem

Kim, Nilles (1984)

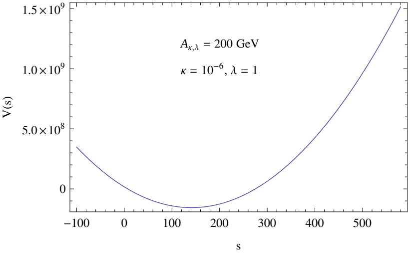
The NMSSM

MSSM + singlet S, such that

$$W = W_{MSSM} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

$$V(s) = -2\lambda A_\lambda v_u v_d s + m_S^2 s^2 + (\kappa s^2 - \lambda v_u v_d)^2 + (\lambda v_d s)^2 + \frac{2}{3}\kappa A_\kappa s^3$$

E.g. the (slightly) broken PQ limit ($\kappa \ll 1$)



$$\rightarrow \quad \mu = \lambda\langle s\rangle \gtrsim 100 \text{ GeV}$$

NMSSM: the PQ limit

The $\mathrm{U}(1)_{PQ}$ symmetry

$$W_{NMSSM} = \lambda S H_u H_d \quad \Rightarrow \quad H_{u,d} \to e^{\mathrm{i}\alpha} H_{u,d},\ S \to e^{-2\mathrm{i}\alpha} S$$

spontaneous breaking of $\mathrm{U}(1)_{PQ}$ produces a CP-odd scalar:

$$\to \qquad a_{\mathrm{PQ}} = \sin 2\beta (a\,\mathrm{Im}\, H_u + b\,\mathrm{Im}\, H_d) + c\,\mathrm{Im}\, S$$

More importantly

$$Br(h \to 2\ a_{\mathrm{PQ}}) \gg Br(h \to b\bar{b})$$

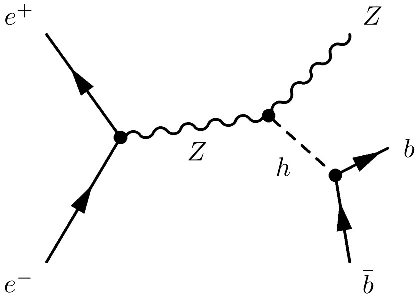
Dobrescu, Landsberg, Matchev (2001)

LEP less sensitive to $h \to 2\ a_{\mathrm{PQ}}$

$\Rightarrow$ bound relaxes $m_h > 90$ GeV ✓

NMSSM: the PQ limit

In the MSSM:



LEP constraint: $m_h > 114$ GeV

NMSSM: the PQ limit

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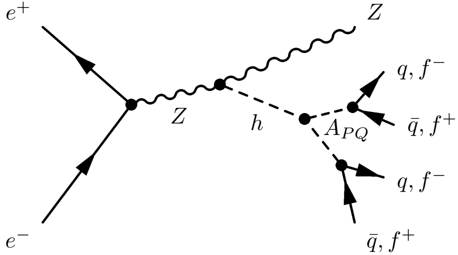

LEP constraints: $m_h > 105$ GeV for τ's
$m_h > 90$ GeV for light quarks

Why string theory ?

- ☺ predicts SUSY
- ☺ includes gravity
- ☺ can reproduce the *exact* MSSM spectrum
- ☺ there are especially "fertile patches" like

The Heterotic Minilandscape:

- ~ 300 MSSM candidates
- no exotics
- gauge unification
- heavy top
- TeV gravitino mass
- seesaw
- R-parity
- flavor symmetries

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$$\left.\begin{array}{l}\text{no exotics}\\ \text{gauge unification}\\ \text{heavy top}\end{array}\right\}\ \text{demanded}$$

$$\left.\begin{array}{l}\text{TeV gravitino mass}\\ \text{seesaw}\\ R\text{-parity}\\ \text{flavor symmetries}\end{array}\right\}\ \text{for free !!}\ ☺$$

Heterotic NMSSMs: general features

Avoid MSSM fine-tuning/μ–problem in the ML $\quad\longrightarrow\quad$ Find NMSSM

- find "massless" SM singlet S
- sizable coupling $S\,H_u\,H_d$, i.e. $\lambda \sim \mathcal{O}(1)$

