A Supersymmetric One Higgs Doublet Model

Rhys Davies

Mathematical Institute,
University of Oxford

Particle Theory Journal Club,
Oxford, 5th May 2011

Outline

Introduction

Supersymmetrising the Higgs

The Supersymmetric One Higgs Doublet Model (SOHDM)

Basic phenomenology

Outline

Introduction

Supersymmetrising the Higgs

The Supersymmetric One Higgs Doublet Model (SOHDM)

Basic phenomenology

Overview

- Supersymmetry motivated by its solution of the hierarchy problem.
- It typically introduces other problems:
  - Baryon number violation by dimension four and five operators:

$$W \supset \boldsymbol{U^c D^c D^c} \; , \; \boldsymbol{QQQL} \ldots$$

  - Large flavour-changing neutral current (FCNC) couplings.
  - Large CP violation, e.g. fermion electric dipole moments.

Overview

- The Supersymmetric One Higgs Doublet Model (SOHDM):
  - One electroweak doublet gets a VEV and couples to fermions.
  - There is an anomaly-free global R-symmetry.[1]
- This has some very nice consequences:
  - The R-symmetry prevents baryon number violation.
  - Flavour is tied to SUSY breaking, and FCNC's are suppressed.
  - CP violation is greatly reduced compared to the MSSM.

[1] Assumed to be $U(1)_R$ throughout, but conclusions are unchanged if we take $\mathbb{Z}_n$ for $n > 4$.

Outline

The usual story: without supersymmetry

- In the Standard Model:
  - One scalar doublet: $H \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2})$. $\langle H \rangle := \frac{v}{\sqrt{2}} \simeq 174\text{GeV}$.
  - $SU(2) \times U(1)_Y \xrightarrow{\langle H \rangle} U(1)_{\text{EM}}$. Gauge boson masses:

$$\rho := \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$$

  - Fermion masses generated by

$$\mathcal{L}_{\text{Yuk}} = \lambda_U H Q U^c + \lambda_D H^\dagger Q D^c + \lambda_E H^\dagger L E^c$$

The usual story: the MSSM

- Supersymmetry gives H a spin-$\frac{1}{2}$ partner $\tilde{H}$. Two problems:
  - At the quantum level, $SU(2)\times U(1)_Y$ is now anomalous.
  - Yukawa couplings come (most simply) from trilinear superpotential terms. But holomorphy forbids $\int d^2\theta\, \lambda_D \boldsymbol{H}^\dagger \boldsymbol{Q}\boldsymbol{D^c}$.
- Easy to solve: introduce $\boldsymbol{H_d} \sim (\mathbf{1}, \mathbf{2}, -\frac{1}{2})$, and relabel $\boldsymbol{H}$ as $\boldsymbol{H_u}$.

$$\mathcal{L}_{\text{Yuk}} = \int d^2\theta \left(\lambda_U\, \boldsymbol{H_u Q U^c} + \lambda_D\, \boldsymbol{H_d Q D^c} + \lambda_E\, \boldsymbol{H_d L E^c}\right)$$

- Arrange for $\langle H_d \rangle \neq 0$ as well. Still get $\rho = 1$, and all fermions massive.

The MSSM Higgs sector in (more) detail

$$\mathcal{L}_{\text{Higgs}} = \int d^2\theta \, \mu \, \boldsymbol{H_u H_d} - m_u^2 |H_u|^2 - m_d^2 |H_d|^2 - B\mu H_u H_d + \ldots$$

- Given all positive soft masses-squared, radiative corrections drive $m_u^2 < 0$, hence $\langle H_u \rangle \neq 0$.
- For $B\mu \neq 0$, H_u and H_d mix, so we also get $\langle H_d \rangle \neq 0$.
- Phenomenology depends on $\tan\beta := \frac{v_u}{v_d}$.

One Higgs doublet models

- After supersymmetry is broken, we may expect to generate

$$\mathcal{L} = \lambda_D H_u^\dagger Q D^c + \lambda_E H_u^\dagger L E^c$$

  So do we need $\boldsymbol{H_d}$?

