Singlet extensions of the MSSM with $\mathbb{Z}_4^R$-symmetry

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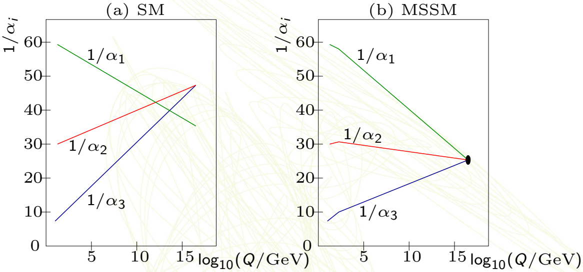
Based on:

- M. Ratz, P. V.: arXiv:1502.07207

Motivation for Supersymmetry

- Unification of gauge coupling constants α_i, $i = 1, 2, 3$



- Hierarchy stabilisation
- Dark matter candidate
- ...

⇒ Minimal Supersymmetric Extension of the Standard Model (MSSM)

Motivation against Supersymmetry

- Little hierachy problem:
  - Higgs mass a bit large
  - SUSY not yet found

$\Rightarrow$ Singlet extension of the MSSM

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M. Dine, N. Seiberg, S. Thomas 2007

- Add SM singlet N coupled to $H_u\,H_d$

$$\mathcal{W} \;\supset\; \underbrace{\mu H_u\,H_d}_{\mu\text{–term}} + \lambda_N\,N\,H_u\,H_d + \frac{1}{2}\mu_N\,N^2$$

- Integrate out N

$$\Rightarrow \mathcal{W}_\text{eff} \;\supset\; \mu H_u\,H_d - \frac{\lambda_N}{2\mu_N}\,(H_u\,H_d)^2$$

- Raise Higgs mass, ameliorate the fine–tuning
- But: μ–problem & proton decay $\Rightarrow \mathbb{Z}_4^R$

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The $\mathbb{Z}_4^R$ symmetry

If one demands:

1. anomaly freedom
2. fermion masses (Yukawa couplings & neutrino mass operator)
3. consistency with SU(5)
4. gauge coupling unification (anomaly universality)

$\Rightarrow$ only R symmetries can forbid the μ–term

If additionally

5. consistency with SO(10)

$\Rightarrow$ only $\mathbb{Z}_4^R$ symmetry can forbid the μ–term, where

H.M. Lee, S. Raby, M. Ratz., G.G. Ross, R. Schieren, K. Schmidt-Hoberg, P.V. 2010/2011

$$R(\text{matter}) = 1\,, \qquad R(\text{Higgs}) = 0\,, \qquad R(\mathcal{W}) = 2\,.$$

K.S. Babu, I. Gogoladze, K. Wang 2002

The $\mathbb{Z}_4^R$ symmetry

- $\mathbb{Z}_4^R$ charges:

$$R(\text{matter}) = 1\,, \qquad R(\text{Higgs}) = 0\,, \qquad R(\mathcal{W}) = 2\,.$$

- Most general superpotential:

$$\begin{aligned}\mathcal{W} &= \mu H_u\,H_d + Y^u\,Q\,\overline{U}\,H_u + Y^d\,Q\,\overline{D}\,H_d + Y^e\,L\,\overline{E}\,H_d \\ &\quad +\kappa\,L\,H_u + \lambda\,L\,L\,\overline{E} + \lambda'\,L\,Q\,\overline{D} + \lambda''\,\overline{U}\,\overline{D}\,\overline{D} \\ &\quad + \frac{1}{M_\mathrm{P}}\left(L\,H_u\,L\,H_u + Q\,Q\,Q\,L + \overline{U}\,\overline{U}\,\overline{D}\,\overline{E} + \ldots\right)\end{aligned}$$

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$\mathbb{Z}_4^R$ broken to matter parity by anomaly $\Rightarrow \mu \sim m_{3/2}$

NMSSM with $\mathbb{Z}_4^R$ symmetry

- Add SM singlet N coupled to $H_u\,H_d$

$$\mathcal{W} \supset \lambda_N\,N\,H_u\,H_d \quad \Rightarrow \quad R(N) = 2$$

- Hence, linear term unconstrained, $\Lambda \sim M_\mathrm{P}$

$$\mathcal{W} \supset \Lambda^2\,N + \lambda_N\,N\,H_u\,H_d$$

- Forbid linear term $\Lambda^2\,N$ by symmetry?

Such symmetry would forbid μ–term

$\Leftrightarrow$

Only $\mathbb{Z}_4^R$ can forbid μ–term

- No symmetry! Use holomorphic zeros!

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NMSSM with $\mathbb{Z}_4^R$ symmetry

- NMSSM with $\mathbb{Z}_4^R \times \mathrm{U}(1)_\mathrm{anom}$
- $\mathrm{U}(1)_\mathrm{anom}$ FI–term $\xi > 0$ cancelled by SM singlet ϕ, $R(\phi) = 0$:

$$D_\mathrm{anom} \;=\; \xi - |\phi|^2 \;\stackrel{!}{=}\; 0 \quad \text{with} \quad \varepsilon = \frac{\langle\phi\rangle}{M_\mathrm{P}} \;\sim\; \sin\vartheta_\mathrm{Cabbibo} \;\sim\; 0.2$$

- Non–perturbative term $e^{-b\,S}$ with $\mathbb{Z}_4^R \times \mathrm{U}(1)_\mathrm{anom}$ charges 2 and $s > 0$

$$\Rightarrow\; \mathcal{W}_\text{non–pert.} \;\supset\; \phi^s\, e^{-b\,S} \;\sim\; m_{3/2}$$

e.g. Arkani-Hamed, Dine & Martin 1998

NMSSM with $\mathbb{Z}_4^R$ symmetry

- Charges

	ϕ	$H_u H_d$	N	$e^{-b\,S}$
$\mathrm{U}(1)_{\mathsf{anom}}$	-1	$h > 0$	$n < 0$	$s > 0$
$\mathbb{Z}_4^R$	0	0	2	2

- Generalised NMSSM

M. Drees 1989

$$\mathcal{W}_{\mathrm{eff}} \supset f^2\,N + \mu\,H_u\,H_d + \lambda\,N\,H_u\,H_d + \mu_N\,N^2 + \kappa\,N^3$$

where

$$f \sim \varepsilon^{n/2} m_{3/2}\,,\ \mu \sim \varepsilon^{h} m_{3/2}\,,\ \lambda \sim \varepsilon^{n+h}$$

$$\mu_N \sim \varepsilon^{2n} m_{3/2}\,,\ \kappa \sim \varepsilon^{3n} \frac{m_{3/2}^2}{M_{\mathrm{P}}^2}$$

M. Ratz, P.V. 2015

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Conclusion

- The $\mathbb{Z}_4^R$ NMSSM
- Holomorphic zeros forbid linear term
- Effective superpotential

$$\mathcal{W}_{\text{eff}} \supset f^2\, N + \mu\, H_u\, H_d + \lambda\, N\, H_u\, H_d + \mu_N\, N^2 + \kappa\, N^3$$

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