In heterotic orbifolds

- μ–term *very* suppressed

s. talk by Rolf Kappl

- S charged under additional groups
- $S\,H_u\,H_d$ at trilinear order possible
- S^3 only possible at higher orders

$$\Rightarrow \quad \lambda = \text{const} + \langle s_{a_1} ... s_{a_n} \rangle, \qquad \kappa = \langle s_{b_1} ... s_{b_n} \rangle$$

Heterotic NMSSMs: general features

Size of $\langle s_i \rangle$ determined by

$$D_{\mathrm{FI}} = \xi + \sum_i q^i_{\mathrm{anom}} |\langle s_i \rangle|^2 \overset{!}{=} 0\,, \quad \xi \sim \mathcal{O}(0.1) \text{ in Planck units}$$

$$\rightarrow \quad \langle s_i \rangle \sim \mathcal{O}(0.1)$$

$$\rightarrow \qquad \boxed{\kappa \ll 1, \qquad \lambda \lesssim \mathcal{O}(1)} \qquad ☺$$

Two heterotic NMSSM escenarios:

- $\lambda \sim 1,\ \kappa \ll 1$ Peccei-Quinn limit
- $\lambda,\ \kappa \ll 1$ "effective MSSM"

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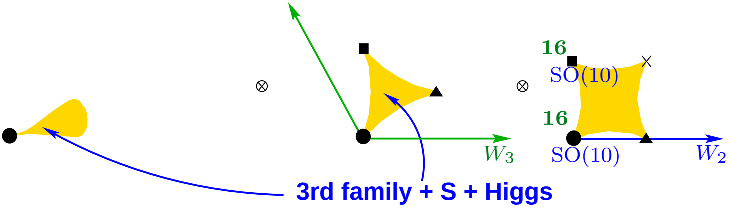
Heterotic NMSSMs: 2WL vs 3WL

$$\mathcal{O} = T^2 \times T^2 \times T^2 \Big/ \mathbb{Z}_6 - \mathrm{II}$$

Scan over the "fertile patch" of the ML



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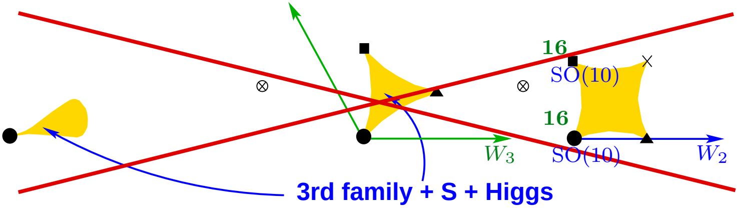


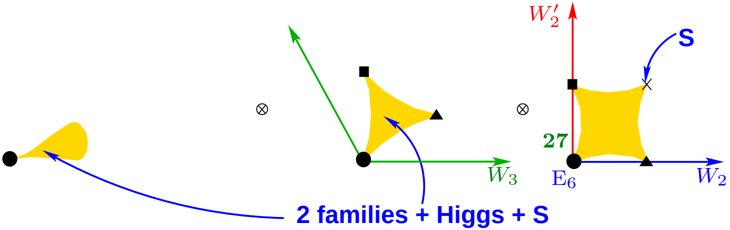
All singlets and exotics decouple simultaneously ☹