- Ibe et al. (arXiv:1012.5099) construct models in which H_d is replaced with a number of other fields, for anomaly cancellation. Problems:
  - New fields cancel anomalies, but otherwise appear arbitrary.
  - Difficult to generate sufficiently large masses for all new particles.
  - Electroweak symmetry breaking becomes much more complicated.

- Our idea: keep $\boldsymbol{H_d}$, but forbid its VEV and Yukawa couplings.

Outline

The SOHDM — Fermion masses

- $\boldsymbol{H_d}$ no longer a 'Higgs', so change notation:

$$\boldsymbol{H} \sim (\mathbf{1}, \mathbf{2}, \frac{1}{2}) \ , \ \boldsymbol{\eta} \sim (\mathbf{1}, \mathbf{2}, -\frac{1}{2})$$

- Let $\boldsymbol{X}$ be a chiral SUSY-breaking spurion: $\langle \boldsymbol{X} \rangle = F_X \theta^2$. Yukawas:

$$\mathcal{L}_{\rm Yuk} = \int d^2\theta \, \lambda_U \, \boldsymbol{HQU^c} + \int d^4\theta \, \frac{\boldsymbol{X}^\dagger \boldsymbol{H}^\dagger}{M^2} (\lambda'_D \, \boldsymbol{QD^c} + \lambda'_E \, \boldsymbol{LE^c})$$

where M is the messenger scale.

- The bottom quark mass now provides information about SUSY breaking

$$\frac{\lambda'_b F_X}{M^2} 174\text{GeV} \simeq 5\text{GeV} \quad \Rightarrow \quad \frac{F_X}{M^2} \simeq \frac{1}{35\lambda'_b}$$

So, assuming $\lambda'_b \lesssim 1$, we get $\frac{F_X}{M^2} \gtrsim \frac{1}{35}$.

The SOHDM — Higgs sector

- We need a weak-scale μ term (for chargino masses), but do *not* want a $B\mu$ term (to ensure $\langle\eta\rangle = 0$). R-symmetry!
- To implement Giudice-Masiero mechanism, take global $U(1)_R \times \mathbb{Z}_2$.

Field	Gauge rep.	R-charge	$\mathbb{Z}_2$-parity
$\boldsymbol{H}$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	0	1
$\boldsymbol{\eta}$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	2	-1
$\boldsymbol{X}$	$(\mathbf{1}, \mathbf{1}, 0)$	2	-1

$$\mathcal{L}_\mu = \int d^4\theta \, \frac{\boldsymbol{X}^\dagger}{M} \lambda_\mu \boldsymbol{H}\boldsymbol{\eta} \quad \Rightarrow \quad \mu = \lambda_\mu \frac{F_X}{M}$$

All matter: R-charge 1. $\boldsymbol{D^c}$ and $\boldsymbol{E^c}$ are $\mathbb{Z}_2$-odd.

- Note that $\langle \boldsymbol{X} \rangle = F_X \theta^2$ breaks SUSY and $\mathbb{Z}_2$, but not $U(1)_R$.

The SOHDM — Gauge sector

- Gauginos have R-charge 1, so cannot have Majorana masses.
- Introduce new chiral adjoints, $\boldsymbol{O} \sim (\mathbf{8}, \mathbf{1}, 0)$, $\boldsymbol{T} \sim (\mathbf{1}, \mathbf{3}, 0)$, with R-charge 0.
- For acceptable Dirac masses, need a D-term spurion: $\langle \boldsymbol{W'_\alpha} \rangle = D'\theta_\alpha$

$$\mathcal{L}_{\mathrm{D}} = \int d^2\theta \, \frac{\boldsymbol{W}'_\alpha}{M} \left(\lambda_G \mathrm{Tr}(\boldsymbol{O}\boldsymbol{G}^\alpha) + \lambda_W \mathrm{Tr}(\boldsymbol{T}\boldsymbol{W}^\alpha) \right)$$

$$\rightarrow \quad M_3 \mathrm{Tr}(\widetilde{O}\widetilde{G}) + M_2 \mathrm{Tr}(\widetilde{T}\widetilde{W}) + \dots \ ,$$

- In a concrete scenario realising this (Benakli and Goodsell, arXiv:1003.4957), the adjoint scalars are significantly heavier.