$\boxed{\text{Models with 3 WL are more suitable! ☺}}$

Example

Gauge embedding

$$\begin{aligned}
V_{SE} &= \left(\tfrac{1}{6},\, -\tfrac{1}{3},\, -\tfrac{1}{2},\, 0,\, 0,\, 0,\, 0,\, 0\right)(0,\, 0,\, 0,\, 0,\, 0,\, 0,\, 0,\, 0)\ ,\\
W_2 &= \left(1,\, \tfrac{1}{2},\, 0,\, \tfrac{1}{2},\, \tfrac{1}{2},\, -\tfrac{1}{2},\, -1,\, 0\right)\left(-\tfrac{1}{4},\, \tfrac{3}{4},\, \tfrac{1}{4},\, \tfrac{1}{4},\, \tfrac{3}{4},\, -\tfrac{3}{4},\, -\tfrac{3}{4},\, \tfrac{3}{4}\right)\ ,\\
W_2' &= \left(\tfrac{3}{4},\, \tfrac{3}{4},\, -\tfrac{1}{4},\, -\tfrac{1}{4},\, -\tfrac{1}{4},\, \tfrac{3}{4},\, \tfrac{1}{4},\, \tfrac{1}{4}\right)\left(-\tfrac{1}{4},\, -\tfrac{1}{4},\, -\tfrac{1}{4},\, -\tfrac{1}{4},\, -\tfrac{1}{4},\, \tfrac{1}{4},\, \tfrac{1}{4},\, \tfrac{3}{4}\right)\ ,\\
W_3 &= \left(-\tfrac{5}{6},\, -\tfrac{7}{6},\, \tfrac{1}{2},\, \tfrac{1}{2},\, \tfrac{1}{2},\, -\tfrac{1}{2},\, -\tfrac{1}{2},\, -\tfrac{1}{2}\right)\left(0,\, 0,\, \tfrac{1}{3},\, \tfrac{1}{3},\, \tfrac{1}{3},\, 0,\, 1,\, \tfrac{2}{3}\right)\ .
\end{aligned}$$



$\mathbb{Z}_6$–II Example

- $E_8 \times E_8 \xrightarrow{\mathcal{O}} \mathcal{G}_{4D} = \mathcal{G}_{SM} \times [\mathrm{SU}(6) \times \mathrm{U}(1)^7]$

4	$(\mathbf{3},\mathbf{2};\mathbf{1})_{1/6}$	q_i	1	$(\overline{\mathbf{3}},\mathbf{2};\mathbf{1})_{-1/6}$	$\bar{q}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1})_{-1/2}$	H_d	1	$(\mathbf{1},\mathbf{2};\mathbf{1})_{1/2}$	H_u
8	$(\mathbf{1},\mathbf{2};\mathbf{1})_{-1/2}$	ℓ_i	5	$(\mathbf{1},\mathbf{2};\mathbf{1})_{1/2}$	$\bar{\ell}_i$
4	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1})_{-2/3}$	$\bar{u}_i$	1	$(\mathbf{3},\mathbf{1};\mathbf{1})_{2/3}$	u_i
4	$(\mathbf{1},\mathbf{1};\mathbf{1})_{1}$	$\bar{e}_i$	1	$(\mathbf{1},\mathbf{1};\mathbf{1})_{-1}$	e_i
8	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1})_{1/3}$	$\bar{d}_i$	5	$(\mathbf{3},\mathbf{1};\mathbf{1})_{-1/3}$	d_i
1	$(\mathbf{3},\mathbf{1};\mathbf{1})_{1/6}$	v_i	1	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1})_{-1/6}$	$\bar{v}_i$
1	$(\mathbf{1},\mathbf{1};\overline{\mathbf{6}})_{1/2}$	w_i^+	1	$(\mathbf{1},\mathbf{1};\mathbf{6})_{-1/2}$	w_i^-
9	$(\mathbf{1},\mathbf{1};\mathbf{1})_{1/2}$	s_i^+	9	$(\mathbf{1},\mathbf{1};\mathbf{1})_{-1/2}$	s_i^-
6	$(\mathbf{1},\mathbf{2};\mathbf{1})_{0}$	m_i			

62	$(\mathbf{1},\mathbf{1};\mathbf{1})_0$	s_i
1	$(\mathbf{1},\mathbf{1};\mathbf{1})_0$	S
4	$(\mathbf{1},\mathbf{1};\overline{\mathbf{6}})_0$	$\bar{h}_i$
4	$(\mathbf{1},\mathbf{1};\mathbf{6})_0$	h_i

In a SUSY vacuum

$$W_{NMSSM} = S H_u H_d + \tfrac{1}{3}\langle s_i \rangle^6 S^3$$

In this model

$\lambda \sim 1,\ \ \kappa \sim 10^{-6} \ \ \rightarrow$ PQ limit with $m_{a_{PQ}} \sim$ GeV ☺

To take home...

In heterotic orbifolds with appealing features

- NMSSM less common than MSSMs
- suppressed S^3 coupling

  $\rightarrow$ PQ or "effective MSSM" $\checkmark$
- PQ symmetry has stringy origin (*not ad hoc*) $\checkmark$
- μ–problem & fine-tuning can be solved $\checkmark$