The SOHDM — Massless Bino

- We did not introduce $\boldsymbol{S} \sim (\mathbf{1}, \mathbf{1}, 0)$, because:
    - It interferes with breaking of SUSY and electroweak symmetry.
    - We don't need to!
- In the absence of such an $\boldsymbol{S}$, the bino is massless!
  (Actually the combination $-\tilde{\eta}^0 + \frac{\mu}{M_Z \sin\theta_W} \tilde{B}^0$)
- Surprisingly, this is allowed experimentally. Intuition:
    - At low energies, interacts only via sfermion exchange.
    - Behaves like a neutrino, with coupling suppressed by $\frac{M_Z}{\tilde{m}}$.
    - See Dreiner et al. (arXiv:0901.3485) for details.
- A massless bino cannot be dark matter, but that's okay.

The SOHDM — Summary

- Single Higgs doublet — down-type Yukawas after SUSY breaking.
- Combined F-term and D-term SUSY breaking.
- Low SUSY breaking/messenger scales ($\lesssim 100$ TeV).
  - This suggests gauge mediation, but no $\mu/B\mu$ problem!

The SOHDM — Summary

- Anomaly free *unbroken* R-symmetry:
  - No $B\mu$ term or A-terms.
  - Must introduce chiral adjoints to give gauginos Dirac masses.
- Massless mostly-bino neutralino. Can be given a weak-scale mass, but requires more model building.

Comparison to similar models

- Kribs, Poppitz, Weiner's "Minimal R-Symmetric Standard Model" (arXiv:0712.2039)
  - Has H_u and H_d, each with R-charge 0. μ term forbidden.
  - Chargino masses require introduction of R_u, R_d with R-charge 2.
- If $\mathcal{R}_{H_d} = 2$, R-symmetry must be explicitly broken at $\sim$ 5GeV. (e.g. Nelson et al. — arXiv:hep-ph/0206102)

Outline

Higgs sector

- H is now a pure Standard Model Higgs doublet. The physical Higgs mass saturates the MSSM upper bound at tree and one-loop levels.
- η^0 is the only visible-sector field with $\mathcal{R} = 2$. It appears as a complex scalar (i.e. *one* resonance in a collider).

Neutrino masses

- Lepton number violation via neutrino Majorana masses is allowed:

$$\frac{1}{M_*}\int d^2\theta\,\epsilon_{ab}\epsilon_{cd}\boldsymbol{H}^a\boldsymbol{H}^c\boldsymbol{L}^b\boldsymbol{L}^d \supset \frac{1}{M_*}\int d^2\theta\,(H^0)^2(\nu_L)^2\ ,$$

- Luckily, cannot arise from SUSY breaking, due to $\mathbb{Z}_2$ symmetry:

$$\int d^4\theta\,\frac{\boldsymbol{X}^\dagger}{M^3}\boldsymbol{H}^2\boldsymbol{L}^2 \quad \text{forbidden}$$

- Standard seesaw: introduce singlets N with R-charge 1:

$$\mathcal{L}_\nu = \int d^2\theta\left(M_R^2\boldsymbol{N}^2 + \lambda_\nu\boldsymbol{HLN}\right)$$

So $M_* = M_R$.

Flavour changing neutral currents

- Down-type Yukawas and scalar soft masses arise after SUSY breaking.
- Minimal flavour violation (MFV) therefore ‘almost automatic’.
    - Only FCNC couplings are quark-squark-gluino/neutralino, proportional to V_{CKM}.
    - No significant $\mu \to e\,\gamma$ etc.
- $K - \bar{K}$ mixing affected in MSSM by $\frac{1}{m_{\tilde{G}}}\tilde{d}^{\dagger}_{R}\tilde{s}_{L}\bar{d}_{R}s_{L}$. Forbidden by R-symmetry. See Kribs, Poppitz, Weiner (arXiv:0712.2039).

CP violation, proton decay

- Phases from A-terms are now gone.
- MFV suppresses off-diagonal soft masses, which may have large phases.
- Usual one-loop electric dipole-moments are not generated.

- The R-symmetry forbids baryon number violation.

Conclusion

- With only a small addition to the MSSM spectrum (chiral adjoints), we can address a number of issues in a nice way.
- The SOHDM (and R-symmetric models more generally) should be taken seriously in LHC searches.